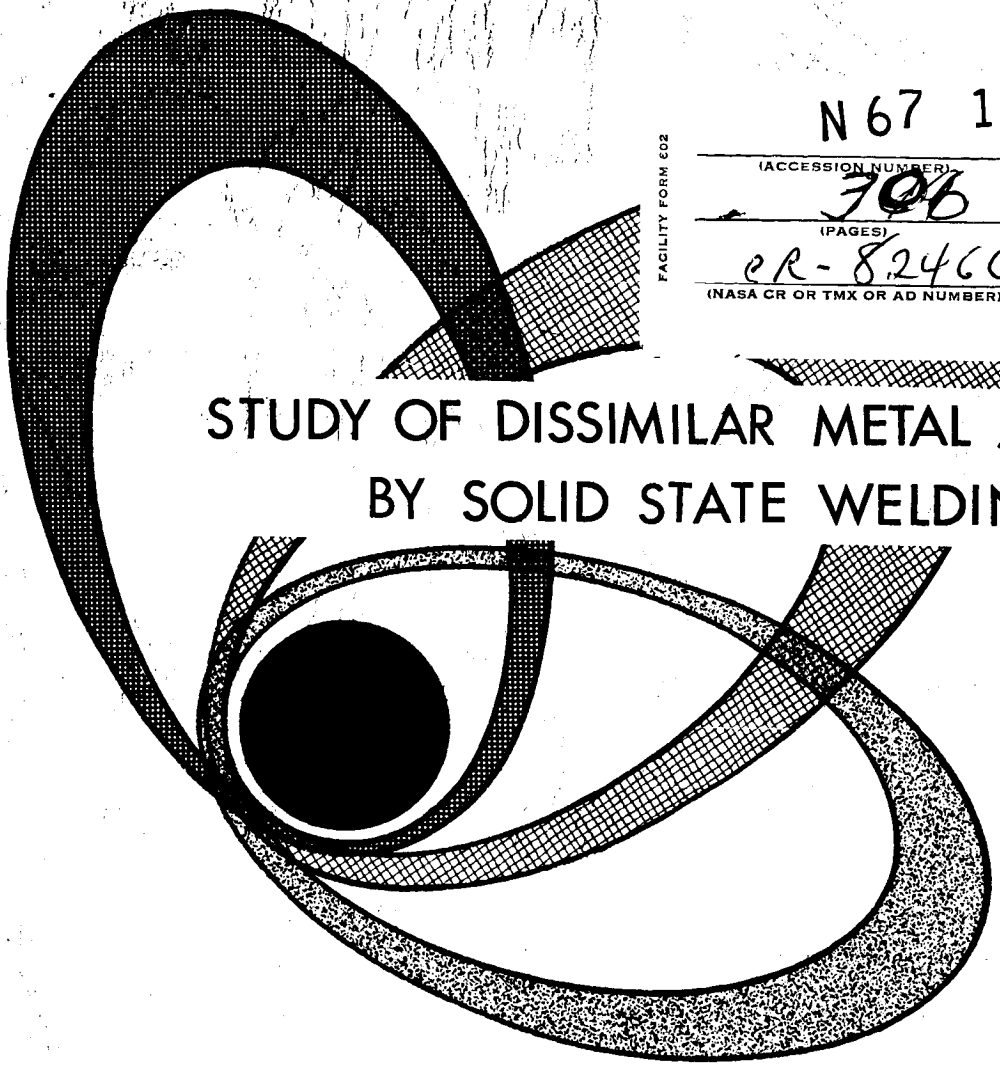
N67 19274
(ACCESSION NUMBER) 106 (PAGES)
CR-82460 (NASA CR OR TMX OR AD NUMBER)
(THRU) 1 (CODE) 15 (CATEGORY)
FACILITY FORM 602

STUDY OF DISSIMILAR METAL JOINING BY SOLID STATE WELDING



by

C. H. Crane
R. T. Torgerson
D. T. Lovell
W. A. Baginski

Prepared under Contract NAS 8-20156
Control Number DCN 1-5-54-01169 (1F)

by

THE BOEING COMPANY
Aerospace Group
Materials and Processes
Seattle, Washington

For

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Huntsville, Alabama

Final Report

October 1, 1966

This report was prepared by The Boeing Company under Contract NAS 8-20156, "Study of Dissimilar Metal Joining by Solid State Welding", for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration with W. A. Baginski as program supervisor, D.T. Lovell as technical leader and C. H. Crane and R. T. Torgerson as principal investigators. The work was administered under the technical direction of the Propulsion and Vehicle Engineering Laboratory, Materials Division of the George C. Marshall Space Flight Center with Melvin G. Olsen acting as project manager.

ABSTRACT

The objectives of this program were as follows:

1. To study the solid state welding of six dissimilar alloy combinations by press and roll diffusion welding and to establish the influence of major processing variables upon diffusion phenomena.

2. To determine the characteristics of diffusion welded joints between the six dissimilar metal combinations.

The influence of the primary diffusion parameters (time, temperature and pressure) and of the process variables (surface preparation, atmosphere and diffusion aid materials) were studied on the following six diffusion couples:

1. 2219 aluminum alloy to 321 stainless steel
2. 7106 aluminum alloy to 321 stainless steel
3. 2219 aluminum alloy to Ti-5Al-2.5Sn titanium alloy
4. 321 stainless steel to Ti-8Al-1Mo-1V titanium alloy
5. 321 stainless steel to Inconel 718 alloy
6. Inconel 600 to Ti-8Al-1Mo-1V titanium alloy

Metallurgical analyses were performed to follow element migration, to identify the compositions of the diffusion zones, and to determine the influence of thickness and hardness of the diffusion zones on the properties of the joint. Additional studies were made on the effect of material condition (heat treatment and strain hardening) on diffusion welding. The most promising diffusion welding techniques were further identified by metallurgical evaluation, mechanical and thermal shock testing, leak testing, and by corrosion studies.

The joining techniques which were determined to be the most promising were further analyzed by a theoretical projection of the diffusion welding process for production applications.

TABLE OF CONTENTS

	Page
INTRODUCTION	1
CONCLUSIONS	3
EXPERIMENTAL PROCEDURE	5
PHASE I - SURVEY OF SOLID STATE WELDING	11
PHASE II - DIFFUSION WELDING BY THE PRESS METHOD	12
WELDING OF BARE MATERIAL	12
WELDING WITH DIFFUSION AIDS	28
PHASE III - EFFECT OF MATERIAL SURFACE CONDITION	41
EFFECT OF STRAIN HARDENING AND HEAT TREATMENT	41
EFFECT OF MATERIAL SURFACE CONDITION	42
PHASE IV - DIFFUSION WELDING BY THE ROLL METHOD	45
WELDING OF BARE MATERIAL	45
WELDING WITH DIFFUSION AIDS	46
PHASE V - JOINT EVALUATION	48
SHEAR TESTS	48
CORROSION TESTS	53
PHASE VI - PROJECTION OF DIFFUSION WELDING APPLICATIONS	56
DESIGN STUDY	56
PROTOTYPE HARDWARE	57
REFERENCES	59
ACKNOWLEDGEMENT	60
APPENDIX A - LITERATURE SURVEY	A1-A51
APPENDIX B - MATERIAL CLEANING METHODS	B1-B2
APPENDIX C - ELECTROPLATING PROCEDURES	C1-C5
APPENDIX D - WELD DEVELOPMENT TESTS	D1-D51
APPENDIX E - PROCEDURES FOR PREPARATION OF METALLOGRAPHIC SPECIMENS	E1-E5

LIST OF TABLES

Table		Page
I	Nominal Chemical Composition of Selected Alloys	61
II	Melting Temperatures and Thermal Treatments for Selected Alloys	62
III	Hardness of As-Received Base Materials	63
IV	Thermal Expansion of Selected Alloys	64
V	Press Welding Test Schedule	65
VI	Press Welding Test Schedule	66
VII	Press Welding Test Schedule	67
VIII	Summary of Peel Test Results	68
IX	Press Welding - Effect of Air Atmosphere	69
X	Press Welding - Effect of Vacuum Environment	70
XI	Metal Foil Diffusion Aid Screening Test	71
XII	Electroplated Metal Diffusion Aid Screening Test	72
XIII	Diffusion Aid Parametric Study	73
XIV	Effect of Strain Hardened Material Condition	74
XV	Effect of Strain Hardening and Heat Treat Condition	75
XVI	Effect of Material Surface Condition	76
XVII	Roll Welding of Bare Material	77
XVIII	Summary of Shear Test Results - 2219 Aluminum Alloy to 321 Stainless Steel	78
XIX	Summary of Shear Test Results - 7106 Aluminum Alloy to 321 Stainless Steel	79

LIST OF TABLES (Cont'd)

Table		Page
XX	Summary of Shear Test Results - 2219 Aluminum Alloy to Ti-5Al-2.5Sn Alloy	80
XXI	Summary of Shear Test Results - Inconel 600 to Ti-8Al-1Mo-1V Alloy	81
XXII	Summary of Shear Test Results - 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy	82
XXIII	Summary of Shear Test Results - Inconel 718 to 321 Stainless Steel	83
XXIV	Summary of Roll Welded Shear Test Results	85
XXV	Welding and Test Conditions for Dissimilar Metal Tubular Joints	87

LIST OF FIGURES

Figure		Page
1	Comparison of Thermal Expansion of Selected Alloys	88
2	Microstructure of 2219-T6 Aluminum Alloy	89
3	Microstructure of 7106-T6 Aluminum Alloy	89
4	Microstructure of AISI 321 Stainless Steel	90
5	Microstructure of Ti-5Al-2.5Sn Titanium Alloy	90
6	Microstructure of Ti-8Al-1Mo-1V Titanium Alloy	91
7	Microstructure of Inconel 600 Alloy	91
8	Microstructure of Inconel 718 Alloy	92
9	Retort and Press Configuration	93
10	Retort and Specimen Configuration Used for Roll Welding	94
11	Rolling Mill Facility	95
12	Photograph Showing Surface of Welded 7106 Aluminum Alloy After Bend Test	96
13	Photograph Showing Surface of Welded 321 Stainless Steel After Peel Test	97
14	Effect of Welding Pressure on Compressive Yielding of 2219 Aluminum Alloy	98
15	Effect of Welding Pressure on Compressive Yielding of 7106 Aluminum Alloy	99
16	Effect of Welding Pressure on Compressive Yielding of 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy	100
17	Effect of Welding Pressure on Compressive Yielding of Inconel 600 to Ti-8Al-1Mo-1V Alloy	101
18	Effect of Welding Pressure on Compressive Yielding of Inconel 718 to 321 Stainless Steel	102

LIST OF FIGURES (Cont'd)

Figure		Page
19	Microstructure of Diffusion Welds of 2219 Aluminum Alloy to 321 Stainless Steel, 7106 Aluminum Alloy to 321 Stainless Steel and 2219 Aluminum Alloy to Ti-5Al-2.5Sn Alloy	103
20	Microstructure of Diffusion Welds of 2219 Aluminum Alloy to Ti-5Al-2.5Sn Alloy	104
21	Electron Microprobe Analysis of 2219 Aluminum Alloy to 321 Stainless Steel, 7106 Aluminum Alloy to 321 Stainless Steel and 2219 Aluminum Alloy to Ti-5Al-2.5Sn Alloy	105
22	Microstructure of Inconel 600 to Ti-8Al-1Mo-1V Alloy Diffusion Welds	106
23	Effect of Time, Temperature and Pressure on Diffusion Zone Thickness of Inconel 600 to Ti-8Al-1Mo-1V Alloy	107
24	Microstructure of Inconel 600 to Ti-8Al-1Mo-1V Alloy Diffusion Zone Welded at 1200°F	108
25	Microstructure of Inconel 600 to Ti-8Al-1Mo-1V Alloy Diffusion Zone Welded at 1350°F	109
26	Microhardness Traverse of Inconel 600 to Ti-8Al-1Mo-1V Diffusion Weld	110
27	Electron Micrograph of Diffusion Zone in Inconel 600 to Ti-8Al-1Mo-1V Diffusion Weld	111
28	Microprobe Analysis of Inconel 600 to Ti-8Al-1Mo-1V Alloy Diffusion Weld (90° Section)	112
29	Microprobe Analysis of Inconel 600 to Ti-8Al-1Mo-1V Alloy Diffusion Weld (15° Section)	113
30	Effect of Time, Temperature and Pressure on Diffusion Zone Thickness of 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy	114
31	Microstructure of 321 Stainless Steel to Ti-8Al-1Mo-1V Diffusion Welds (90° Section)	115
32	Microstructure of 321 Stainless Steel to Ti-8Al-1Mo-1V Diffusion Welds (1350°F)	116

LIST OF FIGURES (Cont'd)

Figure		Page
33	Microstructure of 321 Stainless Steel to Ti-8Al-1Mo-1V Diffusion Welds (1450°F)	117
34	Microhardness Traverse of 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy Diffusion Weld	118
35	Microprobe Analysis of Stainless Steel to Ti-8Al-1Mo-1V Diffusion Weld	119
36	Microstructure of 321 Stainless Steel to Inconel 718 Diffusion Weld	120
37	Effect of Time, Temperature and Pressure on Diffusion Zone Thickness of 321 Stainless Steel to Inconel 718 Alloy	121
38	Microstructure of Diffusion Zone of 321 Stainless Steel to Inconel 718 Weld	122
39	Microhardness Traverse of 321 Stainless Steel to Inconel 718 Diffusion Weld	123
40	Microprobe Analysis of 321 Stainless Steel to Inconel 718 Diffusion Weld	124
41	Microstructure and Microprobe Analysis of 2219 Aluminum Alloy to 321 Stainless Steel	125
42	Microstructure of Fractured 7106 Aluminum Alloy to 321 Stainless Steel Diffusion Weld	126
43	Microstructure and Microprobe Analysis of 2219 Aluminum Alloy to Ti-5Al-2.5Sn Alloy Diffusion Specimen	127
44	Microprobe Photographs of Tungsten Marker in 2219 Aluminum Alloy to Ti-5Al-2.5Sn Alloy Diffusion Weld	128
45	Microstructure of Inconel 600 to Ti-8Al-1Mo-1V Alloy Diffusion Weld Containing Tungsten Wire Markers	129
46	Microstructure of 321 Stainless Steel to Ti-8Al-1Mo-1V Diffusion Weld Containing Tungsten Wire Markers	130
47	Microprobe Analyses of Inconel 600 to Ti-8Al-1Mo-1V Alloy Diffusion Welds	131

LIST OF FIGURES (Cont'd)

Figure		Page
48	Microprobe Analyses of 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy Diffusion Welds	132
49	Microprobe Photographs of Inconel 600 to Ti-8Al-1Mo Diffusion Welds	133
50	Microprobe Photographs of 321 Stainless Steel to Ti-8Al-1Mo-1V Diffusion Welds	134
51	Electron Microscope Photographs of Inconel 600 to 321 Stainless Steel to Ti-8Al-1Mo-1V Diffusion Welds After 100 Hours at 1450°F	135
52	Microhardness Traverse of Inconel 600 and 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy Diffusion Welds After 100 Hours at 1450°F	136
53	Photographs of Inconel 600 and 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy Diffusion Welds	137
54	Microstructure and Microprobe Analysis of Inconel 718 to 321 Stainless Steel Diffusion Weld After 100 Hours at 1600°F	138
55	Photomicrographs Showing the Appearance of the Diffusion Weld of 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy With Silver and Vanadium Foils	139
56	Photomicrographs Showing the Diffusion of Gold and Copper Into Ti-8Al-1Mo-1V Alloy	140
57	Photomicrographs Showing the Appearance of Diffusion Weld Between 321 Stainless Steel and Inconel 718 with Copper and Nickel Foils	141
58	Photomicrograph Showing the Appearance of Diffusion Welds Between 7106 Aluminum Alloy and 321 Stainless Steel with Nickel Plating	142
59	Photomicrographs Showing the Appearance of Diffusion Welds Between Inconel 600 and Ti-8Al-1Mo-1V Alloy with Copper and Nickel Plating	143

LIST OF FIGURES (Cont'd)

Figure		Page
60	Microstructure of 2219 Aluminum Alloy to 321 Stainless Steel - Silver Electroplated	144
61	Microhardness Traverse and Microprobe Analysis of 321 Stainless Steel to 2219 Aluminum Alloy - Silver Electroplated	145
62	Microstructure of 321 Stainless Steel to 2219 Aluminum Alloy Diffusion Welds with Tungsten Wire Markers	146
63	Microstructure of 7106 Aluminum Alloy to 321 Stainless Steel Diffusion Weld - Silver Electroplated	147
64	Microhardness Traverse and Microprobe Analysis of 321 Stainless Steel to 7106 Aluminum Alloy Diffusion Weld - Silver Electroplated	148
65	Microstructure of 2219 Aluminum Alloy to 321 Stainless Steel Diffusion Weld - Copper Electroplated	149
66	Microstructure of 2219 Aluminum Alloy to 321 Stainless Steel Diffusion Weld - Copper Electroplated	150
67	Microhardness Traverse and Microprobe Analysis of 321 Stainless Steel to 2219 Aluminum Alloy Diffusion Weld - Copper Electroplated	151
68	Microstructure of 7106 Aluminum Alloy to 321 Stainless Steel Diffusion Weld - Copper Electroplated	152
69	Microhardness Traverse and Microprobe Analysis of 321 Stainless Steel to 7106 Aluminum Alloy - Copper Electroplated	153
70	Microstructure of Ti-5Al-2.5Sn to 2219 Aluminum Alloy Diffusion Weld - Silver Electroplated	154
71	Microhardness Traverse and Microprobe Analysis of Ti-5Al-2.5Sn to 2219 Aluminum Alloy Diffusion Weld - Silver Electroplated	155
72	Microstructure of 321 Stainless Steel to Ti-8Al-1Mo-1V Diffusion Weld - Silver Electroplated	156
73	Microstructure of 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy Diffusion Weld - Vanadium Foil	157

LIST OF FIGURES (Cont'd)

Figure		Page
74	Microhardness Traverse and Microprobe Analysis of 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy Diffusion Weld - Vanadium Foil	158
75	Microhardness Traverse and Microprobe Analysis of Inconel 600 to Ti-8Al-1Mo-1V Alloy Diffusion Weld - Vanadium Foil	159
76	Microstructure and Microprobe Photograph of 321 Stainless Steel to Inconel 718 Diffusion Welds - Nickel Foil	160
77	Microstructure of Strain Hardened Inconel 718 and 321 Stainless Steel After Diffusion Welding	161
78	Photomicrographs Showing the Effect of Surface Preparation on the Appearance of the Diffusion Weld Between Inconel 600 and Ti-8Al-1Mo-1V Alloy	162
79	Photomicrographs Showing the Effect of Surface Preparation on the Appearance of the Diffusion Weld Between Inconel 600 and Ti-8Al-1Mo-1V	163
80	Photomicrographs Showing the Effect of Surface Preparation on the Appearance of the Diffusion Weld Between the Inconel 718 and 321 Stainless Steel	164
81	Photomicrographs Showing the Effect of Surface Preparation on the Appearance of the Diffusion Weld Between Inconel 718 and 321 Stainless Steel	165
82	Microstructure of 321 Stainless Steel to 7106 Aluminum Alloy Diffusion Roll Weld	166
83	Microstructure of 321 Stainless Steel to Inconel 718 Diffusion Roll Weld	166
84	Microstructure of Ti-5Al-2.5Sn Alloy to 2219 Aluminum Alloy Diffusion Roll Weld	167
85	Photomicrograph of Ti-8Al-1Mo-1V Alloy to 321 Stainless Steel Diffusion Roll Weld - Aluminum Foil Interleaf	167

LIST OF FIGURES (Cont'd)

Figure		Page
86	Shear Specimen Configuration	168
87	Photomicrographs of Diffusion Welded Joints After Corrosion Testing	169
88	Arrangement for Diffusion Welding Cryogenic Heat Shields	170
89	Arrangement for Diffusion Welding Dissimilar Metal Tubular Joints	171
90	Configuration of Dissimilar Metal Tubular Assembly	172
91	Cross Section View of Dissimilar Metal Tubular Assemblies	173

INTRODUCTION

The design of components and systems for aerospace vehicles often requires the joining of dissimilar metals to meet the environmental conditions and the high performance requirements of the vehicle. Dissimilar metals joining is normally performed by mechanical methods because of the difficulties in obtaining metallurgically satisfactory joints by fusion welding or brazing. However, mechanical fasteners increase joint weight and present problems in maintaining a pressure-tight joint. Therefore, this research program was undertaken to study solid state joining by the diffusion welding method for six commonly used dissimilar metal combinations.

The development of design and processing data necessary to permit adaptation of a new joining method for use on complex structural systems requires an approach that will ensure integrity and reliability. This type of approach requires the development of (1) a basic understanding of the method, (2) practical processing controls for adaptation to production, and (3) property data obtained under simulated service conditions. This program was concentrated on the first item (i.e., basic understanding of solid-state welding), with sufficient fabrication and property data to evaluate the last two items.

The six dissimilar metal combinations selected for investigation were as follows:

1. 2219 aluminum alloy to 321 stainless steel
2. 7106 aluminum alloy to 321 stainless steel
3. 2219 aluminum alloy to Ti-5Al-2.5Sn titanium alloy
4. 321 stainless steel to Ti-8Al-1Mo-1V titanium alloy
5. 321 stainless steel to Inconel 718 alloy
6. Inconel 600 to Ti-8Al-1Mo-1V Titanium Alloy

These combinations were investigated by the press and roll welding methods to determine the nature and extent of diffusion welding obtainable and to establish the influence of the major processing variables upon diffusion mechanisms.

The program was conducted in six major phases:

I. Survey of Diffusion Welding

II. Diffusion Welding by the Press Method

III. Effect of Material Condition on Diffusion Welding

IV. Diffusion Welding by the Roll Method

V. Joint Evaluation

VI. Projection of Diffusion Welding Applications

Phase I consisted of a comprehensive state-of-the-art survey with emphasis placed on review of the press and roll welding methods. In Phase II, the effect of time, temperature and pressure on the diffusion welding of bare metal couples and couples with diffusion aids was investigated. In addition, the effect of air, argon and vacuum environments were determined. This phase included comprehensive metallurgical analysis of the diffusion zones. The effect of heat treatment and prior strain hardening on diffusion welding characteristics were evaluated in Phase III. In Phase IV, roll welding was conducted on the six metal couples. However, the roll welding studies were more limited in scope and emphasis was placed on the study of diffusion phenomena and comparison of results obtained for the press method. Joint evaluation, including helium-leak, mechanical and corrosion testing, was conducted in Phase V on the most promising press and roll welding processes. Based upon the results of the foregoing phases, a theoretical projection was made to determine how the processes developed can be adapted to production applications.

The results of the program are presented in the order of the above phases, except for inclusion of an "Evaluation Procedure" section prior to Phase I.

CONCLUSIONS

1. Diffusion mechanism studies of the six dissimilar metal combinations have achieved (1) significant advances in the understanding of diffusion characteristics and intermediate phase formation of the couples studied and (2) advances in techniques for metallurgical analysis of diffusion couples.

2. Temperature was the most influential of the primary diffusion parameters (time, temperature and pressure) in producing solid state diffusion of the dissimilar metal combinations.

3. Pressure was the least influential diffusion parameter; pressure greater than that required for intimate contact did not have a measurable effect on diffusion.

4. Metallurgically sound diffusion welds of excellent strength and toughness can be developed in the bare condition for the 321 stainless steel to Inconel 718 couple.

5. Diffusion welds of acceptable strength and ductility can be obtained in the bare condition with the aluminum alloy to stainless steel or titanium alloy couples provided critical parametric control and welding temperatures to 950°F are used.

6. Formation of brittle phases was the principal barrier to realizing high quality diffusion welds in the Ti-8Al-1Mo-1V to Inconel 600 and 321 stainless steel bare metal couples.

7. Acceptable joint peel strength and metallurgical characteristics can be obtained for all six dissimilar parent metal couples by using various diffusion aids. The major advantages of using diffusion aids were (1) lower welding temperature could be used, (2) the formation of detrimental intermediate phases could be controlled or prevented, and (3) greater tolerance of the diffusion parameters of time, pressure and temperature.

8. Silver electroplating produced the best overall joint characteristics when used as a diffusion aid in all couples except the Inconel 718 to 321 stainless steel, where nickel electroplate was the best. Silver is an excellent diffusion aid due to its inability to form a stable oxide (low negative free energy of formation) and therefore presents no surface barrier in air to the diffusion process at the selected welding temperatures.

9. In general, welding in air produced erratic diffusion weld quality in all but the silver-electroplated joints. Welding in argon produced weld strength, joint ductility and metallurgical characteristics which are comparable to those obtained under vacuum. Welding in a vacuum, however, completely eliminated any joint surface contamination during welding.

10. Some form of joint surface preparation was necessary for consistent, reliable welds. Chemical cleaning was the most acceptable method for bare couples, except for the 2219 aluminum alloy to Ti-5Al-2.5Sn couples for which light abrasive cleaning was preferred. Abrasive cleaning was the most acceptable method for joints with diffusion aids.

11. Strain hardening up to 65 percent reduction in sheet cross-sections prior to diffusion welding did not result in any measurable process or metallurgical difference in the diffusion zone width or weld quality when compared to welds in unstrained sheet material of the same alloy.

12. Diffusion welds made using Inconel 718 in the age-hardened condition exhibited similar strength and the same type of diffusion zone when compared to welds made in the annealed material.

13. The press method is adaptable to a greater variety of structural configurations than roll welding. However roll welding offers the advantages of (1) shorter diffusion times and (2) lower welding temperatures.

14. Based upon corrosion testing, all roll welded specimens appear resistant to a high humidity environment. All press welded specimens (except Inconel 718 to 321 stainless steel) appear to be somewhat susceptible to corrosion in a high humidity environment.

15. The consistency and strength of single lap joint shear tests for bare metal couples was, in general, good from room temperature to 800°F. For couples containing silver electroplated diffusion aids, shear strengths were acceptable and consistent from -423°F to approximately 300°F.

16. Numerous potential applications of the dissimilar metal joining methods developed in this program are anticipated for future aerospace structures, e.g., in fabrication of cryogenic propulsion and storage systems.

EXPERIMENTAL PROCEDURE

The following describes the material selection, surface preparation, electroplating procedure, welding procedure and evaluation technique used on all experimental work conducted in this program.

MATERIAL SELECTION

SHEET MATERIALS

The following seven materials, selected for joining in this program, were procured in the following heat treat condition and thickness:

1. 2219 aluminum alloy - solution treated and aged (-T6) - 0.058" thick
2. 7106 aluminum alloy - solution treated and aged (-T63) - 0.060" thick
3. 321 stainless steel - annealed - 0.081" thick
4. Ti-5Al-2.5Sn titanium alloy - annealed - 0.056" thick
5. Ti-8Al-1Mo-1V titanium alloy - duplex annealed - 0.059" thick
6. Inconel 600 alloy - annealed - 0.060" thick
7. Inconel 718 alloy - annealed - 0.060" thick

Nominal chemical composition of the selected alloys are shown in Table I. The melting temperatures and thermal treatments are shown in Table II. The hardness of the alloys are shown in Table III and the thermal expansion characteristics are listed in Table IV and are shown graphically in Figure 1. The microstructure of the alloys in the above conditions are shown in Figures 2 through 8. This reference information was used to establish testing parameters and to aid in evaluating program results.

All work was conducted with the sheet materials in the foregoing conditions except for the following:

1. Inconel 718 was also welded in the solution treated and aged condition.
2. Several of the alloys were welded in the strain hardened condition. The material was prepared by cold rolling to gage reductions which varied from 10 to 70 percent.

FOIL MATERIALS

Based on the results of the diffusion welding survey conducted in Phase I (Appendix A) the following commercially pure metal foils and thicknesses were selected for diffusion aid studies discussed in this program:

1. Gold (0.001")
2. Silver (0.001")
3. Copper (0.001")
4. Nickel (0.001")
5. Titanium (0.001")
6. Iron (0.001")
7. Vanadium (0.002")
8. Aluminum (0.005")

All the foregoing foils were used for diffusion aids in the as-received condition (without annealing or cleaning) with the exception of the copper and aluminum foils which were cleaned as described in the following section.

SURFACE PREPARATION

The various surface preparations used in the welding program are as described below:

SHEET MATERIAL

The seven sheet materials were welded (1) in the bare condition, (2) in the chemically cleaned and (3) in the abrasively cleaned conditions. Chemical cleaning was performed using the solutions shown in Appendix B. The material was welded within 6 hours after cleaning. Abrasively cleaned material was prepared by taking material which had been previously chemically cleaned, followed by sanding with 80 grit sandpaper and wiping with acetone. Abrasively cleaned material was welded within 2 hours after cleaning.

The sheet materials were also welded with polished surfaces and with surfaces having a 1000 RHR finish. Polished surfaces were prepared on metallurgical polishing equipment using 0.25 micron diamond paste followed by solvent cleaning. The 1000 RHR finish was produced by milling with a fly cutter and followed by solvent cleaning. The polished and machined surfaces were welded within 24 hours after surface preparation.

FOIL MATERIAL

The foil materials were all used in the as-received condition except for copper and aluminum. These two metals were deoxidized using nitric acid for copper and nitric-hydrofluoric acid solution for aluminum as outlined in Appendix B.

ELECTROPLATING

All seven sheet materials were electroplated with various metals for the diffusion aid studies. The faying surfaces of each material in the weld combination were electroplated. Prior to welding, the plated surfaces were lightly sanded and wiped with acetone. The sheet alloys were plated with the metals as follows:

1. 2219 aluminum alloy - copper, silver
2. 7106 aluminum alloy - copper, silver
3. 321 stainless steel - copper, silver, nickel
4. Ti-5Al-2.5Sn alloy - copper, silver
5. Ti-8Al-1Mo-1V alloy - copper, silver
6. Inconel 600 alloy - copper, silver
7. Inconel 718 alloy - silver, nickel

The aluminum alloys and the titanium alloys had the copper and silver electroplated on with the sheet material both in the bare condition and with anodized surfaces. Complete electroplating processing for all materials is given in Appendix C.

WELD PROCEDURE AND JOINT EVALUATION

The following describes the procedures used for welding and joint evaluation in this program.

PRESS WELDING

Press welding was conducted using the following equipment:

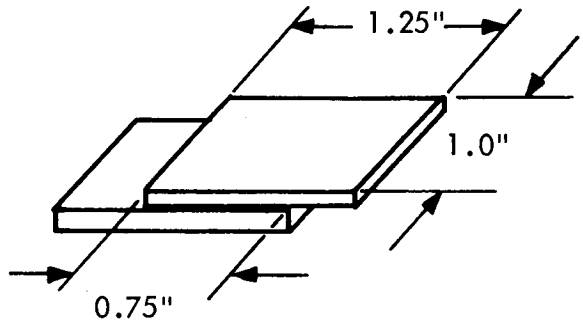
1. Welding requiring a high temperature inert or air atmosphere was conducted in a 15,000 pound press located within an air atmosphere furnace having a 1900°F maximum operating temperature. When welding required an inert atmosphere, retorts were used in this facility as shown in Figure 9.

2. Welding requiring a vacuum environment was conducted in a 40,000 pound press located in a cold wall vacuum chamber. Heating of the specimen was accomplished using strip heaters which were located between the press ram and platen. The maximum operating temperature of the facility was 1750°F. The vacuum varied between 2×10^{-5} and 5×10^{-6} mm Hg during welding.

3. Welding requiring a low temperature air atmosphere environment was conducted in a 40,000 pound open press having heated platens. The maximum operating temperature of the facility was 750°F.

Specimen Preparation

Lap specimens having the configuration shown in the following sketch were used for the diffusion welding studies.



Prior to welding the specimens were given the desired surface preparation as previously described.

Welding Procedure

Specimens which were welded at temperatures above 750°F required a parting material to be placed between the specimen and retort or ram to prevent welding at these surfaces. Thin sheets of alumina-silica ceramic fiber paper were used for this purpose. Usually three specimens were welded in tandem as shown in Figure 9 to expedite the welding process studies.

After the specimens were prepared and inserted in the welding press, a low pressure (~ 2500 psi) load was applied. This pressure was increased to the desired welding pressure after the specimens reached the welding temperature. All processing data for each specimen was tabulated as shown in Appendix D. After the welding cycle was completed, the specimens were cooled to room temperature without pressure. The specimens were then evaluated for weld quality as described in the following sections.

Evaluation Procedure

The welded specimens were visually inspected for evidence of welding and measured for the amount of material deformation which occurred during welding. Specimens were then subjected to thermal shock test by immersion in LN_2. Specimens which passed the thermal shock test were cut in half with an abrasive cut-off wheel. One-half was reserved for metallurgical analysis and one-half was used for a peel test.

The peel test was performed by peeling one-half of the specimen with a pair of pliers while gripping the other half in a vise. The peel test was used only as a qualitative method of estimating diffusion bond quality. When the peeling action resulted in a substantial deformation of one of the metals in the specimen, the failure mode was termed ductile. When little or no deformation occurred during peeling, the failure was termed brittle. The relative force required to accomplish the peeling, which is a qualitative indication of bond strength, was noted. After peeling, the faying surfaces were inspected visually to evaluate the degree of bonding. The results of this evaluation are tabulated in Appendix D.

Specimens which were judged to warrant further evaluation (based on visual examination, peel tests and thermal shock tests) were subjected to metallurgical analysis. The initial step in the metallurgical evaluation was to prepare a microsection and examine the joint interface for degree of welding and presence of diffusion zones. From this initial study, specimens were selected for further metallurgical investigation. The extent of the additional evaluation varied dependent upon the particular specimen, but included preparation of appropriate photomicrographs and measurement of diffusion zone thickness and hardness. Where applicable, intermediate phases at the interface were further analyzed by electron microprobe analysis, and electron microscopy. To facilitate these analytical studies, 15-degree taper microsections, which permit a four-fold "bandspread" of a perpendicular cross section were prepared.

ROLL WELDING

Sheet material was prepared for roll welding using the same surface preparation as discussed previously. Roll welding was conducted in an inert atmosphere using sealed retorts as shown in Figure 10. The retort was purged with argon gas prior to heating, during heating and during rolling. The roll welding was accomplished in one pass using a laboratory rolling mill, Figure 11, having 5-inch diameter rolls capable of exerting a roll pressure of 100,000 pounds. After rolling, the retort was stripped and the roll welded specimen was subjected to the following evaluations.

Process Evaluation

After roll welding, the specimens were measured to determine the amount of material thinning for each alloy combination. Pieces were cut from the roll welded specimen for testing as shown in Figure 10. The peel test was used to determine relative weld strength as described in the press welding section. The bend and torsion tests were used to determine if the roll welded sheets contained adequate strength and ductility to permit forming and machining operations which might be required in fabrication of future parts. The results of this evaluation were tabulated in Appendix D.

Metallurgical Evaluation

Roll welded specimens which were satisfactorily joined during rolling were subjected to metallurgical analysis to determine the degree of welding and for the presence of a diffusion zone. Photomicrographs were prepared of the diffusion zone microstructure.

PHASE I - SURVEY OF SOLID STATE WELDING

A comprehensive state-of-the-art survey was conducted on joining of dissimilar metals by solid state welding. The survey consisted of a literature search and a state-of-the-art tour to selected organizations believed to be the most able to provide useful information. The emphasis of the survey was on joining of the types of dissimilar metal combinations which were selected for study in the experimental program.

Consideration was given to joining with and without the use of diffusion aids. Review was made of the various solid state welding methods, but emphasis was placed on press and roll diffusion welding since these techniques were used in the program.

The information from the state-of-the-art survey has been compiled as a separate report and is included in Appendix A.

PHASE II - DIFFUSION WELDING BY THE PRESS METHOD

In this phase of the program the press welding of the six dissimilar alloy combinations was investigated. Comprehensive studies were conducted for pressing welding of (1) bare metal couples and (2) couples with interfacial diffusion aids. The effect of air, argon and vacuum environments on diffusion characteristics were also investigated. Weld characteristics were determined by thermal shock, peel and metallurgical testing, using the procedures as previously described.

The major investigative effort of the program was conducted in this phase. Therefore, the results and discussion will be presented in two major sections:

1. Welding of Bare Material

2. Welding with Diffusion Aids

WELDING OF BARE MATERIAL

The press welding of the couples in the bare condition was initially conducted in an argon atmosphere from a high-purity liquid argon source. The welding procedures used are described in detail in the previous section. The selection of the major test variables and test results are described below.

TEST VARIABLES

From the results of screening tests, three times, three temperatures and three pressures for a total of 27 test conditions were chosen for each alloy combination as shown in Tables V, VI, and VII. The following describes the method used in selecting these variables:

1. Welding Temperature

   The lowest temperature used was one at which the alloy combination would show consistent diffusion welding in a time of approximately 1 hour and with a pressure which was adequate for bringing the materials into intimate contact. The higher temperatures selected were those which were compatible with the thermal processing requirements of each alloy and yet high enough to produce a discrete diffusion zone to facilitate the diffusion studies. However, in the case of the alloy combinations containing aluminum base alloys a measurable diffusion zone could not be observed (metallographically) at any temperature up to 1000°F, which is considered the maximum exposure temperature of these alloys.

2. Welding Pressure

The lowest welding pressure selected for each combination was one that produced very low or no specimen deformation at the lower welding times and temperatures. The higher pressures selected were those that permitted an adequate pressure gradient for the diffusion studies but without producing excessive (over 50 percent) specimen deformation.

3. Welding Time

The shortest welding time selected for each combination was that which would produce consistent diffusion welding at the selected welding temperature. The longer welding times selected were those that permitted an adequate time gradient for the diffusion studies.

THERMAL SHOCK TESTING

The thermal shock test very seldom resulted in a failure of the joined specimens at the diffusion weld interface. In the majority of the cases in which failure did occur the specimens contained a very small amount of effective welded area and thus permitted the differential thermal contraction rates of the materials in the combination to shear the joint interface. See Appendix D.

However, the 7106 aluminum alloy to 321 stainless steel combination, when welded at 1000°F, always failed or partially failed during the thermal shock test. Visual inspection of the faying surfaces of these specimens revealed that they had been completely welded; however, brittle fracture occurred at the interface. Figure 12 shows a photograph of the faying surface of 7106 aluminum alloy after a 0.25-inch radius free bend test. The closely spaced horizontal lines in the photograph are cracks in the brittle phase which adhered to the surface of the aluminum. These same cracks were observed on the surface of the 321 stainless steel after bending.

PEEL TESTING

The peel tests were conducted on the six dissimilar alloy couples welded in the bare condition as a method to estimate the strength and ductility of the joint and to permit observations as to the completeness of the weld and the appearance of the fracture interface. The following describes the results of these tests:

a. 2219 Aluminum Alloy to 321 Stainless Steel

The attainment of a complete solid state weld between this couple in the bare condition is difficult. Strength levels achieved were low and are considered inadequate. Table VIII summarizes the results of the peel tests.

b. 7106 Aluminum Alloy to 321 Stainless Steel

A solid state weld may be developed in this couple with relative ease. The joint faying surfaces after peeling always appear smooth and glossy.

The specimens, as previously noted during thermal shock testing, were brittle when joined at 1000°F. The joints exhibited moderate strength when joined at the 900° and 950°F temperatures as shown in Table VIII.

c. 2219 Aluminum to Ti-5Al-2.5Sn Alloy

This alloy combination exhibited a medium to high peel strength when joined at temperatures from 900° to 1000°F as shown in Table VIII. The faying surfaces of the aluminum after peeling occasionally appeared crazed indicating the interface contains a zone consisting of a brittle phase. However, the strength and ductility of the joints are considered good.

d. Inconel 600 Alloy to Ti-8Al-1Mo-1V Alloy

This combination produced sound diffusion welded joints with relative ease. The fractured surfaces where shiny and extremely smooth. The joints were always brittle which made the peel strength of the joint difficult to estimate.

e. 321 Stainless Steel to Ti-8Al-1Mo-1V Alloy

This combination welded with relative ease. During peeling the specimens failed in the same manner described for the Inconel 600 to Ti-8Al-1Mo-1V combination.

f. 321 Stainless Steel to Inconel 718

This combination was difficult to join consistently at 1325°F. The combination joined with ease at the 1600° and 1725°F temperatures. These specimens were extremely difficult to peel. Peeling, when possible, could only be accomplished by driving a sharp chisel into the joint interface. Peeled specimens exhibited smooth, grey-colored surfaces. These surfaces tarnished in air very quickly. Observation of the 321 stainless steel revealed a thin metallic film present on the faying surface. Figure 13, a photograph of 321 stainless steel after peeling, shows where this film was removed when it adhered to the Inconel 718. The vertical lines on the photograph are imprints on the thin layer resulting from the sanded surface of the Inconel 718 alloy.

COMPRESSIVE DEFORMATION MEASUREMENTS

The compressive yielding of the specimens as a result of the welding pressure is shown for each specimen in Appendix D and is summarized graphically for each combination in Figures 14, 15, 16, 17, and 18. The figures show the relationship between the three major parameters (time, temperature, and pressure) and the amount of compressive yielding.

The thermal shock and peel tests showed that a minimum total specimen compressive yielding of approximately 0.002 to 0.003-inch is required for alloy combinations to insure that the faying surfaces were uniformly in intimate contact. When pressures were insufficient, welding would only occur in the localized areas where the material surfaces were in contact. Compressive yielding, once beyond the range of approximately 0.003-inch, had no measurable effect on the strength, ductility or appearance of the diffusion welded joint.

METALLURGICAL STUDIES

In view of the complexity of the six alloy couples being investigated in this program, involving diffusion of five or more major elements, classical analyses of the Kirkendall type were not attempted. Instead, predictions of diffusion mechanisms and correlation of experimental diffusion behavior were made on the basis of a firm knowledge of pertinent phase diagrams, specific diffusion coefficients, solubility rules and physical constants. Extensive use was made of References 1, 2, 3 and 4 in the analysis of diffusion characteristics and identification of intermediate phases in the diffusion zones.

The metallurgical studies of the couples in the bare condition were initially conducted using diffusion welding parameters which "bracketed" what was considered the general range of the best overall schedules. However, in order to obtain more detail information of the interdiffusion mechanisms (i.e., element migration), pre-placed inert markers (0.0005-inch diameter tungsten wire) were used in the joint interface. Diffusion welding times up to 100 hours were used to develop discrete diffusion zones.

The results of these two studies are presented separately for each alloy couple. The metallographic procedures used have been previously described.

Aluminum Alloy Combinations - Bare Condition

The following three combinations were evaluated:

1. 2219 Aluminum Alloy to 321 Stainless Steel
2. 7106 Aluminum Alloy to 321 Stainless Steel
3. 2219 Aluminum Alloy to Ti-5Al-2.5Sn

Typical microstructures of specimens diffusion welded at 950°F for each of these three combinations are illustrated in Figure 19. Metallurgical examination of the three alloy combinations welded at 900°, 950°, and 1000°F revealed no diffusion zone of sufficient thickness to be measurable for any of the 27 diffusion welding test conditions. Electron microscopic studies were conducted to further define the microstructure and measure the thickness of the diffusion zones. Optical and electron micrographs of the 2219 aluminum alloy to Ti-5Al-2.5Sn combination are shown in Figure 20. The extremely thin diffusion zone (approximately 0.5 microns) is revealed in the electron micrograph. This electron micrograph is typical of all three diffusion couples containing an aluminum alloy.

The electron microprobe analyses of the three aluminum combinations are shown in Figure 21. Based upon the optical and electron micrographs, it is evident that the diffusion zone widths of Al and Fe, and Al and Ti, indicated by the microprobe results, can be misleading. Figure 21 indicates a diffusion zone width of approximately 4 microns, whereas the electron micrograph, Figure 20, indicates a zone of 0.5 micron. This apparent discrepancy is caused by the diameter of the electron microprobe beam, which is 1 to 2 microns. During scanning of an extremely thin zone, such as that shown in Figure 20, the microprobe beam senses the zone from the time the initial outer periphery contacts it until the beam has completely passed over the zone. Therefore, the microprobe indications may be approximately 1 to 2 microns wider on each side of the zone than the actual zone width.

The results of the metallurgical evaluations for the aluminum-containing couples in the bare condition indicate an acceptable solid state weld can be obtained. However, critical parametric control and diffusion welding temperatures between 900° to 950°F are required. At these temperatures the aluminum alloys will necessarily be in the low-strength condition after welding.

Inconel 600 to Ti-8Al-1Mo-1V - Bare Condition

Metallographic examinations were conducted on press welded specimens for the 27 diffusion welding test conditions listed in Table VI. Examination for diffusion weld quality revealed complete solid state welding had resulted for specimens of all of the 27 test conditions except those which were welded at 1200°F with 12.5 ksi pressure. These specimens contained approximately 15 percent of void area.

Photomicrographs were taken of 90° cross-sections of each specimen and measurements made of the total diffusion zone thickness. Microstructures of typical specimens diffusion welded at 1200°, 1350° and 1450°F are shown in Figure 22. Polishing and etching techniques used in preparation of the metallographic specimens are described in Appendix E.

Results of the diffusion zone thickness measurements are presented graphically in Figure 23 as a function of time, temperature and pressure parameters. These data reveal that the welding temperature is the most sensitive parameter in producing solid state diffusion of the alloy combination. This test work also showed that a welding pressure of a magnitude sufficient to bring the faying surfaces of the metal into intimate contact is required, and that greater pressures have no measurable effect on the growth of the diffusion zone.

Metallurgical studies conducted with 15° taper microsections revealed that the diffusion zone is composed of four zones or bands of varying thickness. Generally only three of these zones can be observed in the microstructure of specimens welded at 1200°F as shown in Figure 24. All four zones are evident with the more extensive diffusion of specimens welded at 1350°F as shown in Figure 25. In the unetched condition (Figure 25a) only one zone is apparent in the microstructure. However, after etching (Figure 25b), the weld microstructure resolves as one thick zone and three much thinner zones.

Microhardness measurements revealed that the thick zone in the weld is significantly harder than either base metal. A typical microhardness traverse of a 90° cross-section is shown in Figure 26 for a specimen diffusion welded at 1450°F. Accurate hardness measurements were difficult to obtain for the thinner diffusion zones even using 15° taper microsections, but in general the values ranged between the hardness of the thick zone and the hardness of the base metals. Hardness values obtained for the thick zone were as high as 450 KHN for measurements conducted on 15° taper microsections.

Results of electron microscope examination of selected specimens revealed additional information on the character of the four zones in the diffusion weld. An electron micrograph of a carbon replica of a specimen diffusion welded at 1350°F is shown in Figure 27. The microstructure of the diffusion zone indicates that zone 2 is probably an intermediate (intermetallic) phase. Zone 1 could also be a single phase layer while zones 2 and 4 appear to be mixtures of two or more phases. Study of the microstructure indicates that zone 4 is probably composed of the zone 3 phase and titanium alloy. The zone 3 intermediate phase appears to form at a faster rate along the grain boundaries which causes formation of islands of titanium alloy.

Typical electron microprobe analyses of the diffusion zones of Inconel 600 to Ti-8Al-1Mo-1V diffusion welds are presented in Figures 28 and 29. The concentration of elements is indicated by values of uncorrected line intensity. Since the relationship of line intensity to element concentration is not linear, more accurate chemical compositions in specific areas were determined by point count techniques. Microprobe traverses conducted on 90° cross-section specimens, Figure 28, revealed several very significant features of the diffusion zone.

Additional microprobe traverses conducted on 15° taper microsections, Figure 29, provided better resolution of the chemical variation in the diffusion zone.

The following observations were made from the results of the electron microprobe studies:

1. Migration of Ni into the titanium-base alloy proceeds very rapidly at the higher diffusion welding temperatures (1350° and 1450°F).

2. Fe in the Inconel 600 migrates somewhat slower than Ni while Cr diffuses very slowly into Ti alloy compared to Ni. The result is a band of high Cr and Fe content. This reverse migration or Cr and Fe atoms is tentatively attributed to phenomena related to the "Kirkendahl effect". The rapid diffusion of Ni atoms results in an interface shift with an increase in concentration of Cr and Fe atoms relative to Ni atoms on the Inconel alloy side of the interface.

3. Flattening of the Ni and Ti concentration curves coincides with the thick zone (Zone 3) in the diffusion weld and is indicative of an intermediate phase of Ni and Ti. The presence of only one intermediate phase is evident in microprobe traverses of diffusion zones of welds made at 1200°, 1350° and 1450°F.

More accurate analyses of composition were made at various spots in the diffusion zone by microprobe point count techniques. This type of analysis conducted on 15° taper microsections of specimens welded at 1350° and 1450°F revealed that the average composition of the diffusion zone at the flat part (Zone 3) of the Ni concentration curve is approximately 52% Ni, 3%Fe and 45% Ti. Review of equilibrium phase diagrams for the Ni-Ti system shows three intermediate phases which might be expected to be present. These are: $TiNi_3$ (78 wt. % Ni), TiNi (55 wt. % Ni) and Ti_2Ni (40 wt. % Ni). The microprobe analysis of the thick zone (Zone 3) in the Inconel 600 to Ti-8Al-1Mo-1V welds corresponds to the composition of the TiNi intermediate phase.

Although the presence of the two other intermediate phases $TiNi_3$ and Ti_2Ni might be expected, the rate of formation of these phases may be too slow at the welding temperatures to achieve sufficient layer thickness to permit observation in the diffusion zone by microprobe analysis. A further complicating factor is the effect of the principal alloying elements Fe, Cr and Al on the formation of diffusion zones. This did not present a problem with analysis of Zone 3 since its formation proceeded at such a rapid rate that the amount of other alloying elements diffusing into this phase was not significant.

321 Stainless Steel to Ti-8Al-1Mo-1V - Bare Condition

The thickness of diffusion zones of specimens diffusion welded under 27 test conditions of time, temperature and pressure are presented in Figure 30. Comparison of these data to Figure 23 reveals much slower diffusion at 1200°F and 1350°F for the 321 stainless steel to Ti-8Al-1Mo-1V combination than for Inconel 600 to Ti-8Al-1Mo-1V, but similar rate of diffusion at 1450°F. Typical microstructures of specimens diffusion welded at 1200°, 1350° and 1450°F are shown in Figure 31. These specimens were etched lightly using only the titanium alloy etch since attempts to develop the 321 stainless steel microstructure resulted in destroying the microstructure of the diffusion zone. Metallographic preparation procedures are described in Appendix E.

Metallographic examination revealed varying degrees of scattered voids (lack of bonding) at the interface of specimens welded at 1200°F and for specimens welded for 10 minutes at 1350°F. Several of the latter specimens fractured along the interface during preparation of the metallographic specimens. The diffusion zone for these specimens was generally too thin ($\sim$ 0.02 mils) to be measured.

Figure 32 shows the unetched and etched microstructure of a 15° taper microsection of a specimen diffusion welded at 1350°F. No diffusion zone is evident in the unetched microstructure (Figure 32a) but two distinct diffusion zones can be observed in the etched condition (Figure 32b). Two diffusion zones can be observed in the microstructure of specimens welded for 10 minutes at 1450°F as shown in Figure 33. Three diffusion zones can be observed in the microstructure of specimens welded 120 minutes at 1450°F (Figure 33).

A microhardness traverse across the diffusion zone of a specimen welded at 1450°F is shown in Figure 34. Zone 2 exhibits high hardness (KHN 480) while no accurate hardness could be obtained for the thinner zones.

Typical electron microprobe analyses of the diffusion zone of 321 stainless steel to Ti-8Al-1Mo-1V diffusion welded at 1450°F are presented in Figure 35. Observations from the microprobe studies are as follows:

1. Migration of Fe into Ti alloy proceeds quite rapidly at 1450°F and is accompanied by rapid migration of the Ni content of the stainless steel.

2. Cr migrates slowly into Ti alloy compared to the Fe and Ni diffusion rate. The result is a zone of high Cr content on the stainless steel side of the interface. This reverse migration of Cr is attributed to the same phenomenon as previously discussed for Inconel 600 to Ti-8Al-1Mo-1V diffusion welds.

3. Flattening of the Fe curve which takes place at a relatively low concentration of Fe appears to coincide with Zone 2.

Microprobe point count techniques indicate an average Fe content of 24%, a Ni content of 2% and a Ti content of 74% for the flat portion of the curve. The total Fe and Ni content is approximately 26% which does not correspond to any of the intermediate phases which, from the equilibrium phase diagram, might be expected to be present in the diffusion zone. Available data indicates that TiFe (54 wt. % Fe) and $TiFe_2$ (70 wt. % Fe) are the most likely intermediate phases under equilibrium conditions, while Ti_2Fe (40 wt. % Fe) and $TiFe_3$ (78 wt. % Fe) intermediate phases are indicated as possibly being present.

321 Stainless Steel to Inconel 718 - Bare Condition

Typical microstructures of 321 stainless steel to Inconel 718 specimens diffusion welded at 1325°, 1600° and 1750°F are shown in Figure 36. Incomplete welding and/or fracturing shown by the specimen welded at 1325°F, Figure 36, is characteristic of specimens diffusion welded at this temperature. Specimens welded at 1600° and 1750°F were completely welded and displayed diffusion zones of measurable thickness, Figue 37.

Metallographic examination revealed varying degrees of scattered voids (lack of welding) at 1325°F for times up to 2 hours. However, at the 1600° and 1750°F welding temperature, complete and effective solid state welding occurred. At 1600°F for 2 hours, Figure 38, the visible diffusion zone at 500X appears to have changed from a distinct zone to one in which intergranular diffusion (up to 0.0008-inch) is predominant.

Results of electron microscope examination of specimens welded at 1600°F revealed two prominent zones. An electron micrograph of a carbon replica of the diffusion welded specimen is shown in Figure 38.

A typical microhardness traverse of a 90° cross-section is shown in Figure 39 for a specimen diffusion welded at 1750°F for 1 hour. No significant hardness variations were indicated. The maximum hardness at the center of the diffusion zone was 361 KHN with variations from 321 KHN in the 321 stainless steel to 384 KHN in the Inconel 718. This confirms what would be anticipated in the diffusion zone due to the high degree of mutual solid solubility of Fe, Ni and Cr.

Typical electron microprobe analyses of the diffusion zones of 321 stainless steel to Inconel 718 welds are presented in Figure 40.

The following observations were made from the results of the electron microprobe studies:

1. The concentration of Cr across the diffusion zone is constant (approximately 18 percent).

2. Fe and Ni have uniform concentration gradients from the 321 stainless steel and Inconel 718 parent metals.

The metallurgical analysis conducted on the diffusion welding of bare 321 stainless steel to Inconel 718 indicates that the development of a reliable and metallurgically sound process can be accomplished for this combination in the bare condition.

Diffusion Studies Using Tungsten Markers

1. 2219 Aluminum Alloy to 321 Stainless Steel
   7106 Aluminum Alloy to 321 Stainless Steel
   2219 Aluminum Alloy to Ti-5Al-2.5Sn

   Metallographic examination and electron microprobe analyses were conducted on diffusion weld specimens representing diffusion times of 1, 10 and 100-hours for each material combination. Specimens containing tungsten wire markers

(0.0005-inch diameter) were prepared and studied in the as-welded condition and after diffusion for an additional 9 and 99 hours. The welding and diffusion conditions for the three alloy combinations are given below:

Alloy Combinations	Welding Time and Temp.	Diffusion Time and Temp.
2219 Al to 321 SS	1 hour @950°F	9 hrs. & 99 hrs. @950°F
7106 Al to 321 SS	1 hour @950°F	9 hrs. & 99 hrs. @860°F
2219 Al to Ti-5Al-2.5Sn	1 hour @950°F	9 hrs. & 99 hrs. @950°F

More refined analytical techniques were employed in the microprobe analyses used in this portion of the program than had been used previously. As a result, the new data represent quantitative chemical analyses. The improved techniques included use of continuous line recording and subsequent corrections of concentration profiles by point count measurements. Microprobe analyses presented in the previous studies were qualitative or semi-quantitative and results were given as uncorrected line intensity or approximate weight percent.

2219 Aluminum Alloy to 321 Stainless Steel

Diffusion zone thicknesses for the 1, 10 and 100-hour diffusion specimens were 0.1, 0.5 and 2.0 mils respectively. Two well defined diffusion zones were observed in the 10-hour and 100-hour diffusion specimens. Microstructure and microprobe results for the 10-hour diffusion specimen are shown in Figure 41. The microprobe analysis indicates that Zone 1 is an intermediate phase with a uniform concentration. Although the Fe to Al ratio corresponds to the $FeAl_2$ phase, the presence of significant amounts of Ni, Cr and Cu indicates the possibility of more complex phases. Zone 2 contains a high concentration of Cu (23%). This results from the rapid diffusion rate of aluminum compared to that of copper. This concentration of an alloying element in diffusion couples of alloys was previously explained as resulting from the "Kirkendall effect". The high Cu content of Zone 2 gives a rapid etching rate which accounts for its dark appearance in Figure 41. No identification of the phases contained in Zones 1 or 2 could be made as a result of these studies. The 100-hour specimen was extremely brittle and fractured during mounting which prevented a comprehensive analysis of this specimen.

7106 Aluminum to 321 Stainless Steel

Diffusion weld specimens were extremely brittle and the 10-hour and 100-hour specimens fractured before or during mounting. This prevented satisfactory

microprobe analysis results for these specimens. A micrograph of the fractured 100-hour diffusion specimen is shown in Figure 42. One diffusion zone of approximately 0.1 mil in thickness is evident for the 100-hour specimen, but no diffusion zone of measurable thickness was revealed by examination of the 1 and 10-hour diffusion specimens.

2219 Aluminum Alloy to Ti-5Al-2.5Sn

Diffusion specimens of this combination revealed no diffusion zone of measurable thickness for 1 and 10-hour diffusion and a diffusion zone of approximately 0.1 mil for 100-hour diffusion. This diffusion zone showed a relatively high hardness, 520 KHN, indicating an intermediate phase formation. Microstructure and microprobe analyses of the 100-hour diffusion specimen are shown in Figure 43. The uniform concentration gradient confirms the relatively small amount of interdiffusion between the 2219 aluminum alloy and the Ti-5Al-2.5Sn alloy at 950°F diffusion temperature. However, a rather unusual reaction took place between the tungsten wire marker and the base metals after 100-hour diffusion. Interdiffusion with the tungsten resulted in a growth of the wire to 2.0 mils or approximately four times the original wire diameter as shown in Figure 43. This was wholly unexpected because no reaction had previously occurred with 2219 aluminum alloy under the same time-temperature conditions or with Ti-8Al-1Mo-1V alloy at 1450°F for times up to 100 hours.

Microprobe analysis conducted on the reacted tungsten wire revealed that interaction had taken place between tungsten and aluminum resulting in the apparent formation of a tungsten aluminide. Electron microprobe photographs of characteristic x-ray fluorescence for W, Al, Sn, Cu and Ti are shown in Figure 44. Microprobe profiles across the reacted wire confirmed that the wire contained W and Al with no measurable amounts of Sn, Cu or Ti. It is not known what triggered the interaction of aluminum and tungsten in this particular alloy combination, whereas no reaction with aluminum was evident for the 2219 aluminum alloy to 321 stainless steel combination under the same diffusion conditions. It is possible that the presence of Ti or Sn is responsible for accelerating the Al-W interdiffusion, but this would have to be established by a more comprehensive experimental study using binary and ternary diffusion couples.

Improved knowledge of diffusion characteristics and intermediate phase formation have been achieved for the three aluminum containing couples. Excessive formation of brittle intermediate phases result with the longer diffusion times.

2. Inconel 600 to Ti-8Al-1Mo-1V
   321 Stainless Steel to Ti-8Al-1Mo-1V

Metallographic, electron microprobe and electron microscope studies were conducted on 1, 10 and 100-hour diffusion weld specimens of each alloy combination. The microstructure of the diffusion zone after 1, 10 and 100-hours for the

Inconel 600 to Ti-8Al-1Mo-1V alloy combination is shown in Figure 45, and after 100 hours for the 321 stainless steel to Ti-8Al-1Mo-1V alloy combination is shown in Figure 46. Microprobe analyses of these same specimens showing concentration profiles for Ni, Fe, Cr, Al and Ti are presented in Figure 47 for Inconel 600 to Ti-8Al-1Mo-1V specimens and in Figure 48 for 321 stainless steel to Ti-8Al-1Mo-1V specimens. These data confirm results of the preliminary microprobe analyses of weld specimens. The 10 and 100-hour diffusion specimens provided significant additional information on diffusion mechanisms for these two alloy combinations.

Back scattered electron and sample current photographs were taken with superimposed concentration profiles to orient the element concentration with respect to the various diffusion zones. Microprobe photographs for the Inconel 600 to Ti-8Al-1Mo-1V diffusion specimens are shown in Figure 49 and those for the 321 stainless steel to Ti-8Al-1Mo-1V diffusion specimens are shown in Figure 50. These superimposed concentration profiles represent qualitative chemical analyses but permit orientation of the diffusion zones with respect to the quantitative analysis results given in Figures 47 and 48. Using these data, the identification of the thickest diffusion zone in the Inconel 600 to Ti-8Al-1Mo-1V diffusion welds was confirmed as the intermetallic compound TiNi.

A review was made of phase diagram data available in the literature for the Ni-Ti and the Fe-Ti systems[1,2,3]. These data indicated that for a 1450°F diffusion temperature, the phases which are most likely to be present in binary diffusion couples of Ni-Ti and Fe-Ti are as follows:

Ni-Ti System		Fe-Ti System	
Phase	Composition Weight Percent	Phase	Composition Weight Percent
Ni	100% Ni	Fe	100% Fe
Ni Solid Solution	Max. 8% Ti @1450°F	Fe Solid	Max. 3% Ti @1450°F
$TiNi_3$	78.6% Ni	$TiFe_2$	70% Fe
TiNi	55% Ni	TiFe	54% Fe
Ti_2Ni	40% Ni		
β Ti Solid Solution	Max. 6% Ni @1450°F	β Ti Solid Solution	Max. 17% Fe @1450°F
α Ti	< 0.2% Ni	α Ti	Nil Fe
Ti	100% Ti	Ti	100% Ti

These binary alloy phase data serve only as a guide in attempting to understand the diffusion mechanism and phase formation of the complex nickel alloy to titanium alloy and iron alloy to titanium alloy diffusion couples which were studied on this program.

Five distinct diffusion zones were observed in the microstructure of Inconel 600 to Ti-8Al-1Mo-1V diffusion welds. The appearance of these zones are shown in Figure 51a which is an electron microscope photograph of the 100-hour diffusion specimen. A microhardness traverse across the diffusion zone of this specimen is shown in Figure 52a. Analysis of the data from metallographic, electron microprobe and electron microscope studies permit several observations and conclusions to be made on diffusion mechanisms and phase identification for the Inconel 600 to Ti-8Al-1Mo-1V alloy combination. These are given below for the various zones:

Zone 1 — A high concentration of Cr and Fe occurs in this zone due to the more rapid migration of Ni compared to Cr and Fe. No phase identification.

Zone 2 — No phase identification.

Zone 3 — Principal intermediate phase. Identified as TiNi intermetallic compound by microprobe analysis.

Zone 4 — No phase identification.

Zone 5 — Two phases present; tentatively identified as Ni-rich β Ti and Al-rich α Ti solid solutions. This zone is enriched in Al due to the more rapid diffusion rate of Ti compared to Al in the Ti-8Al-1Mo-1V alloy.

The Cr and Fe enrichment of Zone 1 and the Al enrichment of Zone 5 are the result of the significant differences in diffusion rates of these elements in comparison to the base constituent of their respective alloys. This phenomena, as previously discussed, is attributed to the "Kirkendall effect".

Six diffusion zones can be observed in the 321 stainless steel to Ti-8Al-1Mo-1V diffusion welds. The appearance of these six zones are shown in Figure 51b, which is an electron microscope photograph of the 100-hour diffusion specimen. A microhardness traverse for this specimen is shown in Figure 52b. Observations on diffusion mechanism and phase identification for this combination are as follows:

Zone 1 A high concentration of Cr and deletion of Ni is attributed to the "Kirkendall effect" resulting from extreme differences in diffusion rates of Cr, Ni and Fe. No phase identification.

Zone 2 No phase identification.

Zone 3 No phase identification.

Zone 4 No phase identification.

Zone 5 Tentatively identified by microprobe analysis as Fe-rich β Ti solid solution.

Zone 6 Two phases present; tentatively identified as Fe-rich β Ti and Al-rich α Ti solid solutions. This zone is enriched in Al due to the more rapid diffusion rate of Ti compared to Al.

Phase identification could not be made for three zones in the Inconel 600 to Ti-8Al-1Mo-1V welds and four zones in the 321 stainless steel to Ti-8Al-1Mo-1V welds as a result of these studies. This was primarily due to the thinness and complex chemistry of these diffusion zones. The high hardness common to each of these zones indicates the probability that the phases present are intermetallic compounds. The complex chemistry of the diffusion zones results from the considerable number of alloying elements involved; many of which have widely different diffusion rates. In order to achieve further phase identification, longer diffusion times, higher diffusion temperatures and use of binary diffusion couples would be required.

Diffusion voids were observed in localized areas of the 100-hour Inconel 600 to Ti-8Al-1Mo-1V diffusion specimen. This diffusional porosity, "Kirkendall voids", was evident in the Inconel 600 base metal adjacent to each tungsten wire marker. No diffusional porosity was observed in the 1-hour and 10-hour Inconel 600 to Ti-8Al-1Mo-1V specimens or in any of the 321 stainless steel to Ti-8Al-1Mo-1V diffusion specimens. Figure 53 shows the presence of diffusion voids adjacent to the tungsten markers of the 100-hour Inconel 600 to Ti-8Al-1Mo-1V specimens as revealed by microprobe photographs and by conventional micrographs. The 100-hour 321 stainless steel to Ti-8Al-1Mo-1V specimen is shown for comparison. These studies indicate that the localized diffusional porosity in the 100-hour Inconel 600 to Ti-8Al-1Mo-1V specimen is the result of the "Kirkendall effect". The explanation for this localized porosity is that nickel from the Inconel 600 base metal diffuses rapidly around the tungsten wire to form intermediate phases with titanium at the interface. This results in a phenomenon which tends to move the wire in the opposite direction to the nickel diffusion ("Kirkendall Shift"). However, the large size of the tungsten wire and the restricting influence of

adjacent metal prevents the wire from moving the full amount. The result is that as the lattice of the base metal shrinks due to loss of nickel atoms, voids are formed due to incomplete shrinkage caused by the constraint in lateral contraction. It is evident from Figure 53 that the tungsten wire acts as a partial barrier to the growth of the intermediate phases.

These data have contributed significantly to a better understanding of diffusion characteristics and intermediate phase formation in diffusion welds of these two alloy combinations. In addition, advances have been made in techniques for metallurgical analysis of diffusion couples. Although the thinness and complex chemistry prevented identification of several intermediate phases, the extreme hardness and presumed brittleness of these phases indicate that the development of an acceptable diffusion weld schedule requires that these phases must be kept very small and if possible discontinuous.

3. Inconel 718 to 321 Stainless Steel

Diffusion zone thicknesses for 1, 10 and 100-hour diffusion specimens of this combination were 0.2, 0.3 and 0.6 mils respectively. Each specimen shows two indistinct diffusion zones. Microprobe analyses show uniform concentration gradients for all alloying elements. Microstructure and microprobe analyses for the 100-hour diffusion specimen are shown in Figure 54. These data indicate no intermediate phases form at the interface. This would be expected since both alloys are austenitic and contain the same major alloying elements.

Absence of intermediate phase formation for the Inconel 718 to 321 stainless steel combinations with diffusion times up to 100 hours indicate diffusion welding of bare material should be feasible for this combination.

EFFECT OF AIR AND VACUUM ENVIRONMENTS

Air Atmosphere

The following combinations were diffusion welded in an air atmosphere using the welding parameters shown in Table IX:

(a) 2219 aluminum alloy to 321 stainless steel

(b) 7106 aluminum alloy to 321 stainless steel

(c) 2219 aluminum alloy to Ti-5Al-2.5Sn

(d) Inconel 718 to 321 stainless steel

The above four alloy combinations were welded with surfaces prepared by polishing and by abrasive cleaning and by (1) heating to temperature prior to applying the pressure and by (2) applying the pressure prior to heating to temperature.

The two material combinations containing Ti-8Al-1Mo-1V were omitted because of excessive contamination which occurs in air at the 1350° to 1450°F welding temperature required for these combinations.

Peel tests were conducted on the four alloy combinations welded in an air atmosphere, Table IX. These results are shown in Appendix A (Specimens 264 through 295). In general, the results revealed that an air atmosphere produces erratic diffusion weld quality.

Welds having good peel strength were obtained in several specimen couples containing an aluminum alloy, regardless of whether the pressure was applied prior to or after the specimen reached welding temperature. Preliminary metallurgical examination of the specimen welded in air showed, when welding occurred, the joint had the same appearance as those welded in an argon atmosphere. The results of this work indicate that some oxidation of the material will not prevent successful welding; however, erratic results can be expected.

The 321 stainless steel to Inconel 718 alloy combination could not be welded in air due to excessive oxidation if the pressure was applied after the specimen reached the welding temperature. Diffusion welds with good peel strength were obtained if the welding pressure was applied prior to heating. However, metallurgical examination of these welds showed the presence of metal oxides at the faying surface.

Vacuum Environment

All six combinations were diffusion welded in a vacuum environment using the test parameters shown in Table X. These specimens were heated in the vacuum environment to the desired welding temperature prior to applying the welding pressure. During heating the vacuum varied between 1×10^{-5} and 7×10^{-5}torr due to outgassing of the specimens and their parting agents. During welding, the pressure varied between 2×10^{-5} and 1×10^{-6}torr.

All six material combinations were successfully welded in a vacuum environment. Peel testing of the specimens resulted in a peel strength which was comparable to those specimens welded in an argon atmosphere (Appendix A - Specimens 403 to 426). Metallurgical examination of the diffusion welds showed they contained approximately the same diffusion zone width and appearance as those welded in argon.

The specimens welded in vacuum exhibited an exterior surface which was considerably brighter than of those welded in argon. Apparently the specimens which were diffusion welded in a retort with argon gas (liquid source) atmosphere are being slightly contaminated from outgassing of the parting agents which are placed between the specimens. The vacuum environment completely prevented contamination.

WELDING WITH DIFFUSION AIDS

In this portion of the investigation, diffusion welding studies were conducted using metal foils and electroplating at the joint interface. Screening tests were initially conducted to evaluate a large variety of diffusion aids. More comprehensive studies were then conducted on selected transition materials.

SCREENING TESTS

Metal Foils

The following couples were welded using metal foils and welding parameters shown in Table XI:

(a) Inconel 600 to Ti-8Al-1Mo-1V

(b) 321 Stainless Steel to Ti-8Al-1Mo-1V

(c) Inconel 718 to 321 Stainless Steel

Prior to welding, the base material was abrasively cleaned followed by solvent cleaning. The metal foils were used in the as-received condition. Welding was conducted in an argon atmosphere using the same techniques described for the bare material combinations.

Preliminary investigations using metal foils on material combinations containing an aluminum alloy revealed difficulty in obtaining a solid state weld between the foil and the titanium alloy or stainless steel at temperatures below 1000°F. Therefore, metal foils with the aluminum alloy combinations were not investigated further.

1. Inconel 600 to Ti-8Al-1Mo-1V
   321 Stainless Steel to Ti-8Al-1Mo-1V

   Based on peel tests and preliminary metallurgical examination of diffusion welds prepared using the parameters shown in Table XI, the following results were observed:

a. Vanadium and silver are the most promising foil materials. These foils produced diffusion welds having a good strength and better ductility than the welds produced using bare material on the above combinations. Figure 55 shows typical microstructure of diffusion welds using these metal foils.

b. Copper, gold, nickel and titanium produced low strength and brittle diffusion welds. The problem with these foils appears to be an intermediate phase formation between the foil and the base materials. This phase formation could not be prevented by lowering the welding temperatures without eliminating the weld between the opposite foil-base material interface. Figure 56 shows the intermediate phase which forms between the Cu and Au foils and the Ti-8Al-1Mo-1V parent metal.

2. Inconel 718 to 321 Stainless Steel

The copper, nickel and silver foils produced welded joints having medium strength and ductility. These foils did not match the joint strength which was obtained when welding the above combination in the bare condition. However, they did permit successful diffusion welding at lower temperatures than those required for welding in the bare condition. Typical photomicrographs of diffusion welds where copper and nickel foils were used are shown in Figure 57.

The iron and gold foils produced welded joints having low peel strength in the Inconel 718 to 321 stainless steel combination.

Electroplated Metals

All six material combinations were welded in the electroplated condition. The welding parameters are shown in Table XII. Prior to welding, the plated surfaces were abrasively cleaned followed by solvent cleaning. Welding was conducted in an argon atmosphere using the techniques previously described for bare material combinations.

1. 2219 Aluminum to 321 Stainless Steel
   7106 Aluminum to 321 Stainless Steel
   2219 Aluminum to Ti-5Al-2.5Sn

The above alloy combinations were plated (Table XII) with copper, silver, and nickel with the material (1) in the bare condition and (2) with the aluminum and the titanium alloys anodized (see Appendix C). The anodized surface on the aluminum alloys was evaluated as a barrier coating to prevent the formation of undesirable phases during diffusion welding. The titanium fluoride anodize was used on the titanium alloy to increase electroplating adherence.

The peel testing and metallurgical examination of the foregoing specimens revealed the following results:

a. Anodizing of the aluminum alloys effectively prevented phase formation between the aluminum and electroplating. However, adherence of the electroplating to the anodized surface was poor resulting in low joint strength and ductility. Figure 58 shows two photomicrographs of nickel plated 7106 aluminum (anodized) to 321 stainless steel. The lower photomicrograph in Figure 58 shows the formation of an intermediate phase where the anodized surface was broken. The photomicrograph in Figure 58a shows no phase formation when the coating is continuous.

b. From the results of both peel tests and metallurgical examination, the silver electroplating on bare material gave the best diffusion weld quality on aluminum alloys to stainless steel. Copper electroplating resulted in erratic diffusion weld quality. This is apparently caused by the varying degrees of oxidation of the copper surface during welding.

c. The diffusion welding of 2219 aluminum to Ti-5Al-2.5Sn with electroplated metals was generally unsuccessful. During peel testing, the plating would usually peel off the titanium alloy. Apparently, diffusion welding temperatures for this combination are too low to permit diffusion between the plating and the titanium alloy. In later work (discussed on page 31) it was found that silver produced good adherence to titanium alloys if the plated titanium was prediffused at temperatures of 1300°F.

2. Inconel 600 to Ti-8Al-1Mo-1V
   321 Stainless Steel to Ti-8Al-1Mo-1V

The above material combinations were diffusion welded using silver, copper and nickel electroplating. The plating was applied to the titanium alloy (1) with the titanium in the bare condition and (2) with a titanium fluoride anodize. The titanium fluoride treatment gave the best plating adherence, and had no measurable effect on diffusion characteristics when compared with plating on bare material.

The results of peel testing and metallurgical examination of the above combinations showed that silver produced a fair joint strength and ductility at welding temperatures ranging from 1100° to 1500°F. No significant diffusion zone between the silver and titanium alloy was evident at 500X magnification, Figure 59a. Copper and nickel plating produce joints having marginal strength and ductility after welding at 1300°F for 10 minutes. At this time and temperature considerable diffusion occurred between the plating and the titanium alloy, Figures 59b and 59c.

3. Inconel 718 to 321 Stainless Steel

The above material combination was diffusion welded using copper and nickel plating. As previously discussed, the copper plating produced erratic weld quality because of oxide contamination in the copper surface prior to applying weld pressure. Nickel produced excellent weld quality; however, strength and ductility of the weld joint is not as good as in the bare material combination. Nickel plating reduces the welding temperature required to produce a welded joint as compared with the temperatures used for the bare material combination.

COMPREHENSIVE STUDIES

Parametric studies were conducted on the six alloy combinations using the diffusion aids as shown in Table XIII. The two most promising diffusion aids for each combination (except for 2219 Al to Ti-5Al-2.5Sn) were chosen based on the results of the previously discussed screening tests. The work conducted in the foregoing screening tests showed that silver electroplating had poor adherence to Ti-8Al-1Mo-1V if the welding temperature was below 1100°F. The silver electroplating also exhibited poor adherence to Ti-5Al-2.5Sn at the 500° and 700°F welding temperature (when welded to 2219 aluminum alloy). Therefore, diffusion welding tests were conducted in which silver electroplated Ti-8Al-1Mo-1V and Ti-5Al-2.5Sn were prediffused at 1300°F for 10 minutes in vacuum. After this prediffusion, the titanium alloys were welded to the silver electroplated metal in their respective combination at a temperature of 600°F. Peel testing of these specimens showed that the prediffusion cycle was successful in creating good adherence of the electroplating to the titanium alloys.

Based on this work, the parametric study shown in Table XIII includes a series of specimens in which the titanium alloys are subjected to various prediffusion cycles prior to welding.

The results of the diffusion aid study include an analysis of the process and metallurgical investigations conducted on each condition. The process investigations included thermal shock and joint peel testing. Since all specimens satisfactorily passed the thermal shock testing, no further discussion of this test will be given. The parent metal and diffusion aid combinations evaluated will be discussed either separately or where more complete analysis of the data can be obtained; various combinations will be discussed concurrently.

1. 2219 Aluminum Alloy to 321 Stainless Steel
   7106 Aluminum Alloy to 321 Stainless Steel

   Based upon the joint peel testing and metallurgical evaluation of welded specimens of the above combinations using silver and copper electroplated diffusion aids, the following results were observed.

Silver Electroplate

Silver plating produced welded joints having good peel strength at the 500°, 600°, and 700°F welding temperature. However, joint ductility decreased with increase in welding temperature. At the 500°F temperature the welded joints peeled primarily through the silver electroplating. An increase in welding temperature caused the joints to peel primarily through the silver to 2219 aluminum alloy interface. The 7106 aluminum alloy combination exhibited better joint ductility than the 2219 aluminum alloy combination at all welding temperatures.

Typical microstructure of the 321 stainless steel to 2219 aluminum alloy welds using electroplated silver as a diffusion aid are shown in Figure 60 after welding at 500° and 700°F. Evidence of the original Ag-Ag electroplate interface has virtually disappeared as a result of diffusion and accompanying recrystallization and grain growth. This characteristic of Ag to develop a complete solid state weld at the Ag-Ag interface in an air atmosphere is attributed to the lack of detrimental oxide or other non-metallic films. In the 400° to 700°F temperature range, the free energy of silver oxide formation is so low, and the probability of dissociation so high, that the presence of an inhibiting oxide at the Ag-Ag interface would not be expected. This relationship of temperature and the free energy of formation of Ag_2O is shown below:

Heat and Free Energy of Formation of Ag_2O
Ref. 5

Temperature, °F	ΔF (cal/mole) $= RT \ln k$
80	-2500
300	- 650
400	+ 200
500	+1050
600	+1900
700	+2700

It is evident from the above that silver has the characteristics to be an excellent diffusion aid for welding temperatures from 400° to 700°F.

Figure 60 illustrates that the major diffusion zone development is at the 2219 aluminum alloy-silver electroplate interface. At 500°F for 2 hours the zone is very small, Figure 60a, and is not the prime site for initiation of peel failure. However, at the 700°F for 1 hour welding schedule, five distinct diffusion zones can be readily detected, Figure 60b. Peel failures of the 700°F welding schedule appeared to initiate in Zones 1 or 2.

In order to study these zones more thoroughly, special metallurgical specimens were prepared for microhardness traverses and electron microprobe analysis. The specimens were welded at 700°F for 10 minutes and then diffusion treated for an additional 8 hours at 700°F. The diffusion treatment produced diffusion zones of significant widths. The specimens were metallographically prepared with a 90° cross-section since it has been observed that consistent microhardness and microprobe results could not be obtained with 15° taper sections due to the tapered or "feathered" edges of the diffusion zones or interfaces.

Results obtained in the microhardness traverse and microprobe studies of 321 stainless steel to 2219 aluminum alloy weld with electroplated silver as a diffusion aid are summarized in Figure 61. Six diffusion zones are indicated, 5 zones at the Ag to Al interface and one zone at the Ag to stainless steel interface. However, it should be noted that no discrete diffusion zone is evident at the Ag to stainless steel interface (Zone 6). Surface preparation for electroplating results in the observed intergranular penetration of the Cu flash and Ag electroplating into the 321 stainless steel.

Zones 1 through 5 are of particular interest. Zone 1 includes the diffusion of the Cu flash and Ag electroplate into the 2219 aluminum alloy. Zone 2 consists of a discontinuous phase and has the highest microhardness (314 KHN) of all the zones, Figure 61. The microprobe analysis revealed that the predominant constituents of this zone are Cu and Al with Ag present only as the minor constituent. Equal parts of Cu and Al, as represented on the microprobe, would represent a composition only slightly off the stoichiometry for θ (Cu-Al)-(54 wt. % Cu-46 wt. % Al), which has a reported hardness of 480 KHN[7]. The difference in the two hardness values (314 KHN and 480 KHN) can be explained on the basis of the slight chemistry difference and the presence of the slight amount of Ag. Although θ (Cu-Al) phase is generally given the fixed composition $CuAl_2$, this phase is actually of variable Berthollide composition[7]. Therefore, the light appearing phase in Zone 2, Figure 61, can be regarded as truly of θ composition. Zone 3 is a light appearing phase with dispersed particles, probably the θ (Cu-Al) phase. Zone 4 is a single phase with a chemical composition of approximately 90 wt. % Ag-10 wt. % Al, as shown in the microprobe analysis, Figure 61b. The Ag-Al equilibrium diagram shows the presence of three intermediate (Ag-Al) phases (β , δ , μ), situated in the silver-rich region. All of these phases are secondary solid solutions and all reportedly include an Ag_3Al phase of the approximate 90 Ag-10 Al composition[3]. Since the β (Ag-Al) phase is stable only at high temperatures ($\sim$ 1100°F), Zone 4 probably is either the δ or μ (Ag-Al) phase. The significance of Zones 3 and 4 is that the microhardness is relatively low, indicating the phases are not particularly undesirable. In fact, future studies wherein the Cu flash on the Al substrate would be eliminated in favor of a direct (Ag-Al) phase development may be warranted.

The growth of the diffusion zones at the 2219 aluminum alloy-silver electroplate interface is illustrated by the tungsten marker study shown in Figure 62. It is apparent that growth of Zones 2 and 3 is primarily by diffusion of Al from the silver electroplate interface. (Al migrates at a much greater rate than Ag across the silver electroplate interface.)

The microstructures of the 7106 aluminum alloy to 321 stainless steel couple using silver electroplate as a diffusion aid are shown in Figure 63. Diffusion zones obtained are similar to those developed in the 2219 aluminum alloy to 321 stainless steel combination at the same weld schedules.

The microhardness and electron microprobe analyses are summarized in Figure 64. The major difference between diffusion welds containing the 2219 and the 7106 aluminum alloys is that (1) a smaller width of copper concentration is detected by microprobe in the 7106 aluminum alloy, (2) lower microhardness of Zone 2 (137 KHN compared to 314 KHN), and (3) greater depth of Ag diffusion in the 7106 aluminum alloy. These factors are believed to contribute to the slightly higher peel strength detected with the 7106 aluminum alloy combination.

Copper Electroplate

Copper electroplating produced joints in both the 2219 and 7106 aluminum alloy to 321 stainless steel combinations having a peel strength which appeared to be lower than that obtained with the silver electroplated specimens. In the joint peel test the joints also exhibited less ductility and failed primarily at the copper electroplate to aluminum alloy interface. Some oxidation was observed at the copper interface.

Typical microstructures of the 321 stainless steel to 2219 aluminum alloy combination using copper electroplate as a diffusion aid are shown in Figures 65 and 66. The microstructures after welding at 500°, 600° and 700°F are shown. One significant observation in all photomicrographs is the existence of a discontinuous oxide film present at the original interface of all welds. The oxide film did not appear to be an initiation site for peel failure. However, considering the thermodynamic stability of cuprous and cupric oxides, it is very unlikely this condition can be eliminated unless welding was conducted under critically controlled conditions in an inert gas atmosphere or a vacuum, or unless very high welding pressures were used.

The critical diffusion zone is at the 2219 aluminum alloy-copper electroplate interface. This zone appears to consist of three relatively thin zones as shown in Figure 66b.

A summary of the microhardness traverse and microprobe analysis of a 2219 aluminum alloy to 321 stainless steel weld using copper electroplate as a diffusion aid is shown in Figure 67. In order to develop wider diffusion zones for this study, the specimen was diffusion treated for 8 hours at 700°F after welding. The significance of this study is the high microhardness of Zone 3 (642 to 713 KHN). The Cu content of this zone ranges from approximately 60% to 90%, Figure 67b. The Al-Cu equilibrium diagram reveals 11 intermediate phases within this composition range. No specific phase definition can be made; however, one or more of these phases are undoubtedly responsible for the high microhardness.

Below 60 wt. % Cu only one intermediate phase, θ (Cu-Al), is reported present on the equilibrium diagram. Zones 1 and 2 consist of a Cu composition from 6% to 60% Cu and probably contain the θ (Cu-Al) phase. Zone 1 has a greatly reduced microhardness (209-271 KHN) as compared to Zone 3, Figure 67a. The dark etch for Zone 1 in Figure 67a is believed due to etching technique. Zone 4 includes the Ni and Cu electroplates and reveals only slight diffusion occurred during welding.

Based upon the results of this analysis, Zone 3 appears to be responsible for the relatively brittle joint peel failures. All joint peel failures occurred in this zone.

The microprobe analysis, Figure 67b, indicates that Al diffuses at a much greater rate than Cu across the 2219 aluminum alloy-copper electroplate interface.

The microstructure of the 7106 aluminum alloy to 321 stainless steel combination using copper electroplate as a diffusion aid is shown in Figure 68. Discontinuous oxide film as well as Cu-Al diffusion zones similar to those obtained on the 2219 aluminum alloy combination, are readily apparent.

A summary of the microhardness and microprobe analyses on a long time diffusion treated weld of the above combination is shown in Figure 69. Four distinct diffusion zones are visible. Zone 3 has a very high microhardness (726 KHN) and a Cu content range from 60% to 90%. The microhardness and Cu content of Zone 3 are almost identical to those obtained in the 2219 aluminum alloy combination. Zone 1 has a slightly higher microhardness than Zone 1 in the 2219 aluminum alloy combination (406 to 271 KHN). All joint peel specimens failed in these Cu-Al rich zones.

Based upon the results of the foregoing diffusion aid evaluation, silver electroplate and a welding temperature of approximately 500°F, is the preferred diffusion welding process for the 2219 and 7106 aluminum alloys to 321 stainless steel combinations.

2. 2219 Aluminum Alloy to Ti-5Al-2.5Sn

Welded specimens were prepared with the Ti-5Al-2.5Sn alloy having the silver in the (1) as-electroplated condition and (2) with the silver electroplate prediffused at 1100°, 1300°, 1500° and 1700°F for ten minutes.

Joint peel testing of specimens prepared with the titanium in the as-electroplated condition showed that the silver has poor plating adherence to the titanium alloy. After prediffusion treatments of 1100°, 1300° and 1500°F, the welded specimens exhibited good peel strength with the joint failure occurring in the silver or at the 2219 aluminum alloy-silver electroplate interface. The prediffusion treatments at 1700°F resulted in very low peel strength with failure at the silver electroplated interface.

A photomicrograph of a specimen which was diffusion welded at 600°F for 30 minutes in the as-electroplated condition is shown in Figure 70a. The joint failed during welding at the Ti-5Al-2.5Sn and silver electroplate interface.

The microstructure of a weld in which the silver electroplate on the Ti-5Al-2.5Sn was prediffused at 1300°F for 10 minutes is shown in Figure 70b. No visible diffusion is apparent at the Ti-5Al-2.5Sn interface. A small diffusion zone is visible at the 2219 aluminum alloy interface. The microhardness traverse and microprobe analysis summary is shown in Figure 71 for the same weld discussed above. The microhardness traverse indicates an increase in hardness in the 2219 aluminum alloy-silver electroplate interface (Zone 1). Due to the short time used (30 minutes) only one zone (Zone 1) is visible; however, the phases in this zone should be similar to the three zones shown in the 321 stainless steel to 2219 aluminum alloy weld using silver diffusion aid, Figure 60b. The microprobe analysis revealed approximately 4 to 6 microns interdiffusion between the Ti-5Al-2.5Sn and silver electroplate. However, considering the scanning characteristics of the microprobe, approximately a 2 micron tolerance must be allowed for the electron beam diameter. Therefore, it would appear that 2 to 4 microns interdiffusion of Ti-Ag has occurred.

Based on this work, a satisfactory diffusion welded joint can be produced in the Ti-5Al-2.5Sn to 2219 aluminum alloy combination by using silver electroplating on both alloys and prediffusing the silver electroplate at about 1300°F on the titanium alloy.

3. 321 Stainless Steel to Ti-8Al-1Mo-1V
Inconel 600 to Ti-8Al-1Mo-1V

Based on the joint peel testing and metallurgical investigation of welded specimens of the above combinations using silver electroplating and with vanadium foil (Table XIII) the following results were observed.

Silver Electroplate

Silver plated specimens welded at 600°F, without the prediffusion treatment, resulted in poor joint peel strength because the silver exhibited little or no adherence to the titanium alloy.

Silver plated specimens welded at 1300°F, without the prediffusion treatment, produced satisfactory strength and ductility and failed through the silver plating.

Silver plated titanium specimens, having an acceptable plating, and when prediffused at 1300° and 1500°F and welded at 600°F produced specimens having satisfactory strength and ductility. The 1100°F prediffusion temperature was too low to produce adherence of the silver to the titanium alloy and the 1700°F temperature was too high and caused excess diffusion of the silver into the titanium. The prediffusion cycle occasionally resulted in specimens having a discolored and/or blistered surface. The cause of this appears to be related to the anodizing techniques used prior to silver plating. Specimens having this type of surface produced welded joints having erratic quality.

Metallurgical examination of welded specimens up to 500X magnification revealed no distinct diffusion zones at the Ti-8Al-1Mo-1V to silver electroplate interface after the prediffusion treatments. Figure 72 illustrates two weld microstructures, (1) with no prediffusion treatment and welded at 1300°F for 1 hour, and (2) with a 1330°F for 10 minutes prediffusion treatment and welded at 600°F for 30 minutes. No interdiffusion is noted. Microprobe analyses revealed only minimal ($\sim$ 4 microns) diffusion. As mentioned above, all specimens in these conditions failed during peel testing in the silver electroplating.

The metallurgical results for the Inconel 600 to Ti-8Al-1Mo-1V combination using silver diffusion aid were similar to those described above.

Vanadium Foil

Specimens welded using vanadium foil for a diffusion aid did not exhibit satisfactory strength and/or ductility. When diffusion welding was accomplished at the 1400°F temperature the specimens exhibited low joint peel strength because of poor adherence of the foil to the titanium. At higher temperature the foil had good adherence to the titanium alloy and the specimens exhibited high peel strength; however, the peel failure always initiated at the Inconel 600 or 321 stainless steel side of the joint in a brittle manner.

Typical microstructures of welds in the 321 stainless steel to Ti-8Al-1Mo-1V combination using vanadium foil are shown in Figure 73. At 1500°F for

30 minutes no distinct diffusion zones can be detected, Figure 73a. After welding at 1600°F for 1 hour, three distinct zones are visible at the 321 stainless steel interface while two zones are visible at the Ti-8Al-1Mo-1V interface, Figure 73b.

Figure 74 illustrates the microhardness and microprobe analysis of the combination containing 321 stainless steel. The extremely high microhardness of Zone 2 (953 KHN) at the 321 stainless steel to vanadium foil interface appears to be detrimental in this diffusion weld combination, Figure 74a. Study of the potential phases possible in this zone revealed that Ni-V phases would probably be the most detrimental. Above 20 wt. % V in the Ni-V system, 3 intermetallic phases and numerous secondary solid solutions are reported. The microprobe analysis, Figure 74b, indicates that the hard Zone 2 contains a Ni-V composition wherein the V is greater than 20%. However, due to the alloy complexity of this joint combination, no phase identification can be made with the data obtained. It is interesting to note that approximately 6 to 8% Cr has diffused completely across the vanadium foil from the 321 stainless steel.

The metallurgical findings for the Ti-8Al-1Mo-1V to Inconel 600 combination using vanadium foil were very similar to those discussed above. Figure 75 shows the microhardness and microprobe studies conducted on this combination. Only two zones were detected at the Inconel 600 interface. A microhardness of 1038 KHN was detected in Zone 2, Figure 75a.

The high hardness zones detected at the 321 stainless steel and Inconel 600 interfaces of the two above combinations were believed responsible for the reported brittle joint peel failures.

Silver electroplating, if properly applied, can result in satisfactory welds without detrimental metallurgical phase development by using prediffusion treatments or welding at 1300°F (without prediffusion).

The peel test results indicate that vanadium foil will not produce satisfactory diffusion welded joints.

4. Inconel 718 to 321 Stainless Steel

Based upon the peel testing and metallurgical examination of welded specimens in this combination using silver and nickel electroplating for diffusion aids (Table XII), the following results were observed.

Silver Electroplate

Silver electroplated specimens when welded in air at 500° to 800°F produced joints having a strength level which may be expected of silver metal. However, this strength level is considerably less than the strength of the Inconel 718 to 321 stainless steel combination welded in the bare condition at 1600°F. These specimens peeled primarily through the silver electroplate and with a small amount of the silver peeling from the copper flash electroplating on the Inconel 718. The silver plated specimens welded in air at 900°F and in argon at 110° and 1300°F resulted in a lower peel strength as compared with the specimens at 500° to 800°F in air.

Metallurgical examination revealed intergranular penetration of the copper flash and silver electroplate into the 321 stainless steel and Inconel 718 parent metals with no visible diffusion (at 500X magnification). The microstructure was similar to that shown in Figure 60a for the 321 stainless steel interface.

Nickel Electroplate

Nickel electroplated specimens welded at 1100°, 1300° and 1500°F in an argon atmosphere all showed a strength level superior to silver metal, but still considerably less than for the alloy combination welded at 1600°F in the bare condition. All nickel plated specimens failed through the nickel electroplate during the peel testing.

Results of the metallurgical examination are shown in Figure 76. Two diffusion zones are revealed in Figure 76a. The microprobe sample current and profile photographs shown in Figure 76b, indicate that these zones consist of fairly continuous decreasing (or increasing) diffusion gradients.

The Inconel 718 to 321 stainless steel combination can be satisfactorily diffusion welded with the silver electroplate or nickel electroplate diffusion aids. However, except for lower welding temperatures allowed, joint characteristics and strength are not improved over that obtained in the bare metal conditions.

DISCUSSION

Diffusion mechanism studies of the six dissimilar metal combinations have significantly aided in the understanding of diffusion characteristics and intermediate phase formation of these combinations with and without the use of diffusion aids. The findings of the above studies have indicated that detrimental phases can develop in the joint interface, particularly for the Ti-8Al-1Mo-1V containing couples. However, it should be noted that excessively large diffusion zones were deliberately developed in portions of this study to allow for detail analysis. For actual component applications the diffusion

zones should be kept as narrow as possible consistent with obtaining interdiffusion between the various elements of the joint materials. The theory being that if detrimental phases can be kept discontinuous or very thin, the drastic effect on joint characteristics can be minimized.

Based upon the work in Phase II, the following press welding schedules are considered to be the best overall compromise for obtaining consistent welding, and where applicable, of minimizing detrimental phase formation.

Combination	Diffusion Aid	Diffusion Welding Parameters			
		Temperature	Time	Pressure[1]	Environment
1. 2219 Al/321 SS					
(a) Bare Condition	-	940°F ±10°F	30 Min.		Vacuum
(b) Diffusion Aid	Ag Plate	500°F	2 Hrs.		Air
2. 7106 Al/321 SS					
(a) Bare Condition	-	940°F ±10°F	30 Min.		Vacuum
(b) Diffusion Aid	Ag Plate	500°F	2 Hrs.		Air
3. 2219 Al/Ti-5Al-2.5Sn					
(a) Bare Condition	-	940°F ±10°F	30 Min.		Vacuum
(b) Diffusion Aid	Ag Plate[2]	500°F	2 Hrs.		Air
4. Inconel 600/Ti-8Al-1Mo-1V					
(a) Bare Condition	-	1325°F±25°F	10 Min.		Vacuum
(b) Diffusion Aid	Ag Plate[2]	700°F	30 Min.		Air
5. 321 SS/Ti-8Al-1Mo-1V					
(a) Bare Condition	-	1425°F±25°F	10 Min.		Vacuum
(b) Diffusion Aid	Ag Plate[2]	700°F	30 Min.		Air
6. Inconel 718/321 SS					
(a) Bare Condition	-	1625°F±25°F	15 Min.		Vacuum
(b) Diffusion Aid 1	Ag Plate	600°F	30 Min.		Air
(c) Diffusion Aid 2	Ni Plate	1325°F±25°F	30 Min.		Vacuum

[1] Pressure adjusted to allow 0.003 to 0.006-inch compressive thinning during welding.

[2] Prediffused at 1350°F for 10 minutes prior to welding.

PHASE III - EFFECT OF MATERIAL CONDITION ON DIFFUSION WELDING

This phase of work was performed to determine the effect of strain hardening, heat treat condition and surface finish on the most acceptable diffusion welding schedules established in Phase II for sheet material in the bare condition. The purpose of this work was to determine what variations in material condition would be acceptable in establishing diffusion welding schedules in future production applications.

EFFECT OF STRAIN HARDENING & HEAT TREATMENT

EFFECT OF MODERATE STRAIN HARDENING

The effect of strain hardening was investigated for the 321 stainless steel and Inconel 600 to Ti-8Al-1Mo-1V and for the Inconel 718 to 321 stainless steel combinations. Strain hardened material containing up to 50% cold reduction in thickness was used in the test work. Table XIV outlines the welding conditions used. In addition to the strain hardened material, materials in the annealed condition were also included as control specimens, Table XIV. The annealed and strain hardened materials were press welded in the same retort to preclude any variation in welding condition. Welded specimens of annealed and strain hardened material were included in the same metallurgical mount to prevent any variation in polishing and etching techniques during evaluation.

Test specimens, Table XIV, were evaluated by peel testing and metallurgical examination. These results did not reveal a measurable difference in specimen peel strength on diffusion zone width as a result of prior moderate strain hardening.

EFFECT OF HIGH STRAIN HARDENING & HEAT TREATMENT

The previous test work, using up to 50% strain hardened material, was conducted at a single temperature for each material combination. The Inconel 718 to 321 stainless steel combination was selected for further investigation using material strain hardened 60 and 65 percent and diffusion welding temperatures from 1300°F to 1800°F, Table XV. In addition, solution treated and aged Inconel 718 was diffusion welded to annealed 321 stainless steel, Table XV. The lower welding temperature limit of 1300°F was chosen because in previous work (Phase II) a 1325°F temperature produced partial joining for this combination. The highest welding temperature of 1800°F was selected because this represents the nominal solution treating temperature for Inconel 718. All three combinations, Table XV, were welded in the same retort and examined in the same metallurgical mount as described in the foregoing section.

Evaluation of the welded specimens by peel testing and metallurgical examination of the diffusion zone did not reveal a measurable difference between similar specimens diffusion welded in the annealed condition. In Figure 77 the photomicrographs show the joint area of strain hardened material welded at various temperatures. The slightly varying diffusion zone shown in these photomicrographs as the temperature of welding is increased is identical to that obtained in annealed material. The base metal is seen to significantly change in microstructure as welding temperatures are increased.

EFFECT OF MATERIAL SURFACE CONDITION

An investigation was conducted to determine the effect of surface finish on the six material combinations. Surface finishes prepared by abrasive cleaning, chemical cleaning, polishing and by machining (1000 RHR) were used. The abrasive cleaned materials were used for control specimens. The machined specimens were prepared by a milling procedure which produced both a rough surface and one which was galled to produce a high amount of surface cold work. The pressing welding was done using the acceptable diffusion welding conditions established in Phase II. Table XVI shows the welding conditions used in this investigation. All four specimens for each material combination (A, B, C, D - Table XVI) were welded in the same retort to permit consistency in evaluation. After welding the specimens were evaluated by peel test and metallurgical examination. The results of this evaluation are described below.

2219 and 7106 ALUMINUM ALLOYS TO 321 STAINLESS STEEL

Peel testing showed chemical cleaning provided the best joint surface preparation for obtaining high strength for the above material combinations when welded at 950°F for 30 minutes.

Polished surfaces occasionally showed an improvement over the abrasively cleaned surfaces (control specimens). Machined surfaces resulted in a peel strength comparable to those cleaned by abrasive sanding. Metallurgical examination of welded specimens at 500X magnification did not reveal that the different surface preparations had an effect on the characteristics of the diffusion zone.

Based on this work, it appears that chemical cleaning plus a fairly short diffusion welding time (950°F) will produce the best joint strength and ductility.

2219 ALUMINUM ALLOY TO Ti-5Al-2.5Sn

The peel test indicated that polished surfaces gave the best weld strength and ductility for this combination. The other three surface preparations produced satisfactory joint strength and consistency. Metallurgical examination did not reveal any difference in the diffusion zone as a result of surface preparation. Because polished surfaces are not practical for production parts, additional test

work was done using material abrasively cleaned (after chemical cleaning) with 150 grit paper. These specimens produced a joint having high peel strength. Based on these results, it appears that lightly sanded surface and welding at 950°F - 30 minutes will produce acceptable joint quality.

INCONEL 600 TO Ti-8Al-1Mo-1V
321 STAINLESS STEEL TO Ti-8Al-1Mo-1V

The peel testing showed that all joints for the above combinations were strong and relatively brittle regardless of the surface preparation used. Metallurgical examination showed that the polished specimens gave a void free joint having a uniform diffusion zone width, while those specimens prepared by the other methods contained some void areas and a more erratic diffusion zone width. A comparison for surfaces prepared by the four methods are shown in Figures 78 and 79 for the Inconel 600 to Ti-8Al-1Mo-1V combination.

INCONEL 718 TO 321 STAINLESS STEEL

Surface preparation did not have a measurable effect on the peel strength of the above material combination. The photomicrographs in Figures 80 and 81 show a welded joint for each of the four surface preparation methods. Polished surfaces provided the most uniform diffusion zone. The microstructure of the Inconel 718 rough-cut machined surface reveals an extremely fine grained sub-structure, Figure 81b. This could be a result of the high work hardenability of the Inconel 718 alloy. The diffusion zone for this machined surface preparation appears to have a greater width. This may be caused by the asperities produced in machining which increased considerably the specimen surface area.

DISCUSSION

The work conducted in Phase III revealed that strain hardening has no measurable effect on the development of a diffusion welded joint. The work conducted on the Inconel 718 to 321 stainless steel combination shows that diffusion welding can be accomplished without appreciable recrystallization of the sheet material, and can also be accomplished with the solution treated and aged Inconel 718 without appreciable loss in base metal hardness.

The work using various surface finishes revealed the following:

1. The chemically cleaned condition (950°F for 30 minute welding schedule) is the superior finish for 2219 and 7106 aluminum alloys to 321 stainless steel.

2. A light sanded finish (150 grit) is the preferred finish for the 2219 aluminum alloy to Ti-5Al-2.5Sn material combination.

3. Any of the four surface finishes evaluated are acceptable for diffusion welding Inconel 600 and 321 stainless steel to Ti-8Al-1Mo-1V, and for Inconel 718 to 321 stainless steel.

PHASE IV - DIFFUSION WELDING BY THE ROLL METHOD

Roll welding was investigated as a method for joining the six alloy combinations. This phase of work was limited in scope and was conducted primarily to determine if the alloy combinations could be joined in the bare material condition using an argon atmosphere. These materials which could not be welded in the bare conditions were welded using diffusion aids.

WELDING OF BARE MATERIAL

CHEMICAL CLEANED MATERIAL

The six alloy combinations were roll welded in the bare condition using the welding conditions shown in Table XVII. All material was chemically cleaned prior to welding. Upon removal of the retorts after welding it was observed that the three alloy combinations containing a titanium alloy were not welded or only partially welded regardless of welding temperature used. The remaining three combinations which were successfully joined were evaluated to peel, bend and torsion tests and to metallurgical examination. This evaluation revealed the following.

2219 and 7106 Aluminum Alloys to 321 Stainless Steel

These combinations had excellent peel strength and ductility when welded at 750° and 850°F. Specimens welded at 650°F were low in peel strength. The specimens welded at 750° and 850°F successfully passed the bend and torsion test without cracking or delamination. Metallurgical examination revealed the joints were free of voids and no evidence of formation of an intermediate phase was observed. The photomicrograph shown in Figure 82 is typical for these combinations.

Inconel 718 to 321 Stainless Steel

This combination was successfully welded at 1400°, 1600° and 1800°F. Peel strength increased with increasing welding temperature. Roll welding at the 1800°F temperature resulted in partial welding of the retort to the specimen and made stripping of the retort difficult. Specimens welded at all the above temperatures successfully passed the bend and torsion test without cracking or delamination. Metallurgical examination revealed the joints were void free and without the formation of detrimental intermediate phases, Figure 83.

ABRASIVELY CLEANED MATERIAL

The three material combinations containing a titanium alloy were welded in the abrasively cleaned condition in an attempt to produce a satisfactory welded joint.

This method was successful on the 2219 aluminum alloy to Ti-5Al-2.5Sn combination when welding was conducted at 950°F, and welded specimens exhibited excellent peel strength and ductility. Specimens also passed the bend and torsion test without cracking or delamination. The welded joints were free of voids and of an observable intermediate phase, Figure 84.

The two alloy combinations containing Ti-8Al-1Mo-1V could not be satisfactorily roll welded in the abrasively cleaned condition where roll welding was attempted at 1400°, 1500° and 1600°F.

WELDING WITH DIFFUSION AIDS

Diffusion aids were employed in an attempt to roll weld the Inconel 600 and 321 stainless steel to Ti-8Al-1Mo-1V alloy combinations. Prior to welding the sheet material was chemically cleaned. Silver and nickel foil were used at temperatures of 1500°, 1600° and 1700°F. The welding with these diffusion aids was unsuccessful due to joint delamination.

Examination of the joint faying surfaces indicated that partial welding did occur during rolling and that delamination occurred from cooling stresses.

Both alloy combinations were roll welded at 1050°F using aluminum foil for a diffusion aid. The sheet material and foil were chemically cleaned prior to welding. These roll welded specimens were successful and exhibited good peel strength and ductility. Bend and torsion tests were successful without cracking or delamination. Metallurgical examination showed the joints were void free and without a detectable intermediate phase. Figure 85 is typical of this roll welded joint.

DISCUSSION

Based on the limited work conducted in obtaining acceptable roll welding schedules for the six material combinations the following schedules were selected as the most satisfactory:

Combination	Surface Preparation	Diffusion Aid	Rolling Temp.	Total Ga Reductior Inches
2219 Al to 321 SS	Chemical clean	-	850°F	.025-.03
7106 Al to 321 SS	Chemical clean	-	850°F	.025-.03
2219 Al to Ti-5Al-2.5Sn	Abrasive clean	-	950°F	.025-.03
321 SS to Ti-8Al-1Mo-1V	Chemical clean	Aluminum Foil	1050°F	.001-.00
Inconel 600 to Ti-8Al-1Mo-1V	Chemical clean	Aluminum Foil	1050°F	.001-.00
Inconel 718 to 321 SS	Chemical clean	-	1600°F	.005-.01

The foregoing roll weld schedules produced welded joints with good strength and ductility and permitted the alloy combinations to be severely formed without delamination. The rolling temperatures shown above resulted in good specimen surface finish and permitted easy removal of the retort.

PHASE V - JOINT EVALUATION

The six alloy combinations were subjected to single lap shear and corrosion tests to evaluate the properties of the diffusion weld joints. The following describes the welding procedure which was used and test results of this work.

SINGLE LAP SHEAR TESTS

PRESS WELDED SPECIMENS

Test Conditions

Press welded specimens having the configuration shown in Figure 86 were prepared for the six alloy combinations using the material in the bare condition and with diffusion aids. The following list shows the welding conditions used for each alloy combination.

Combination	Surface Preparation		Diffusion Welding Parameters		
	Chemical	Abrasive	Temperature	Time	Environment
1. 2219 Al/321 SS					
(a) Bare Condition	X		940°F±10°F	30 min.	Vacuum
(b) Silver Electroplated		X	500°F	2 hrs.	Air
2. 7106 Al/321SS					
(a) Bare Condition	X		940°F±10°F	30 min.	Vacuum
(b) Silver Electroplated		X	500°F	2 hrs.	Air
3. 2219 Al/Ti-5Al-2.5Sn					
(a) Bare Condition		X	940°F±10°F	30 min.	Vacuum
(b) Silver Electroplated		X	500°F	2 hrs.	Air
4. Inconel 600/Ti-8Al-1Mo-1V					
(a) Bare Condition		X	1325°F	10 min.	Vacuum
(b) Silver Electroplated		X	700°F	30 min.	Air
5. 321SS/Ti-8Al-1Mo-1V					
(a) Bare Condition		X	1425°F	10 min.	Vacuum
(b) Silver Electroplated		X	700°F	30 min.	Vacuum
6. Inconel 718/321SS					
(a) Bare Condition		X	1625°F	15 min.	Vacuum
(b) Silver Electroplated		X	600°F	30 min.	Air
(c) Nickel Electroplated		X	1325°F	30 min.	Vacuum

All specimens were welded in dies containing stops which limited the compressive thinning of the lap joint at 0.003 to 0.006 inches. After welding, all specimens were removed from the die after they had cooled to approximately 500°F. During shear testing the silver electroplated specimens containing the Ti-8Al-1Mo-1V alloy produced very erratic shear test results. Macro-examination of the surfaces of the failed joint indicated the faying surfaces had been only partially joined. Apparently, either the welding temperature was too low or the specimens were failing during cooling due to the difference in the thermal contraction of the dissimilar metals in the combination. All silver electroplated specimens containing Ti-8Al-1Mo-1V alloy were then joined by welding at 700°F and by cooling the die under pressure until the specimens reached 275°F. This procedure produced acceptable joint strength and consistency.

Included in this investigation were tests to obtain information on the effect of air and vacuum environments on the diffusion welding characteristics of electroplated silver. These tests included welding the Inconel 600 and 321 stainless steel to Ti-8Al-1Mo-1V combinations in both air and vacuum environments.

After welding, all press welded lap shear specimens were tested at cryogenic temperatures, room temperature and at elevated temperatures. The results of this work are shown in Tables XVIII through XXIII inclusive.

Evaluation of Shear Tests

The results of the shear tests are evaluated for each material combination as follows:

2219 Aluminum to 321 Stainless Steel

This material combination produced satisfactory shear strength when welded in the bare condition. A joint overlap of approximately 0.12 (twice the material thickness) is adequate to produce base metal tensile failures in the 2219 aluminum alloy.

Silver electroplated specimens produced acceptable shear strength at all temperatures. However, at 500°F the shear strength dropped considerably which indicates this temperature may be too high for service application. At room temperature and at elevated temperatures the specimen failed primarily through the silver-to-silver interface (75%), and at cryogenic temperatures the specimens failed primarily through the silver-to-aluminum interface (90%). This indicates that some brittle intermediate phase was present in the diffusion zone on the 2219 aluminum side of the joint.

7106 Aluminum Alloy to 321 Stainless Steel

Material in the bare condition normally failed in shear and with the appearance of a brittle intermediate phase. The occasional base metal failure indicates that the bare material combinations could be joined in a manner which would eliminate or minimize the occurrance of this brittle phase by a closely controlled cleaning and welding procedure.

Silver electroplated material produced acceptable strength at all test temperatures. The low strength obtained at 500°F indicates this temperature is too high for service application. All silver electroplated material failed primarily through the silver-to-silver interface indicating a ductile diffusion zone in the joint.

2219 Aluminum Alloy to Ti-5Al-2.5Sn

Material in the bare condition produced acceptable shear strength at all test temperatures. A joint overlap of approximately 0.12 inch (twice the material thickness) is sufficient to produce base metal tensile failures.

Silver electroplated material produced acceptable strength at room temperature and at -320°F. Silver plated material tested at 300°, 500° and -423°F temperatures produced joints having low strength. This is probably caused by thermal stress resulting from the difference in thermal expansion of the two alloys.

Further testing is required to determine the cause for the lower shear load capability at these temperatures.

Inconel 600 to Ti-8Al-1Mo-1V

Specimens welded in the bare condition produced acceptable shear strength at all test temperatures, Table XXI. The specimen weld joint contained some brittle intermediate phase which resulted in a progressive shear failure which started when the load reached approximately 2/3 of the failure load. However, the joint strength and ductility was sufficient to permit considerable deformation of the joint area during test and sufficient to produce fairly consistent shear strength at all test temperatures.

Silver electroplated specimens produced satisfactory joint strength at room temperature and at cryogenic temperature. Elevated temperature tests resulted in low and erratic shear strength. This is believed to be caused by partial fracturing the joint due to the difference to thermal expansion of the dissimilar metals.

321 Stainless Steel to Ti-8Al-1Mo-1V

Material welded in the bare condition produced acceptable shear strength at all test temperatures, Table XXII. This combination contained a joint interface which was somewhat more brittle than the Inconel 600 to Ti-8Al-1Mo-1V combination. This resulted in a progressive shear failure starting at about one-half of the failure load (observed in room temperature tests by audible cracking).

Silver electroplated specimens produced acceptable and consistent shear strength at cryogenic and room temperature test. At elevated temperatures the silver electroplated joints exhibited low strength as observed with the Inconel 600 to Ti-8Al-1Mo-1V combination.

Inconel 718 to 321 Stainless Steel

Material in the bare condition produced acceptable shear strength at all test temperatures.

Nickel electroplated material was similar to the bare condition except the shear failure loads were somewhat less. Silver electroplated materials produced good acceptable strength and consistency at room temperature and at cryogenic temperatures. Testing at elevated temperatures showed a considerable loss in shear strength, Table XXIII.

ROLL WELDED SPECIMENS

Test Conditions

Single lap shear specimens were prepared for the six alloy combinations. The materials were joined by roll welding using the argon filled retort and the welding conditions shown below.

Combination	Surface Preparation		Diffusion (Roll) Welding Temperature	Diffusion Aid
	Chemical	Abrasive		
1. 2219 Al/321 SS	X		850°F	None
2. 7106 Al/321 SS	X		850°F	None
3. 2219 Al/Ti-5Al-2.5Sn		X	950°F	None
4. Inconel 600/Ti-8Al-1Mo-1V	X		1050°F	Aluminum (0.005-in)
5. 321 SS/Ti-8Al-1Mo-1V	X		1050°F	Aluminum (0.005-in)
6. Inconel 718/321 SS	X		1600°F	None

The specimens were prepared by welding 2 inch x 16 inch strips as shown in Figure 10 and were machined into shear specimens as shown in Figure 86. Specimens were tested at -423°F, room temperature and at elevated temperature. The test conditions and test results are shown in Table XXIV.

Evaluation of Shear Test

The results of the roll welded shear tests are evaluated for each material condition as shown below:

2219 and 7106 Aluminum Alloy to 321 Stainless Steel
2219 Aluminum Alloy to Ti-5Al-2.5Sn

Acceptable and consistent shear strength was exhibited at all test temperatures. All specimens failed by primarily shearing through the aluminum joint, leaving a considerable amount of aluminum on the steel or titanium side of the joint.

Inconel 600 and 321 Stainless Steel to Ti-8Al-1Mo-1V

This combination showed good strength and consistency at all test temperatures. All specimens failed by shearing through the 0.005 inch thick foil, leaving aluminum on both material surfaces. Testing at 400°F revealed that the specimen retained a high proportion of their room temperature shear load capability.

Inconel 718 to 321 Stainless Steel

This alloy showed good strength and consistency at all test temperatures. All shear failures occurred at the original joint faying surfaces.

DISCUSSION

Evaluation of the foregoing mechanical property test results for both roll and press welded material revealed the following:

1. All roll welded specimens produced excellent shear strength at all test temperatures. Press welded material combinations which contained a brittle intermediate phase in the joint showed better strength and consistency at elevated temperature than at cryogenic temperature.

2. Press welded silver electroplated specimens do not exhibit satisfactory strength at elevated temperature, particularly at 400°F and above. It appears that silver electroplate as a diffusion aid possesses a low shear strength at elevated temperatures. This coupled with stresses created by materials having a high difference in thermal expansion (i.e. those containing titanium) result in very erratic test results.

3. Press welded bare material combinations produced joints with usable shear strength at all test temperatures.

4. Based on the work conducted in this program the following tabulation shows the preferred diffusion welding method for each alloy combination for various temperature environments. In making this selection consideration is given first to adequate joint strength, second to joint reliability and third to ease of manufacturing.

Alloy Combination	Preferred Material Condition at Indicated Temperature °F				
	-423°	-320°	RT	RT to 300°F	Above 300°F
2219 Al to 321 SS	Ag Plate	Ag Plate	Ag Plate	Ag Plate	Bare
7106 Al to 321 SS	Ag Plate	Ag Plate	Ag Plate	Ag Plate	Bare
2219 Al to Ti-5Al-2.5Sn	Ag [1] Plate	Ag Plate	Ag Plate	Ag Plate	Bare
Inconel 600 to Ti-8Al-1Mo-1V	Ag [1] Plate	Ag Plate	Ag Plate	Ag Plate	Bare
321 SS to Ti-8Al-1Mo-1V	Ag [1] Plate	Ag Plate	Ag Plate	Ag Plate	Bare
Inconel 718 to 321 SS	Ag Plate	Ag Plate	Ag Plate	Ag Plate	Nickel Plate

[1] Critical control of cooling cycle is required.

CORROSION TESTS

Material combinations prepared using the same materials and welding conditions as used for shear specimens were subjected to 60 day exposure in a condensing humidity cabinet. Examination of these specimens after exposure revealed the following:

PRESS WELDED-BARE CONDITION

1. 2219 Aluminum Alloy to 321 Stainless Steel
   7106 Aluminum Alloy to 321 Stainless Steel
   2219 Aluminum Alloy to Ti-5Al-2.5Sn Alloy

   The aluminum side of the joint was discolored during the exposure. Corrosion at the joint interface occurred to some degree on all specimens, resulting in a 5 to 10% decrease in joint shear area. An example of this corrosion is shown in Figure 87a. Slight pitting of the aluminum was observed. This test shows that the joint area should be protected if the welded joints are to be subjected to moisture during use.

2. Inconel 600 to Ti-8Al-1Mo-1V
   321 Stainless Steel to Ti-8Al-1Mo-1V

   These combinations did not discolor measurably during the exposure. Examination of the joint area at 500X magnification revealed evidence of slight corrosion at the joint interface, Figure 87b. From this test it appears that these dissimilar metal joints may require protective coatings if exposed to moisture.

3. Inconel 718 to 321 Stainless Steel

   No corrosion was detected on this material combination.

PRESS WELDED-DIFFUSION AIDS

1. 2219 Aluminum Alloy to Ti-5Al-2.5Sn
   2219 Aluminum Alloy to 321 Stainless Steel

   The 2219 was severely discolored and contained slight pitting. No corrosion occurred on the opposite side of the joint or in the silver plated joint area. This test shows protective coatings are required if these material combinations are exposed to moisture.

2. 7106 Aluminum Alloy to 321 Stainless Steel

   A small amount of discoloration was detected on the base metals of the 7106 aluminum alloy. No corrosion was detected on any of the silver plating or joint areas. From this test it appears this material combination may require protection if exposed to conditions involving moisture.

3. Inconel 600 to Ti-8Al-1Mo-1V
   321 Stainless Steel to Ti-8Al-1Mo-1V
   Inconel 718 to 321 Stainless Steel

   None of the specimens exhibited discoloration or corrosion on any part of the base metal, silver plating, nickel plating or joint areas. From these tests it appears that the foregoing material combinations may be exposed to moisture without joint protection.

ROLL WELDED

1. 2219 Aluminum Alloy to 321 Stainless Steel
   7106 Aluminum Alloy to 321 Stainless Steel
   2219 Aluminum Alloy to Ti-5Al-2.5Sn

   The aluminum alloy side of the joints were slightly discolored during exposure. Contrary to the press welded specimens little or no evidence was found of corrosion entering the faying surfaces of the joints. Apparently the roll welding process is fast enough to prevent the formation of an intermediate phase such as $FeAl_3$, which was believed to accelerate the corrosion of the press welded specimens. However, under extended exposure corrosion of the aluminum may be expected.

2. Inconel 600 to Ti-8Al-1Mo-1V
   321 Stainless Steel to Ti-8Al-1Mo-1V
   Inconel 718 to 321 Stainless Steel

   These alloys did not exhibit corrosion or discoloration on any part of the base metal or joint faying surfaces.

DISCUSSION

The corrosion testing conducted in this work indicates that corrosion will occur on any dissimilar metal joint. However, the amount may be tolerable on the Inconel 718 to 321 stainless steel and on roll welded specimens containing Ti-8Al-1Mo-1V alloy (aluminum foil interface) for many production applications.

All combinations containing 2219 or 7106 aluminum alloys require protective coatings if exposed to high humidity or moisture.

Inconel 600 and 321 stainless steel (bare) to Ti-8Al-1Mo-1V combinations require a protective coating to prevent corrosion at the joint interface.

Silver electroplating completely protects the joint area from corrosion. However, silver accelrates the corrosion of the base metals.

PHASE VI - PROJECTION OF DIFFUSION WELDING APPLICATIONS

This section of the report summarizes a design study and limited hardware evaluation of the potential applications of diffusion welding as developed in this program.

DESIGN STUDY

A study was conducted to determine applications where the joining of dissimilar metals by diffusion welding would prove to be an advantage in aerospace design concepts. A survey of various engineering design groups within The Boeing Company revealed the following areas where dissimilar metal joints are being considered.

CRYOGENIC TANK DESIGN

1. Transition joints are required in tubing lines which carry cryogens. These joints are needed primarily to provide design flexibility in choosing the best materials (based on total system weight and heat loss) for the pressure vessel, plumbing lines and outer vacuum shell. In providing electrical pass throughs, plumbing inlet and outlet lines and vacuum gages, the following alloy combinations are needed:

   a) 2219 aluminum alloy to 321 stainless steel

   b) 2219 aluminum alloy to titanium alloys

   c) Stainless steel to titanium alloys

   d) Inconel 718 to stainless steel or 2219 aluminum alloy

   In the foregoing applications the dissimilar metal joints must be pressure and vacuum tight and operate at a temperature of 150°F to -423°F.

2. Cryogenic lines located within a vacuum jacket must be attached to heat shields to develop the lowest possible heat leak rate. In this application aluminum alloys will be joined to steel or titanium tubing.

SPACE ANTENNA DESIGN

In the design of space antennas dissimilar metals are required for the purpose of controlling heat flow from the hot side to the cold side of the structure. In this application metal strips having high conductivity (copper or silver) are required to be joined to aluminum or nickel alloys. The joints must provide high conduction and operate in a temperature range of 180°F to -300°F.

SPACE PROBE DESIGN

Space probes such as Voyager, are designed to provide an internal temperature which will remain within a closely controlled operating range.

Dissimilar metals joints are required at contact points between the outer shell and inner structure. Materials are presently used, depending on performance requirements, which will increase or decrease heat flow to the inner structure.

SPACE VEHICLE DESIGN

Studies are being conducted for the use of titanium to beryllium, aluminum to beryllium and stainless steel to beryllium for space structures. The beryllium is desirable for its stiffness in load carrying structure and for meteoroid shielding in extended space missions. In these applications the dissimilar metal joint only carries a moderate load, but must withstand thermal stresses from an operating temperature range of 500°F to -320°F.

SUPERSONIC TRANSPORT

Titanium alloys are used almost exclusively in the design for the proposed supersonic transport. Design studies indicate that the joining of steel alloys to titanium alloys is desirable for various mechanical parts requiring sleeves for antifriction bearings.

AIRCRAFT STRUCTURES

Consideration has been given in the past for the use of steel clad aluminum alloys in applications where structural stiffness and fire protection is required.

From the foregoing survey it is apparent that designers have many potential applications for the use of dissimilar metal joints. However, in many cases they have not considered diffusion welding because a manufacturing process is not known or available to them. The manufacturing and testing of simulated hardware must be conducted to provide the necessary process verification and design data for future dissimilar metal joining applications.

PROTOTYPE HARDWARE

The foregoing study revealed that the major current need for dissimilar metal joints is in the construction of cryogenic storage systems. Accordingly, prototype parts were fabricated to simulate the cryogenic heat shield and the tubular transition joints discussed in the foregoing section. The purpose of this work was to adapt the laboratory processes to production and, in the case of the tubular joints, provide a test article which could be evaluated by helium leak and thermal shock tests. The following describes the manufacturing and testing of these parts:

CRYOGENIC HEAT SHIELDS

Stainless steel tubing having a 0.375-inch diameter and an 0.030-inch wall was joined to 1100 aluminum alloy sheet having a thickness of 0.010-inch. Both the stainless steel and aluminum alloy were silver electroplated prior to joining. The parts were joined using a hot die riveting machine having the dies formed to support the tube and provide a welding contact area as shown in Figure 88. The die length was one-inch and die temperature was 800°F. Welding time and pressure was adjusted (or determined by peel test) until satisfactory welds were obtained. For this application 50% welding of the joint area is adequate for strength and heat conduction. A welding time of approximately one minute was required to produce a satisfactory weld. From this work it appears that in production applications, tooling could be provided for the economical production diffusion welding of heat shield assemblies.

TUBULAR JOINTS

The six material combinations investigated in the experimental program were joined by diffusion welding to produce tubular joints having a 0.500-inch inside diameter. The joints were prepared having a 7 degree taper as shown in Figure 89 and were welded using differential expansion tooling, Figure 89. The external member of the tubular joint was cooled to -320°F and inserted into the die having a temperature of 250°F. Then the internal member was inserted into the taper using a light pressure (100 lbs). The joint was then welded at the desired time and temperature, Table XXV. After welding, the dissimilar metal joint was chilled with LN_2 while the die remained hot and then removed using a light pressing force (hand arbor press). The dissimilar metal joints were then machined to the configuration shown in Figure 90 and were subjected in helium leak and thermal shock tests. After these tests extensions were welded to the tubular joints and then tensile loaded to failure. The results of these tests, Table XXV, show that diffusion welded joints were produced in all material combinations which were helium leak tight before and after thermal shock tests. In the tensile tests all joints failed in the specimen base metal leaving the diffusion welded joint intact.

The Boeing Company Manufacturing Development Group used the diffusion welding concepts developed in this program to produce one-half and one-inch diameter 2219 aluminum alloy to 321 stainless steel joints. Silver electroplating was used for a diffusion aid. Tooling and parts were designed to give a rapid, economical and reliable welded joint. A split die was used for the outer steel restraining ring. The outer 2219 aluminum alloy tube was machined with a straight outside diameter and base. The internal 321 stainless steel tube was machined with a straight outside diameter and with a tapered (Morse) inside diameter. Parts were assembled at room temperature and stainless steel pin (Morse taper) was pressed into the stainless steel tube using a predetermined hydraulic pressure. After welding the pin was pressed from the assembly and the welded part removed by opening the die. Figure 91 shows a cross section of the welded parts. Helium leak, thermal shock tests and metallurgical examination of these joints showed a completely welded joint can be reliably produced using the foregoing procedures.

REFERENCES

1. Hansen, M., Constitution of Binary Alloys, Second Edition, McGraw-Hill Book Company, Inc., New York, 1958.

2. Elliott, R.P., Constitution of Binary Alloys, First Supplement, McGraw-Hill Book Company, Inc., New York, 1965.

3. Pearson, W.B., A Handbook of Lattice Spacings and Structures of Metals and Alloys, Pergamon Press, Inc., New York, 1958.

4. Shewmon, P.G., Diffusion in Solids, McGraw-Hill Book Company, Inc., New York, 1963.

5. "Heats of Free Energies of Formation of Inorganic Oxides", U.S. Bureau of Mines, Bulletin 542.

6. Mondolfo, L.F., Metallography of Aluminum Alloys, John Wiley and Sons, Inc., New York, 1943.

7. Petty, E. R., "Hardness and Other Properties of Some Binary Intermetallic Compounds of Aluminum", Journal of the Institute of Metals, 1960-61, Vol. 89.

ACKNOWLEDGEMENT

The authors are indebted to F. G. Marr for his thoroughness in conducting the many processing investigations and to R. Smith for his fine effort in preparing metallographic specimens. In addition, the support efforts of Dr. E.C. Roberts, G. Buehler, R. C. Racus and C. D. Smith are appreciated.

TABLE I NOMINAL CHEMICAL COMPOSITION OF SELECTED ALLOYS

ALUMINUM ALLOYS

ALLOYS	PERCENTAGE								
	Cu	Zn	Mg	Mn	Ti	V	Zr	Cr	Al
2219	6.3	-	-	0.3	0.06	0.10	0.18	-	Rem.
7106	-	4.3	2.1	0.25	0.04	-	0.17	0.13	Rem.

TITANIUM ALLOYS

ALLOYS	PERCENTAGE								
	Al	Sn	Mo	V	Ti				
Ti-5Al-2.5Sn	5	2.5	-	-	Rem.				
Ti-8Al-1Mo-1V	8	-	1	1	Rem.				

HEAT RESISTING ALLOYS

ALLOYS	PERCENTAGE									
	Cr	Ni	Fe	Mo	Co	Ti	Al	Cb	C	B
321 Stainless Steel	18	10	Rem.	-	-	0.5	-	-	0.07	-
Inconel 600	15	Rem.	7	-	-	-	-	-	0.04	-
Inconel 718	19	Rem.	18	3	-	0.8	0.6	5.2	0.04	-

TABLE II MELTING TEMPERATURES AND THERMAL TREATMENTS FOR SELECTED ALLOYS

Alloy	Melting Range Temp.(°F)	Solution Heat Treat Temp.(°F)	Aging Temp.(°F)	Annealing Temp.(°F)	Other Temperatures(°F)
2219 Aluminum Alloy	1010-1090	995	375	775	
7106 Aluminum Alloy	1090-1185	870	225-300	650-750	
Ti-5A1-2.5Sn Titanium Alloy	2820-3000	None	None	1325-1550	Beta Transus 1900 Stress Relief (Anneal) 1000-1200
Ti-8A1-1Mo-1V Titanium Alloy	3065-3115 (for Ti-8A1-2Cb-1Ta)	1850 (Duplex Anneal 1450)	1100	1450	Beta Transus 1900 Stress Relief (Anneal) 1100-1200
AISI 321 Stainless Steel	~ 2550	None	None	1750-1950	Stabilizing Anneal 1550-1650
Inconel 600 Nickel Alloy	2500-2600	None	None	1800	Stress Relieving 1650
Inconel 718 Nickel Alloy	~ 2570	1700-1800	1325	1750	

TABLE III

HARDNESS OF AS-RECEIVED BASE MATERIALS*

Material	Condition	Hardness		
		VHN	R_B	R_C
2219 Aluminum Alloy	(-T6) Solution Treated and Aged	121	80	--
7106 Aluminum Alloy	(-T6) Solution Treated and Aged	120	67	--
321 Stainless Steel	Annealed	142	75	--
Ti-5Al-2.5Sn	Annealed	308	--	31
Ti-8Al-1Mo-1V	Duplex Annealed	330	--	33
Inconel 600	Annealed	180	87	--
Inconel 718	Annealed	185	89	--

*Vickers Hardness Tester with 10 Kg load.

TABLE IV THERMAL EXPANSION OF SELECTED ALLOYS

Alloy	Percent Thermal Expansion From 75° F to Indicated Temperature (°F)																
	-300	-100	75	200	300	400	500	600	800	1000	1200	1400	1600	1800	2000	2200	2400
2219 Aluminum Alloy	-.36	-.2	-	.16	.30	.43	.57	.71	1.02	1.36							
7106 Aluminum Alloy			-	.16	.31												
Ti-5A1-2.5Sn Titanium Alloy	-.16	-.08	-	.07		.17		.28	.38	.50	.62	.74	.87				
Ti-8A1-1Mo-1V Titanium Alloy	-.15 (-320°)	-.10 (-140°)	-	.07	.12	.17		.27	.38	.50	.56 (1100°)						
AISI 321 Stainless Steel	-.28	-.15	-	.12		.31		.50	.72	.97	1.20	1.40	1.55	1.75	2.0	2.15	2.30
Inconel 600 Nickel Alloy	-.20 (-250°)	-.12	-	.09		.25		.41	.58	.78	.97	1.18	1.39	1.60			
Inconel 718 Nickel Alloy			-	.09		.24		.40	.57	.74	.94	1.18					

TABLE V PHASE II PRESS WELDING TEST SCHEDULE

2219 aluminum alloy to 321 stainless steel alloy
7106 aluminum alloy to 321 stainless steel alloy
2219 aluminum alloy to Ti-5Al-2.5Sn titanium alloy

(Bare Condition - Argon Atmosphere)

Material Combination	Diffusion Welding Conditions										Total Number of Tests
	Temperature °F			Pressure-KSI			Time-Minutes*				
	900	950	1000	3.50	5.5	7.5	30	60	120	240	
2219 Aluminum Alloy to 321 Stainless Steel	x			x	x	x		x	x	x	9
		x		x	x	x	x	x	x		9
			x	x	x	x	x	x	x		9
											27
7106 Aluminum Alloy to 321 Stainless Steel	x			x	x	x		x	x	x	9
		x		x	x	x	x	x	x		9
			x	x	x	x		x	x		9
											27
2219 Aluminum Alloy to Ti-5Al-2.5Sn	x			x	x	x		x	x	x	9
		x		x	x	x	x	x	x		9
			x	x	x	x	x	x	x		9
											27

*Times apply to each pressure condition

TABLE VI PHASE II PRESS WELDING TEST SCHEDULE

Inconel 600 to Ti-8Al-1Mo-1V
321 Stainless Steel to Ti-8Al-1Mo-1V
(Bare Condition-Argon Atmosphere)

Material Combination	Diffusion Welding Conditions										Total Number of Tests
	Temperature °F			Pressure-KSI			Time-Minutes*				
	1200	1350	1450	12.5	20	30	10	60	120	240	
Inconel 600 to Ti-8Al-1Mo-1V	x			x	x	x		x	x	x	9
		x		x	x	x	x	x	x		9
			x	x	x	x	x	x	x		9
											27
321 Stainless Steel to Ti-8Al-1Mo-1V	x			x	x	x		x	x	x	9
		x		x	x	x	x	x	x		9
			x	x	x	x	x	x	x		9
											27

*Times apply to each pressure condition

TABLE VII PHASE II PRESS WELDING TEST SCHEDULE

Inconel 718 to 321 Stainless Steel

(Bare Condition - Argon Atmosphere)

Material Combination	Diffusion Welding Conditions													Total Number of Tests
	Temperature °F			Pressure-KSI					Time-Minutes *					
	1325	1600	1750	7.5	12.5	17.5	22.5	27.5	10	30	60	120	240	
Inconel 718 Alloy to 321 Stainless Steel	x					x	x	x			x	x	x	9
		x			x	x	x			x	x	x		9
			x	x	x	x			x	x	x			9
														27

*Times apply to each pressure condition

TABLE VIII SUMMARY OF PEEL TEST RESULTS

2219 aluminum alloy to 321 stainless steel alloy
7106 aluminum alloy to 321 stainless steel alloy
2219 aluminum alloy to Ti-5Al-2.5Sn titanium alloy

Temperature		900°F			950°F			1000°F		
Material Combination	Time / Pressure	3.5 KSI	5.5 KSI	7.5 KSI	3.5 KSI	5.5 KSI	7.5 KSI	3.5 KSI	5.5 KSI	7.5 KSI
2219 to 321	30 min.				x	x	1	x	1	1
	60 min.	x	1	x	x	1	1	1	2	1
	120 min.	x	x	1	1	1	1	1	1	1
	240 min.	x	x	1						
7106 to 321	30 min.				1	1	2	1	x	1
	60 min.	x	1	1	1	2	2	x	x	x
	120 min	1	2	2	2	2	2	x	x	1
	240 min.	1	2	2						
2219 to Ti-5Al-2.5Sn	30 min.				1	1	2	1	2	2
	60 min	x	2	2	2	3	3	1	2	2
	120 min.	1	2	2	2	2	3	1	2	1
	240 min.	3	3	3						

x - Failed in thermal shock
1 - Low bond strength and ductility
2 - Medium bond strength and ductility
3 - High bond strength and ductility

TABLE IX

PHASE II. PRESS WELDING - EFFECT OF AIR ATMOSPHERE
(Bare Material)

Material Combination	Diffusion Welding Conditions											Total Number of Tests
	Surface Condition [1]		Welding Pressure Application		Temperature-°F		Pressure-KSI		Time-Minutes			
	A	B	Prior to Heating to Temperature	After Heating to Temperature	950	1600	7.5	12.5	10	30	60	
2219 Al to 321 SS	x	x	x	x	x		x			x		4
	x		x	x	x		x		x		x	4
7106 Al to 321 SS	x	x	x	x	x		x			x		4
	x		x	x	x		x		x		x	4
2219 Al to Ti-5Al-2.5Sn	x	x	x	x	x		x			x		4
	x		x	x	x		x		x		x	4
Inconel 718 to 321 SS	x	x	x	x		x		x	x		x	8
												32

[1] A - As-received material chemically cleaned plus abrasive sanding.
B - Polished surfaces plus solvent cleaning.

TABLE X PHASE II. PRESS WELDING - EFFECT OF VACUUM ENVIRONMENT
(Bare Material)

Material Combination	Diffusion Welding Conditions												Total Number of Tests
	Surface Condition [1]		Temperature - °F				Pressure - KSI			Time - Minutes			
	A	B	950	1350	1450	1600	7.5	12.5	20.0	10	30	60	
2219 Al to 321 SS	x	x	x				x				x	x	4
7106 Al to 321 SS	x	x	x				x				x	x	4
2219 Al to Ti-5Al-2.5Sn	x	x	x				x				x	x	4
Inconel 600 to Ti-8Al-1Mo-1V	x			x	x				x	x	x		4
321 SS to Ti-8Al-1Mo-1V	x			x	x				x	x	x		4
Inconel 718 to 321 SS	x			x	x				x				4
	x					x		x		x	x		2

[1] A - As-received material chemically cleaned plus abrasive sanding.
B - Polished surfaces plus solvent cleaning.

TABLE XI PHASE II. PRESS WELDING - METAL FOIL DIFFUSION AID SCREENING TEST
(Argon Atmosphere)

Material Combination	Diffusion Welding Conditions															Total Number of Tests
	Metal Foil							Temperature - °F				Pressure - KSI		Time-Min.		
	Ag	Au	Cu	Fe	Ni	Ti	V	1000	1300	1500	1700	20	12.5	10	60	
Inconel 600 to Ti-8Al-1Mo-1V	x	x			x	x		x				x			x	4
	x	x			x	x			x			x		x		4
			x		x	x	x		x			x			x	4
	x	x	x		x	x	x			x		x		x		6
			x				x				x		x	x		2
321 SS to Ti-8Al-1Mo-1V	x	x			x	x		x				x			x	4
	x	x			x	x			x			x		x		4
			x		x	x	x		x			x			x	4
	x	x	x		x	x	x			x		x		x		6
			x				x				x		x	x		2
Inconel 718 to 321 SS	x	x		x	x			x				x			x	4
	x	x		x	x				x			x		x		4
			x	x	x				x			x			x	3
	x	x	x	x	x					x		x		x		5
			x		x						x			x		2

58

Base material chemically cleaned plus abrasive sanded.
Foil material used in the as-received condition.

TABLE XII PHASE II PRESS WELDING - ELECTROPLATED METAL DIFFUSION AID SCREENING TEST

(Argon Atmosphere)

Material Combination	Diffusion Welding Conditions																		Total Number of Tests
	Electroplated Metal						Temperature - °F						Pressure - KSI			Time - Minutes			
	1 Cu	2 Ag	3 Ni	4 Cu	4 Ag	4 Ni	500	700	900	1100	1300	1500	7.5	12.5	20	10	60	120	
2219 Al to 321 SS	x x	x x		x x	x x	 x	x	x	x				x	x	x	x x	x x	x	8 8 2
7106 Al to 321 SS	x x	x x		x x	x x x		x	x	x				x	x	x	x x	x x	x	8 8 2
2219 Al to Ti-5Al-2.5Sn	x x	x x		x x	x x x	 x	x	x	x				x	x	x	x x	x x	x	8 8 4
Inconel 600 to Ti-8Al-1Mo-1V	x x	x x	x x	x x	x x	x x			x	x	x	x			x x	x	x		6 18
321 SS to Ti-8Al-1Mo-1V	x x	x x	x x	x x	x x	x x			x	x	x	x			x x	x	x		6 18
Inconel 718 to 321 SS	x x		x x						x	x x	x	x				x	x		4 6

114

1 Copper plate on both materials.
2 Silver plate on both materials (copper strike used on aluminum alloys).
3 Nickel plate on both materials.
4 Copper, nickel and silver plated on anodized (phosphoric acid) aluminum alloys, and plated on titanium alloys pretreated with titanium fluoride.

TABLE XIII PHASE II. DIFFUSION AID PARAMETRIC STUDY

Material Combination	Diffusion Welding Conditions																					Total Number of Specimens
	Diffusion Aid [1]				Temperature - °F									Pressure - KSI				Time - Minutes				
	Ag	Cu	Ni	V	500	600	700	900	1100	1300	1400	1500	1600	30	20	15	10	10	30	60	120	240	
2219 Al to 321 SS	x	x			x									x						x	x	x	6
	x	x				x								x					x	x	x		6
	x	x					x								x			x	x	x			6
7106 Al to 321 SS	x	x			x									x						x	x	x	6
	x	x				x								x					x	x	x		6
	x	x					x								x			x	x	x			6
2219 Al to Ti-5Al-2.5 Sn	x				x	x								x					x				2
	x [2]					x								x					x				4
Inconel 600 to Ti-8Al-1Mo-1V	x					x								x								x	1
	x									x					x			x	x	x			3
	x [2]					x								x					x				4
				x							x				x			x	x	x			3
				x								x	x			x	x	x	x	x			6 [3]
321 SS to Ti-8Al-1Mo-1V	x					x								x								x	1
	x									x					x			x	x	x			3
	x [2]					x								x					x				4
				x							x				x			x	x	x			3
				x								x	x			x	x	x	x	x			6 [3]
Inconel 718 to 321 SS	x				x	x	x	x						x					x				4
	x								x					x					x			x	2
	x									x					x			x			x		2
			x						x										x		x	x	3
			x							x								x		x	x		3
			x									x				x		x	x	x			3

[1] Ag, Cu and Ni were electroplated .0005"/.0007" thick on each metal (Appendix B). Vanadium used in foil form .001" thick. 93

[2] Titanium prediffused at 1100, 1300, 1500 and 1700°F prior to welding.

[3] 1500°F specimens welded with 15 KSI pressure only.
1600°F specimens welded with 10 KSI pressure only.

TABLE XIV PHASE III. PRESS WELDING-EFFECT OF STRAIN HARDENED MATERIAL CONDITION

(Bare Condition - Argon Atmosphere) [1]

Material Combination	Diffusion Welding Condition												Total Number of Tests
	Percent Cold Reduction in Each Alloy				Temperature - °F			Pressure - KSI		Time - Minutes			
	None [2]	10	25	50	1350	1450	1600	12.5	20.0	10	60	120	
Inconel 600 to Ti-8Al-1Mo-1V	x				x				x	x	x	x	3
			x		x				x	x	x	x	3
Inconel 718 to 321 SS	x						x	x		x	x	x	3
			x				x	x		x	x	x	3
321 SS to Ti-8Al-1Mo-1V	x				x				x	x	x	x	3
			x		x				x	x	x	x	3
	x					x			x	x	x	x	3
		x				x			x	x	x	x	3
			x			x			x	x	x	x	3
				x [3]		x			x	x	x	x	3
													30

[1] All material chemically cleaned followed by abrasive sanding and solvent cleaning.

[2] Annealed material combination used for control specimen in each retort.

[3] 321 stainless steel cold reduced 50% and Ti-8Al-1Mo-1V was in the annealed condition for this combination.

TABLE XV PHASE III. EFFECT OF STRAIN HARDENING AND HEAT TREAT CONDITION

Inconel 718 to 321 Stainless Steel

Material Combination	Material Condition [1]	Diffusion Welding Conditions													Total Number of Tests
		Temperature - °F						Pressure - KSI					Time-Min.		
		1300	1400	1500	1600	1700	1800	40	30	17.5	12.5	7.5	10	60	
Inconel 718 to 321 SS	Reduced by cold rolling 60%	x	x					x					x	x	4
				x					x				x	x	2
	Reduced by cold rolling 65%				x					x			x	x	2
						x					x		x	x	2
							x					x	x	x	2
Inconel 718 to 321 SS	Annealed	x	x					x					x	x	4
				x					x				x	x	2
	Reduced by cold rolling 65%				x					x			x	x	2
						x					x		x	x	2
							x					x	x	x	2
Inconel 718 to 321 SS	Aged	x	x					x					x	x	4
				x					x				x	x	2
	Annealed				x					x			x	x	2
						x					x		x	x	2
							x					x	x	x	2

[1] Abrasively cleaned - 80 grit paper

TABLE XVI PHASE II. PRESS WELDING - EFFECT OF MATERIAL SURFACE CONDITION

(Bare Material - Argon Atmosphere)

Material Combination	Diffusion Welding Conditions														Total Number of Tests
	[1] Surface Condition				Temperature - °F				Pressure - KSI			Time - Minutes			
	A	B	C	D	950	1350	1450	1600	7.5	12.5	20.0	10	30	60	
2219 Al to 321 SS	x	x	x	x	x				x				x	x	8
7106 Al to 321 SS	x	x	x	x	x				x				x	x	8
2219 Al to Ti-5Al-2.5Sn	x	x	x	x	x				x				x	x	8
Inconel 600 to Ti-8Al-1Mo-1V	x	x	x	x		x					x	x		x	8
321 SS to Ti-8Al-1Mo-1V	x	x	x	x			x				x	x		x	8
Inconel 718 to 321 SS	x	x	x	x				x		x		x		x	8

48

[1] A - As received material chemically cleaned plus abrasive sanding (Control Specimen).
B - As received material chemically cleaned.
C - Polished surfaces plus solvent cleaning.
D - Machined surfaces plus solvent cleaning.

TABLE XVII PHASE IV. ROLL WELDING OF BARE MATERIAL

Welded Retorts - Argon Atmosphere

Material Combination	Roll Welding Conditions											Total Number of Specimens
	Rolling Temperature - °F									Joint Thickness, Inches		
	650	750	850	950	1300	1400	1500	1600	1800	Before Rolling	After Rolling	
2219 Al to 321 SS	x	x	x	x						.205	.175	3
7106 Al to 321 SS	x	x	x							.200	.170	3
2219 Al to Ti-5Al-2.5 Sn			▷ x	▷ x						.180	.150	3
Inconel 600 to Ti-8Al-1Mo-1V					x	x	x	▷ x		.120	.105	4
321 SS to Ti-8Al-1Mo-1V						x	x	x		.140	.125	3
Inconel 718 to 321 SS						x		x	x	.142	.127	3

19

▷ Roll welded in the chemically and abrasively cleaned condition.

TABLE XVIII SUMMARY OF SINGLE LAP SHEAR TEST RESULTS

[1] 2219 Aluminum Alloy to 321 Stainless Steel

Test No.	Test Conditions			Test Results			
	Weld [2] Interface Preparation	Joint Overlap Inches	Test Temp. °F	Shear Load lbs.	Shear Failure Stress psi	Tensile Stress in 2219 Al psi	Failure Mode
545	Bare	0.10	RT	1650	13,200	23,570	Shear + Tensile
546		0.10		1550	12,400	22,140	Shear
547		0.20		1720	-	24,570	Tensile
548		0.20		1700	-	24,280	Tensile
549		0.30		1750	-	25,000	Tensile
550		0.30		1675	-	23,930	Tensile
774	Bare	0.12	+300	1150	7,660	15,750	Shear
775		0.10		1050	8,400	14,380	Shear
776		0.12		980	6,530	13,400	Shear
777	Bare	0.15	+500	800	–	10,950	Tensile
778		0.12		850	–	11,640	Tensile
779		0.12		860	–	11,780	Tensile
780	Bare	0.15	-320	900	10,160	26,000	Shear + Tensile
781		0.10		1020	8,160	13,970	Shear
782		0.12		1080	7,200	14,790	Shear
783	Bare	0.10	-423	1500	12,000	20,540	Shear
784		0.10		1500	12,000	20,540	Shear
785		0.10		1475	11,800	20,200	Shear
786	Silver Plated	0.14	RT	1125	6,420	15,400	Shear
787		0.12		1170	7,800	16,000	Shear
788		0.23		1950	6,960	26,700	Shear
789		0.20		1480	5,920	20,270	Shear
790		0.28		2080	5,940	28,490	Shear
791		0.32		2300	5,750	31,500	Shear
792	Silver Plated	0.22	+300	1440	5,230	19,720	Shear
793		0.24		1600	5,380	21,910	Shear
794		0.22		1680	6,100	23,000	Shear
795	Silver Plated	0.22	+500	900	3,270	12,320	Shear
796		0.22		760	2,760	10,410	Shear
797		0.24		1000	3,360	13,690	Shear
798	Silver Plated	0.21	-320	1460	5,610	20,000	Shear
799		0.20		1700	6,800	23,280	Shear
800		0.20		1760	7,040	24,100	Shear
801	Silver Plated	0.24	-423	4500	15,000	60,810	Shear
802		0.23		3750	13,060	50,670	Shear
803		0.26		2850	8,900	38,500	Shear

[1] 2219 Al was -0.059 inch thick and was in the T6 condition prior to welding.
321 SS was 0.081 inch thick and in the annealed condition.

[2] Bare material was chemically cleaned and welded at 950°F - 30 min.
Silver plated material was abrasively cleaned and welded at 500°F - 2 hours.

TABLE XIX SUMMARY OF PRESS WELDED SINGLE LAP SHEAR TESTS

[1] 7106 Aluminum Alloy to 321 Stainless Steel

Test No.	Test Conditions			Test Results			
	Weld [2] Interface Preparation	Joint Overlap Inches	Test Temp. °F	Shear Load lbs.	Shear Failure Stress psi	Tensile Stress in 7106 Al psi	Failure Mode
551	Bare	0.12	RT	1400	9,720	18,660	Shear
552		0.12		1525	10,590	20,300	Shear
553		0.20		1420	5,680	18,890	Shear
554		0.20		2140	8,560	28,530	Shear
555		0.29		1620	4,470	21,600	Shear
556		0.35		1900	4,350	25,330	Shear
804	Bare	0.20	+300	1570	6,280	20,930	Shear + Tensile
805		0.20		1480	-	19,730	Tensile
806		0.18		1260	5,600	16,800	Shear
807	Bare	0.22	+500	1020	-	13,600	Tensile
808		0.18		800	3,550	10,660	Shear
809		0.20		880	-	11,730	Tensile
810	Bare	0.22	-320	1010	3,670	13,460	Shear
811		0.22		1125	4,090	15,000	Shear
812		0.20		980	3,920	13,060	Shear
813	Bare	0.20	-423	1675	6,700	22,330	Shear
814		0.20		1685	6,740	22,460	Shear
815		0.20		1750	7,000	23,300	Shear
816	Silver Plated	0.12	RT	1760	11,730	23,460	Shear
817		0.10		1320	10,560	17,600	Shear
818		0.22		2250	8,180	30,000	Shear
819		0.23		2530	8,810	33,730	Shear
820		0.32		2800	7,000	37,330	Tensile
821		0.34		2900	6,900	38,660	Tensile
822	Silver Plated	0.22	+300	1810	6,580	24,130	Shear
823		0.22		1600	5,810	21,330	Shear
824		0.24		1650	5,500	22,000	Shear
825	Silver Plated	0.24	+500	770	2,560	10,260	Shear
826		0.22		950	3,450	12,660	Shear
827		0.24		830	2,760	11,060	Shear
828	Silver Plated	0.20	-320	3280	13,120	43,730	Shear
829		0.25		3110	9,960	41,460	Shear
830		0.23		3360	11,700	44,800	Shear
831	Silver Plated	0.27	-423	5760	-	76,660	Grip
832		0.25		6150	19,710	82,000	Shear
833		0.24		6250	20,830	83,330	Shear

[1] 7106 Al - .060 inch thick and in the T6 condition prior to welding.
321 SS - .081 inch thick and in the annealed condition.

[2] Bare material was chemically cleaned and welded at 950°F - 30 min.
Silver plated material was abrasively cleaned and welded at 500°F - 2 hours.

TABLE XX SUMMARY OF PRESS WELDED SINGLE LAP SHEAR TESTS

[1] 2219 Aluminum Alloy to Ti-5Al-2.5Sn Titanium Alloy

	Test Conditions			Test Results			
Test No.	Weld [2] Interface Preparation	Joint Overlap Inches	Test Temp. °F	Shear Load lbs.	Shear Failure Stress psi	Tensile Stress in 2219 Al psi	Failure Mode
557	Bare	0.10	RT	1400	11,200	20,000	Shear
558		0.12		1640	10,930	23,420	Shear + Tensile
559		0.12		1775	-	25,350	Tensile
560		0.20		1850	-	26,420	Tensile
561		0.30		1820	-	26,000	Tensile
562		0.30		1940	-	27,700	Tensile
834	Bare	0.10	+300	1210	9,680	16,570	Shear
835		0.10		930	7,440	12,730	Shear
836		0.08		910	9,100	12,460	Shear
837	Bare	0.10	+500	740	5,920	10,130	Shear + Tensile
838		0.09		700	6,360	9,580	Shear + Tensile
839		0.10		820	6,560	11,230	Shear + Tensile
840	Bare	0.12	-320	980	6,530	13,420	Shear
841		0.10		1200	9,600	16,430	Shear
842		0.10		1310	–	17,940	Grip
843	Bare	0.14	-423	1300	7,420	17,330	Shear
844		0.10		750	6,000	10,130	Shear
845		0.10		600	4,800	8,100	Shear
846	Silver Plated	0.12	RT	1300	8,660	17,800	Shear
847		0.11		1310	9,560	17,940	Shear
848		0.22		1520	5,520	20,820	Shear
849		0.20		1500	6,000	20,540	Shear
850		0.32		2240	5,600	30,680	Shear
851		0.33		2400	5,850	32,870	Shear
852	Silver Plated	0.23	+300	780	2,700	10,680	Shear
853		0.18		530	2,370	7,260	Shear
854		0.22		1250	4,540	17,120	Shear
855	Silver Plated	0.20	+500	280	1,120	3,830	Shear
856		0.22		380	1,380	5,200	Shear
857		0.18		100	440	1,360	Shear
858	Silver Plated	0.24	-320	1790	5,960	24,520	Shear
859		0.22		1400	5,090	19,170	Shear
860		0.23		1280	4,460	17,530	Shear
861	Silver Plated	0.21	-423	675	2,570	9,240	Shear
862		0.22		690	2,500	9,450	Shear
863		0.23		725	2,520	9,930	Shear

[1] 2219 Al - 0.059 inch thick -T6 condition prior to welding.
Ti-5Al-2.5Sn - 0.54 inch thick - annealed condition.

[2] Bare material abrasively cleaned and welded at 950°F - 30 min.
Silver plated material abrasively cleaned and welded at 500°F - 2 hours.

TABLE XXI SUMMARY OF PRESS WELDED SINGLE LAP SHEAR TESTS

[1] Inconel 600 Alloy to Ti-8Al-1Mo-1V Titanium Alloy

Test No.	Test Conditions			Test Results			
	Weld [2] Interface Preparation	Joint Overlap Inches	Test Temp. °F	Shear Load lbs.	Shear Failure Stress psi	Tensile Stress in Ti-8Al-1Mo-1V psi	Failure Mode
563	Bare	0.12	RT	1900	12,600	24,510	Shear
564		0.11		1790	13,060	23,090	Shear
565		0.32		3970	9,920	51,220	Shear
566		0.35		5430	12,420	70,060	Shear
567		0.50		4350	6,690	56,130	Shear
568		0.50		4950	7,920	63,870	Shear
864	Bare	0.52	+400	5350	-	74,300	Grip
865		0.52		4750	-	65,970	Grip
866		0.48		4650	-	64,580	Grip
867	Bare	0.20	+800	2905	16,200	40,340	Shear
868		0.16		2315	11,570	32,150	Shear
869		0.10		1320	10,560	18,330	Shear
870	Bare	0.52	-320	3450	5,310	47,260	Shear
871		0.45		3150	5,630	43,150	Shear
872		0.52		3600	5,380	49,310	Shear
873	Bare	0.53	-423	1625	2,460	22,560	Shear
874		0.53		2925	4,430	40,620	Shear
875		0.50		2650	4,410	36,800	Shear
876	Silver Plated	0.090	RT	980	8,900	13,610	Shear
877		0.12		1210	8,060	16,800	Shear
878		0.18		2150	9,970	29,860	Shear
879		0.24		2510	8,360	34,860	Shear
880		0.30		2700	7,290	37,500	Shear
881		0.28		2900	8,280	40,270	Shear
882	Silver Plated	0.22	+400	200	740	2,780	Shear
883		0.24		170	560	2,360	Shear
884		0.25		440	1,400	6,110	Shear
885	Silver Plated	0.20	+800	Failed with no load	-	-	Shear
886		0.25			-	-	Shear
887		0.24			-	-	Shear
888	Silver Plated	0.24	-320	2910	9,700	40,400	Shear
889		0.24		3110	10,360	43,190	Shear
890		0.22		2850	10,550	39,500	Shear
891	Silver Plated	0.22	-423	1625	5,900	22,260	Shear
892		0.20		1625	6,500	22,260	Shear
893		0.24		1700	5,660	33,280	Shear

[1] Inconel 600 - 0.062 inch thick - annealed condition
Ti-8Al-1Mo-1V - 0.058 inch thick - annealed condition

[2] Bare material abrasively cleaned and welded at 1300°F - 10 min.
Silver plated material abrasively cleaned and welded at 700°F - 30 min.

TABLE XXII SUMMARY OF PRESS WELDED SINGLE LAP SHEAR TESTS

[1] 321 Stainless Steel to Ti-8Al-1Mo-1V Titanium Alloy

Test No.	Test Conditions			Test Results			
	Weld [2] Interface Preparation	Joint Overlap Inches	Test Temp. °F	Shear Load lbs.	Shear Failure Stress psi	Tensile Stress in Ti-8Al-1Mo-1V psi	Failure Mode
569	Bare	0.10	RT	1420	11,360	19,580	Shear
570		0.09		1300	11,600	17,930	Shear
571		0.33		2950	7,160	40,690	Shear
572		0.30		2775	7,400	38,270	Shear
573		0.53		3250	4,910	44,830	Shear
574		0.50		3260	5,120	44,960	Shear
894	Bare	0.54	+400	3875	5,740	53,080	Shear
895		0.50		2940	4,700	40,270	Shear
896		0.50		2780	4,400	38,080	Shear
897	Bare	0.18	+800	1670	7,590	23,010	Shear
898		0.20		3320	13,200	46,010	Shear
899		0.20		3240	12,900	45,000	Shear
900	Bare	0.54	-320	1590	2,350	21,780	Shear
901		0.52		2710	4,160	37,120	Shear
902		0.56		2050	2,920	28,080	Shear
903	Bare	0.53	-423	3200	4,840	44,440	Shear
904		0.58		2100	2,910	29,160	Shear
905		0.52		1625	2,500	22,560	Shear
906	Silver Plated	0.07	RT	740	8,500	10,270	Shear
907		0.15		1840	10,220	25,550	Shear
908		0.22		2010	7,440	27,910	Shear
909		0.20		2150	8,600	29,860	Shear
910		0.26		2740	8,560	38,050	Shear
911		0.29		3190	8,860	44,300	Shear
912	Silver Plated	0.20	+400	150	600	2,050	Shear
913		0.20		770	3,080	10,540	Shear
914		0.20		150	600	2,050	Shear
915	Silver Plated	0.16	+800	Failed	-	-	Shear
916		0.20		with	-	-	Shear
917		0.20		no load	-	-	Shear
918	Silver Plated	0.25	-320	2960	9,480	40,540	Shear
919		0.25		3160	10,120	43,280	Shear
920		0.22		3140	11,410	43,010	Shear
921	Silver Plated	0.25	-423	3300	10,570	45,200	Shear
922		0.21		3750	14,300	51,360	Shear
923		0.25		3050	9,750	41,780	Shear

[1] 321 SS - 0.081 inch thick - annealed condition.
Ti-8Al-1Mo-1V - 0.058 inch thick - annealed condition.

[2] Bare material abrasively cleaned and welded at 1450°F - 10 min.
Silver plated material abrasively cleaned and welded at 700°F - 30 min.

TABLE XXIII SUMMARY OF PRESS WELDED SINGLE LAP SHEAR TESTS

▷ Inconel 718 Alloy to 321 Stainless Steel

Test No.	Test Conditions			Test Results			
	Weld ▷ Interface Preparation	Joint Overlap Inches	Test Temp. °F	Shear Load lbs.	Shear Failure Stress psi	Tensile Stress in Inco 718 psi	Failure Mode
575	Bare	0.10	RT	5250	42,000	70,000	Shear
576		0.10		4950	39,600	66,000	Shear
577		0.22		6260	22,760	83,460	Shear
578		0.21		6430	24,540	85,730	Shear
579		0.31		7075	18,280	94,330	Shear
580		0.30		6910	18,420	92,130	Shear
924	Bare	0.24	+400	6280	-	83,330	Grip
925		0.23		5570	-	74,260	Grip
926		0.20		7540	30,160	100,050	Shear
927	Bare	0.22	+800	7210	26,700	96,130	Shear
928		0.25		5260	-	70,130	Grip
929		0.20		6410	-	85,460	Grip
930	Bare	0.20	-320	5830	-	77,700	Grip
931		0.32		6020	-	80,260	Grip
932		0.20		7070	28,280	94,260	Shear
933	Bare	0.20	-423	6375	25,500	85,000	Shear
934		0.20		6750	27,000	90,000	Shear
935		0.20		7550	-	100,600	Grip
936	Silver Plated	0.16	RT	2400	12,000	32,000	Shear
937		0.14		2210	12,620	29,460	Shear
938		0.32		3610	9,020	48,130	Shear
939		0.30		2850	7,600	38,000	Shear
940	Silver Plated	0.22	+400	520	1,890	6,930	Shear
941		0.22		900	3,270	12,000	Shear
942		0.20		990	3,960	13,200	Shear
943	Silver Plated	0.24	+800	200	600	2,660	Shear
944		0.18		20	90	260	Shear
945		0.20		80	320	1,060	Shear
946	Silver Plated	0.25	-320	2580	8,320	34,400	Shear
947		0.23		1850	6,610	24,660	Shear
948		0.22		2040	7,550	27,200	Shear
949	Silver Plated	0.20	-423	3300	13,200	44,000	Shear
950		0.22		3475	12,630	46,330	Shear
951		0.18		3100	13,770	41,330	Shear

Continued

TABLE XXIII. SUMMARY OF PRESS WELDED SINGLE LAP SHEAR TEST (Cont'd)

[1] Inconel 718 Alloy to 321 Stainless Steel

Test No.	Test Conditions			Test Results			
	Weld [2] Interface Preparation	Joint Overlap Inches	Test Temp. °F	Shear Load lbs.	Shear Failure Stress psi	Tensile Stress in Inco 718 psi	Failure Mode
952	Nickel Plated	0.16	RT	3860	19,300	51,460	Shear
953		0.18		4630	21,040	61,730	Shear
954		0.32		6570	16,420	87,600	Shear
955		0.35		6950	15,790	92,660	Shear
956	Nickel Plated	0.21	+400	3800	-	51,660	Grip
957		0.15		3320	18,440	44,260	Shear
958		0.18		3780	17,180	50,400	Shear
959	Nickel Plated	0.20	+800	2210	8,840	29,460	Shear
960		0.20		2850	11,400	38,000	Shear
961		0.20		2600	10,400	34,660	Shear
962	Nickel Plated	0.22	-320	5425	20,000	72,330	Shear
963		0.22		5080	18,140	67,730	Shear
964		0.24		4690	15,630	62,530	Shear
965	Nickel Plated	0.20	-423	5250	21,000	70,000	Shear
966		0.20		5975	23,900	79,660	Shear
967		0.20		6825	27,300	91,000	Shear

[1] Inconel 718 - 0.060 inch thick - annealed condition.
321 SS - 0.081 inch thick - annealed condition.

[2] Bare material abrasively cleaned and welded at 1600°F - 30 min.
Silver plated material abrasively cleaned and welded at 600°F - 30 min.
Nickel plated material abrasively cleaned and welded at 1300°F - 30 min.

TABLE XXIV. - SUMMARY OF ROLL WELDED SINGLE LAP SHEAR SPECIMENS

Test No.	Test Conditions: Material Combination [1]	Test Conditions: Joint Size Inches	Test Conditions: Test Temp. °F	Test Results: Shear Load lbs.	Test Results: Shear Failure Stress psi	Test Results: Tensile Stress in Al Alloy psi	Test Results: Failure Mode
968-1	2219 Al to 321 SS	.12 x .70	RT	1250	14,880	17,850	Shear
-2		.10 x .95		1450	15,260	15,260	Shear
-3		.10 x 1.0		1240	12,400	12,400	Shear
-4		.10 x .95		1325	13,940	13,940	Shear
-5		.15 x 1.0		2070	13,800	20,700	Shear
-6		.080x1.0		1280	16,000	12,800	Shear
-7		.10 x .95	+300	1200	12,630	12,630	Shear
-8		.10 x .95		1560	16,420	16,420	Shear
-9		.10 x 1.0		1390	13,900	13,900	Shear
-10		.080x1.26	-423	3200	32,000	25,390	Shear
-11		.10 x 1.25		3475	-	27,800	Tensile
-12		.10 x 1.25		3275	-	26,200	Tensile
969-1	7106 Al to 321 SS	.10 x .85	RT	1420	16,700	17,750	Shear
-2		.11 x .7		1470	19,090	22,270	Shear
-3		.10 x .65		1320	20,300	21,630	Shear
-4		.10 x 1.2		2350	19,580	20,600	Shear
-5		.09 x 1.1		2150	21,700	20,670	Shear
-6		.10 x .70		1250	17,850	19,940	Shear
-7		.10 x .97	+300	1830	18,860	19,890	Shear
-8		.10 x .98		1710	17,440	18,380	Shear
-9		.10 x 1.0		1700	17,000	17,890	Shear
-10		.10 x 1.23	-423	2975	24,180	25,640	Shear
-11		.10 x 1.25		3250	26,000	27,540	Shear
-12		.10 x 1.25		3700	29,600	31,350	Shear
970-1	2219 Al to Ti-5Al-2.5Sn	.10 x .98	RT	2270	23,160	23,160	Shear
-2		.10 x .98		2230	-	22,750	Tensile
-3		.10 x .98		2460	-	25,100	Tensile
-4		.10 x .92	+300	2150	23,360	23,360	Shear
-5		.10 x .94		1950	20,740	20,740	Shear
-6		.10 x .94		2160	22,970	22,970	Shear
-7		.10 x 1.2	-423	1200	10,000	10,000	Shear
-8		.10 x 1.2		1275	10,600	10,600	Shear
-9		.10 x 1.2		1375	11,450	11,450	Shear

[1] 2219 Al - 0.100 inches thick, 321 SS-0.080 inches thick, material chemically cleaned, rolled at 850°F, argon atmosphere.

7106 Al - 0.095 inches thick, 321 SS - 0.080 inches thick, material chemically cleaned, rolled at 850°F, argon atmosphere.

2219 Al - 0.100 inches thick, Ti-5Al-2.5Sn - 0.054 inches thick, material abrasively cleaned, rolled at 950°F, argon atmosphere.

TABLE XXIV.- (Cont'd)

Test No.	Test Conditions: Material Combination [1]	Joint Size Inches	Test Temp. °F	Test Results: Shear Load lbs.	Shear Failure Stress psi	Tensile Stress in Titanium or Inco 718 psi	Failure Mode
971-1	321 SS to Ti-8Al-1Mo-1V	.10 x 1.3	RT	1140	8,760	15,000	Shear
-2		.10 x 1.3		1110	8,530	14,600	Shear
-3		.32 x 1.1		2300	6,530	35,930	Shear
-4		.30 x 1.25		3100	8,260	42,460	Shear
-5		.55 x 1.2		4500	6,810	64,280	Shear
-6		.50 x 1.2		4230	7,050	60,420	Shear
-7		.50 x 1.2	+400	3830	6,380	54,700	Shear
-8		.50 x 1.2		3370	5,610	48,140	Shear
-9		.50 x 1.1		3330	6,050	51,230	Shear
-10		.50 x 1.2	-423	6125	10,410	87,500	Shear
-11		.50 x 1.2		4350	7,250	62,140	Shear
-12		.50x 1.22		4400	7,210	61,160	Shear
972-1	Inconel 600 to Ti-8Al-1Mo-1V	.52 x 1.2	RT	5890	9,500	84,140	Shear
-2		.50 x 1.2		5270	8,780	75,280	Shear
-3		.50 x 1.2		5090	8,480	72,700	Shear
-4		.48 x1.18	+400	3880	6,920	56,230	Shear
-5		.50 x1.18		2850	4,850	41,300	Shear
-6		.50 x 1.2		3790	6,360	54,140	Shear
-7		.50x1.15	-423	3250	5,700	48,500	Shear
-8		.50x 1.2		5150	8,580	73,570	Shear
-9		.50x1.18		3450	5,840	50,000	Shear
973-1	321 SS to Inconel 718	.10 x .92	RT	3980	43,260	76,530	Shear
-2		.10 x .90		3700	41,110	72,540	Shear
-3		.10 x .90		4880	54,220	95,680	Shear
-4		.10 x .67		3050	45,500	80,260	Shear
-5		.10 x .67		2790	41,640	73,420	Shear
-6		.10 x .67		2910	43,430	76,570	Shear
-7		.10 x .95	+800	4330	45,570	80,180	Shear
-8		.10 x .95		4470	47,000	82,700	Shear
-9		.10 x .95		3570	37,570	89,250	Shear + Tensile
-10		.10 x1.25	-423	8025	64,200	113,000	Shear
-11		.10 x1.25		6825	54,600	96,120	Shear
-12		.10 x1.25		7500	60,000	105,630	Shear

[1] 321 SS - 0.080 inches thick, Ti-8Al-1Mo-1V - 0.059 inches thick, aluminum foil interleaf 0.005 inches thick, material chemically cleaned, rolled at 1050°F, argon atmosphere.

Inconel 600 - 0.060 inches thick, Ti-8Al-1Mo-1V - 0.059 inches thick, aluminum foil interleaf 0.005 inches thick, material chemically cleaned, rolled at 1050°F, argon atmosphere.

321 SS - 0.077 inches thick, Inconel 718 - 0.057 inches thick, material chemically cleaned, rolled at 1650°F, argon atmosphere.

TABLE XXV- WELDING AND TEST CONDITIONS FOR DISSIMILAR METAL TUBULAR ASSEMBLIES

Test No.	External Member	Internal Member	Welding Conditions			Test Conditions				
			Diffusion Aid	Welding Time and Temperature	Welding Atmosphere	Helium Leak Test	Thermal Shock LN_2	Helium Leak Test	Shear Load Lbs.	Failure Mode
1	2219 Al	321 SS	Silver Plate	500°F 2 Hours	Air	x	x	x	7,800	Tensile in 2219 Al Tube
2	7106 Al	321 SS	Silver Plate	500°F 2 Hours	Air	x	x	x	8,900	Tensile in 7106 Al Tube
3	2219 Al	Ti-5Al-2.5Sn	Silver Plate	500°F 2 Hours	Air	x	x	x	7,400	Tensile in 2219 Al Tube
4	Inconel 600	Ti-8Al-1Mo-1V	Silver Plate	700°F 30 Min.	Air	x	x	x	11,750	Tensile in Ti-8-1-1 Tube
5	321 SS	Ti-8Al-1Mo-1V	Silver Plate	700°F 30 Min.	Air	x	x	x	12,800	Tensile in Ti-8-1-1 Tube
6	321 SS	Rene' 41	Silver Plate	600°F 30 Min.	Air	x	x	x	14,400	Tensile in Rene' 41 Tube
7	2219 Al	321 SS	None	950°F 30 Min.	Argon	x	x	x	5,450	Tensile in 2219 Al Tube
8	2219 Al	Ti-5Al-2.5Sn	None	950°F 30 Min.	Argon	x	x	x	5,750	Tensile in 2219 Al Tube

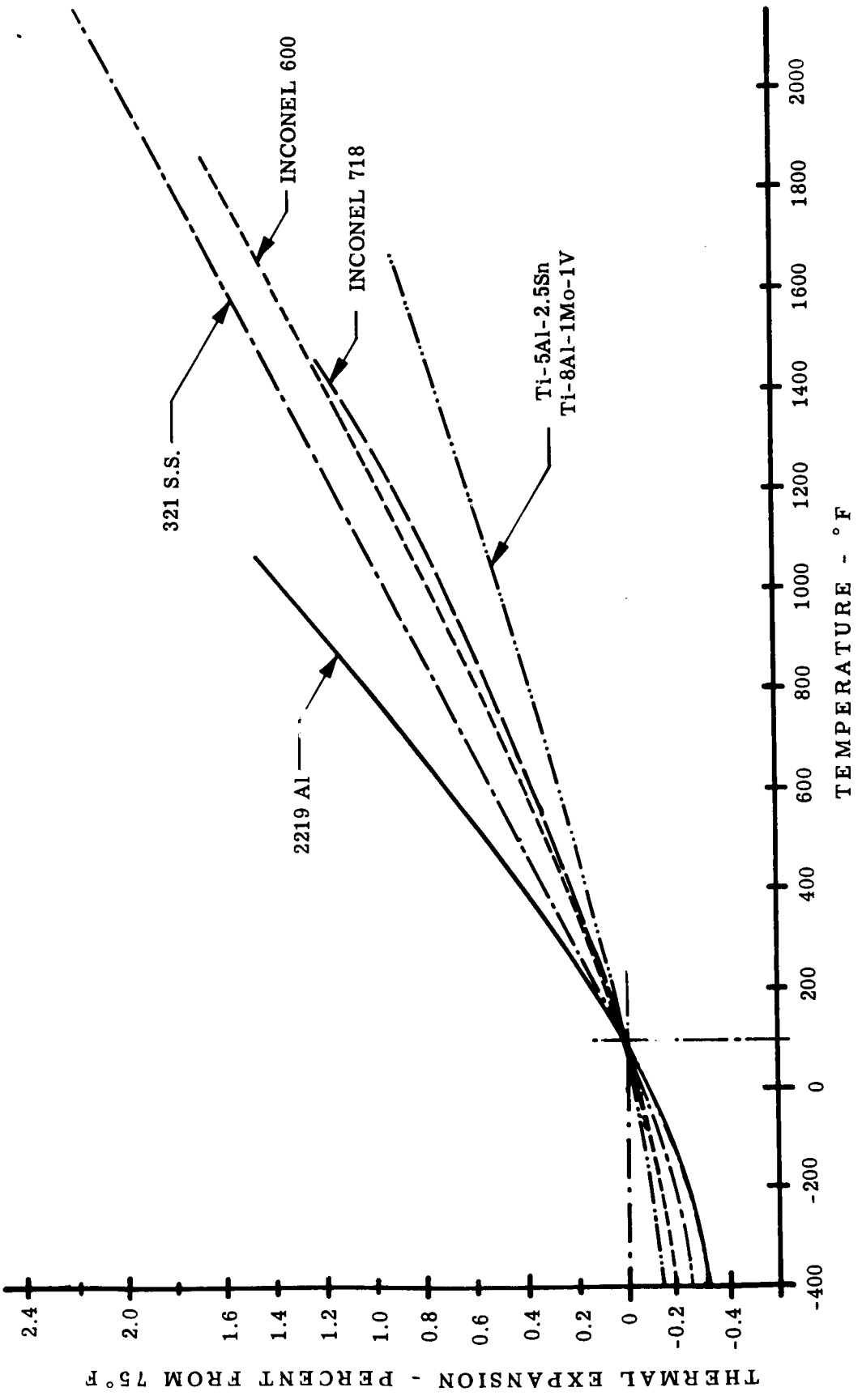
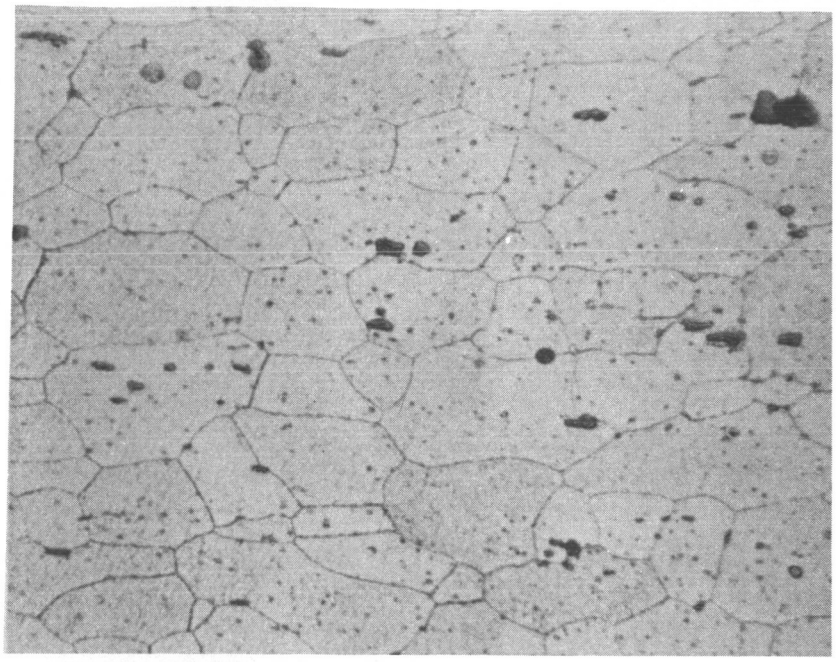
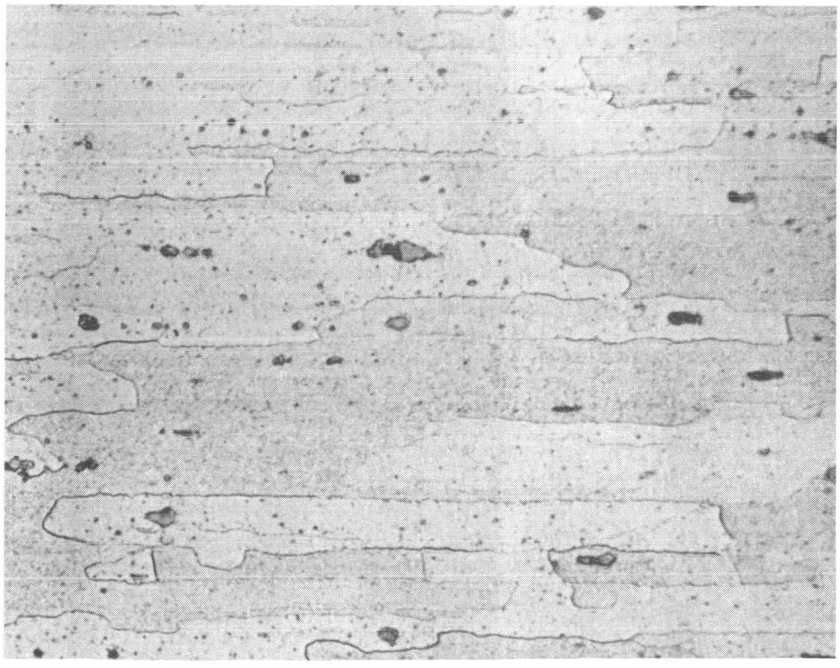


FIGURE 1 COMPARISON OF THERMAL EXPANSION OF SELECTED ALLOYS



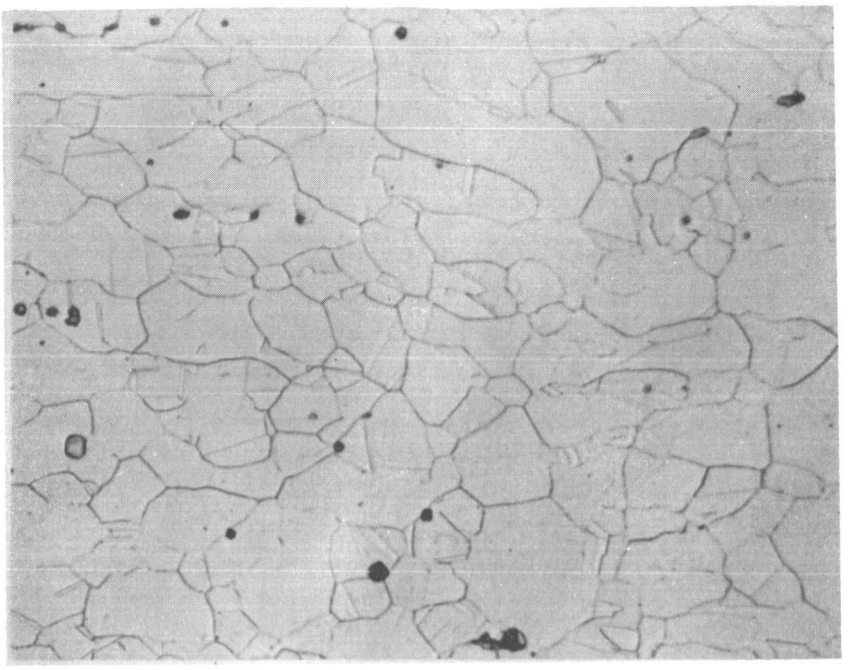
500X 2A206733

FIGURE 2: MICROSTRUCTURE OF 2219-T6 ALUMINUM ALLOY IN THE AS-RECEIVED CONDITION. ETCHED



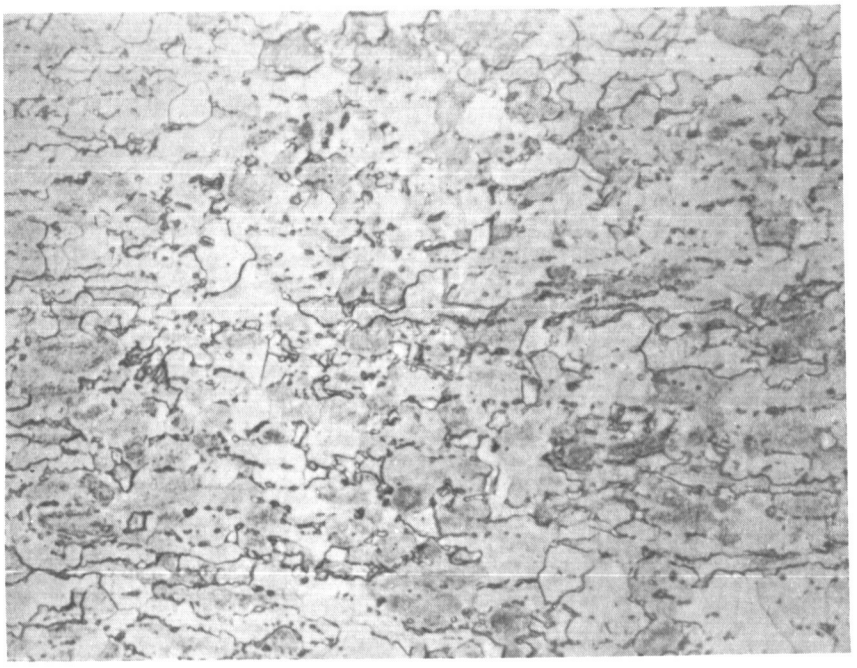
500X 2A206735

FIGURE 3: MICROSTRUCTURE OF 7106-T6 ALUMINUM ALLOY IN THE AS-RECEIVED CONDITION. ETCHED



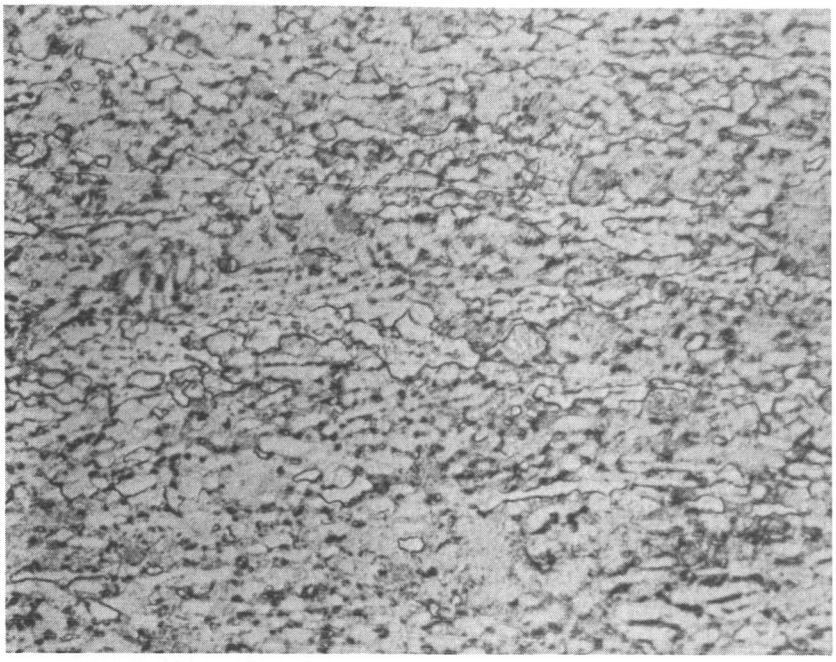
500X 2A206727

FIGURE 4: MICROSTRUCTURE OF AISI 321 STAINLESS STEEL IN THE AS-RECEIVED (ANNEALED) CONDITION. ETCHED



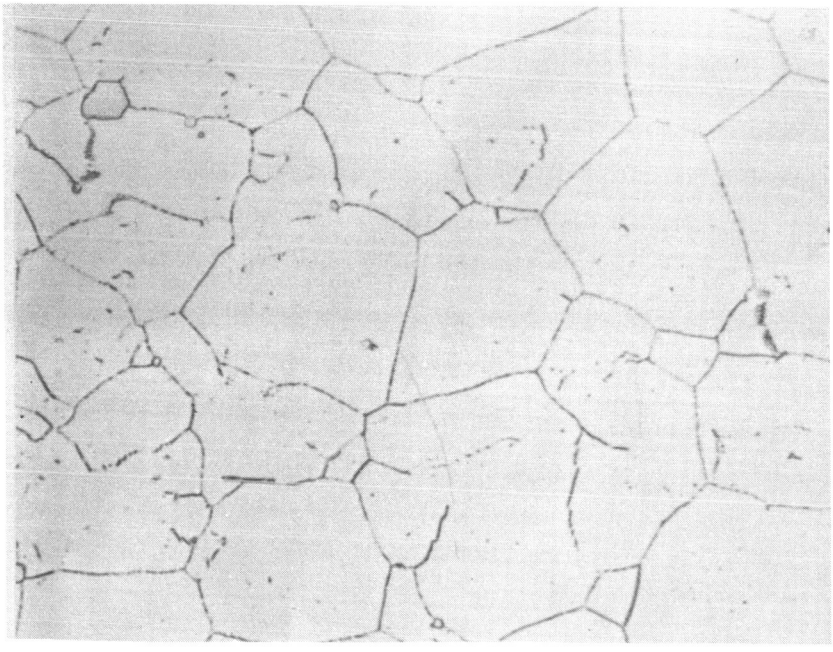
500X 2A206731

FIGURE 5: MICROSTRUCTURE OF Ti-5Al-2.5Sn TITANIUM ALLOY IN THE AS-RECEIVED (ANNEALED) CONDITION. ETCHED



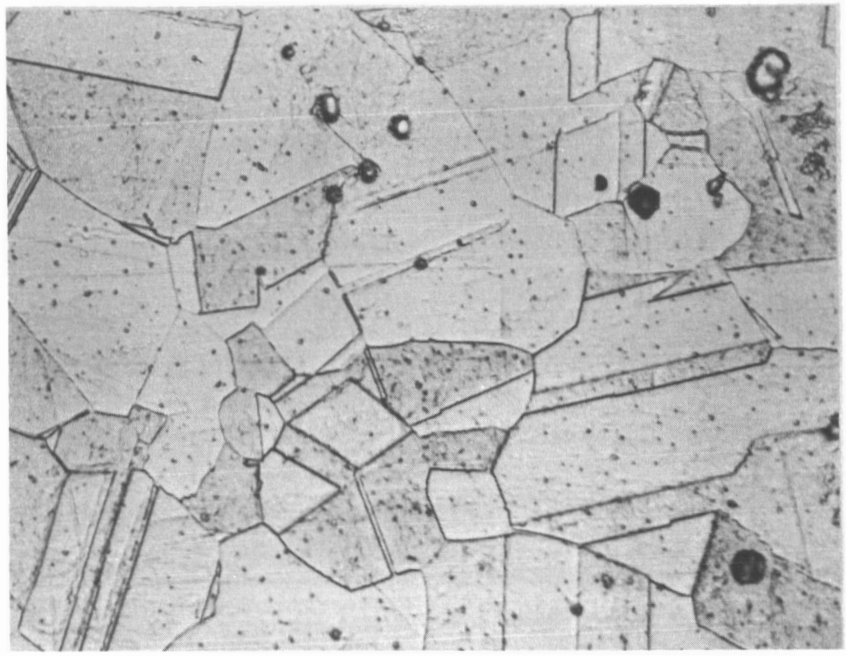
500X 2A206729

FIGURE 6: MICROSTRUCTURE OF Ti-8Al-1Mo-1V TITANIUM ALLOY IN THE AS-RECEIVED (DUPLEX ANNEALED) CONDITION. ETCHED



500X 2A206737

FIGURE 7: MICROSTRUCTURE OF INCONEL 600 ALLOY IN THE AS-RECEIVED (ANNEALED) CONDITION. ETCHED



500X 2A206740

FIGURE 8: MICROSTRUCTURE OF INCONEL 718 ALLOY IN THE AS-RECEIVED (ANNEALED) CONDITION. ETCHED

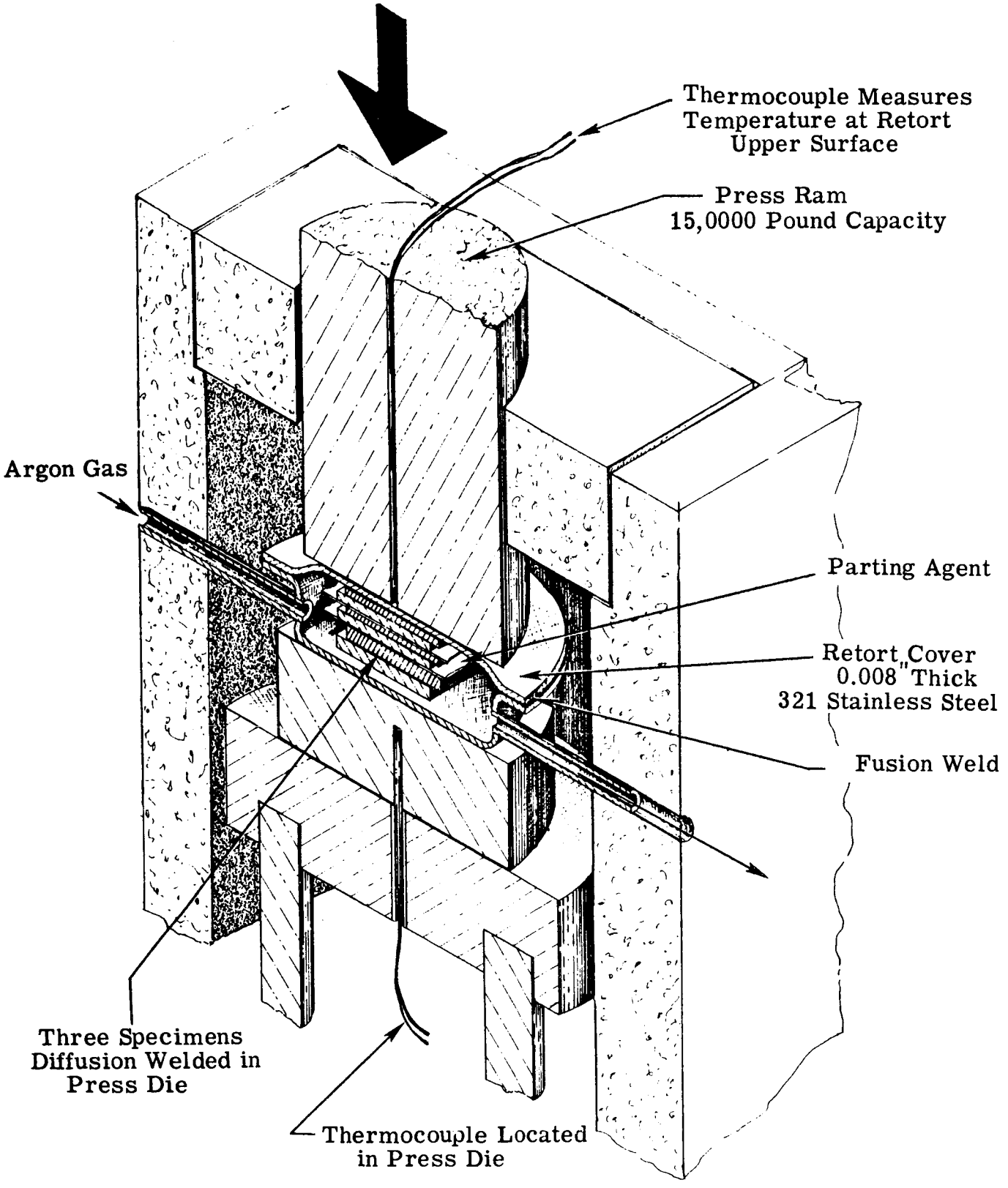


FIGURE 9: RETORT AND PRESS CONFIGURATION

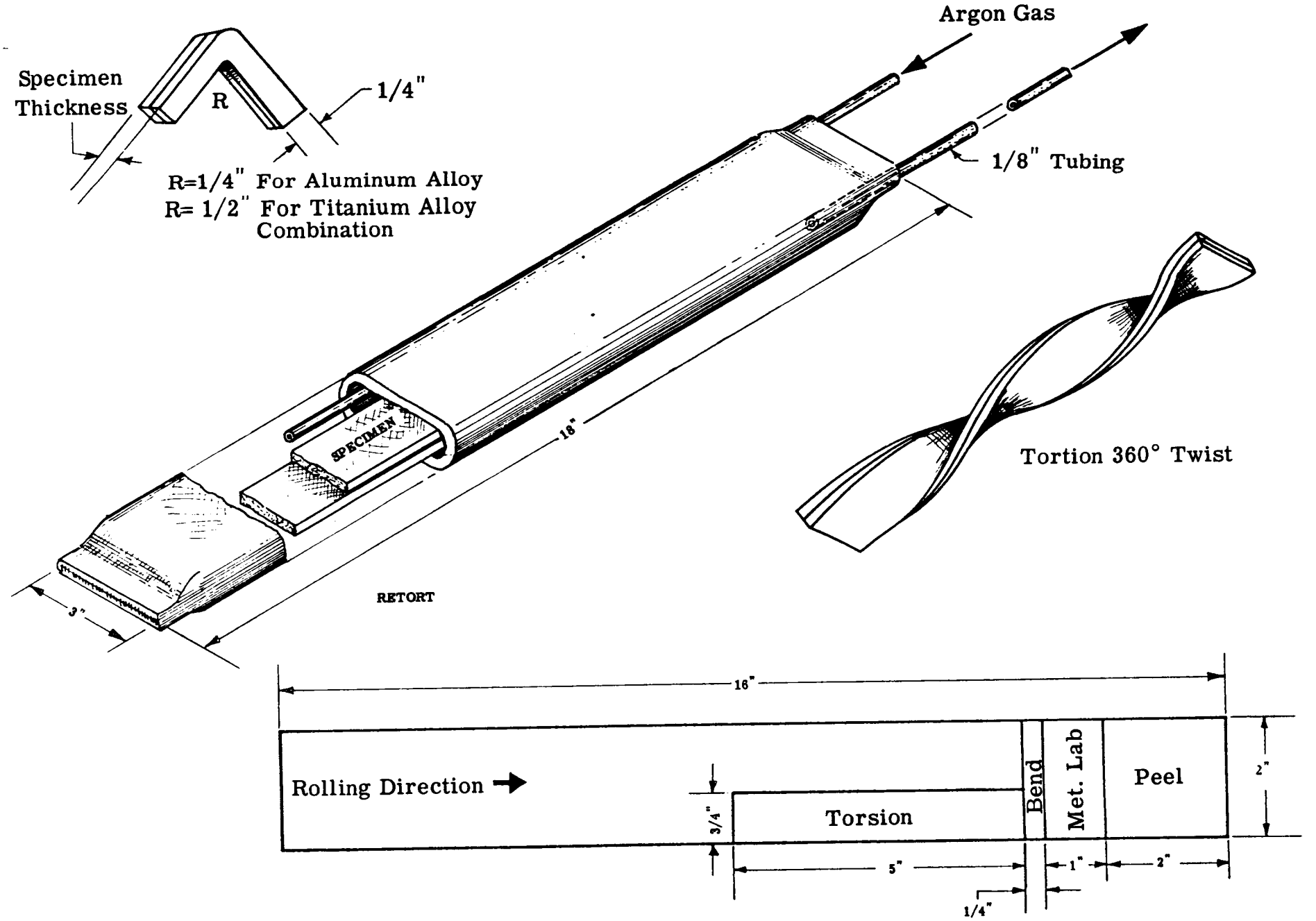
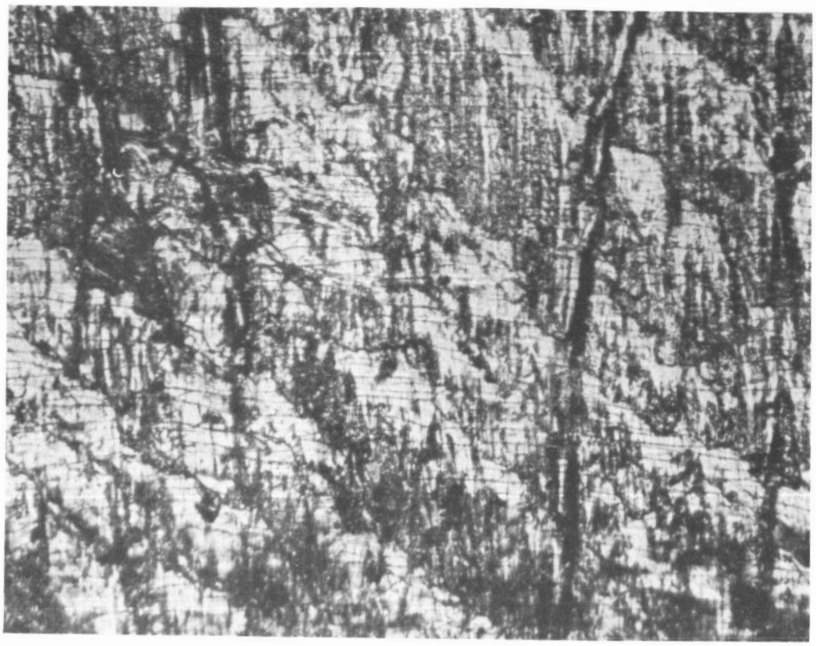


FIGURE 10: DRAWING SHOWING THE DIMENSIONS OF RETORT AND SPECIMEN USED IN ROLL WELDING TEST WORK



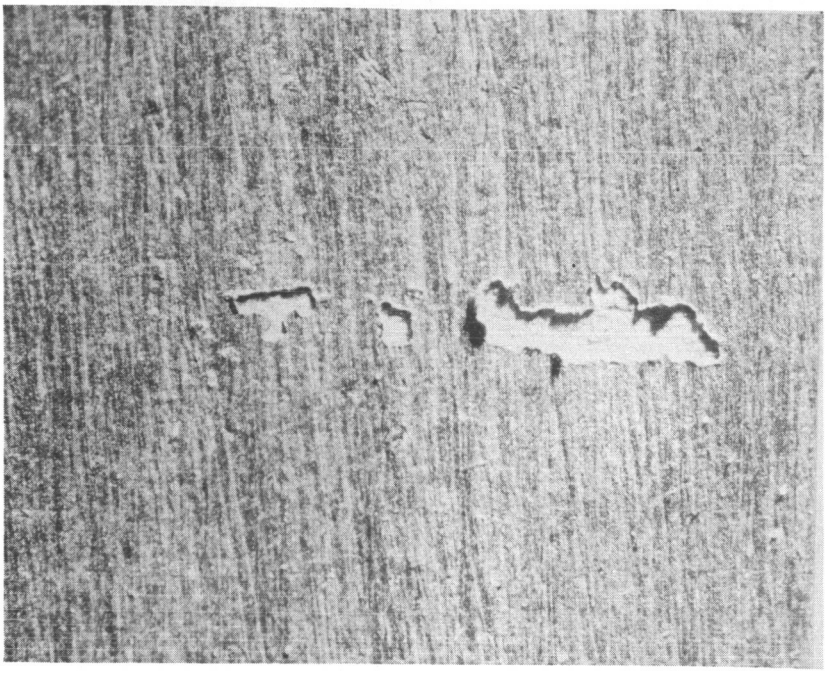
FIGURE 11: ROLL WELDING FACILITY



125X 2A206569
#193 1000°F/5.5 ksi/60 min.

The 7106 aluminum alloy to 321 stainless steel specimen failed during thermal shock. The above photograph shows the interface of the 7106 after bending to 0.25 inch radius The fine horizontal lines are shallow surface cracks caused by bending. The broad vertical lines were believed to be caused by abrasive cleaning prior to welding.

FIGURE 12: PHOTOGRAPH SHOWING THE SURFACE OF A 7106 ALUMINUM ALLOY SPECIMEN WHICH HAD FAILED BY THERMAL SHOCK AFTER BENDING



35X 2A206815

#211 1600°F/17.5 ksi/60 min.

After peeling, a thin metallic layer was found on the interface surface of the 321 stainless steel. The above photograph shows where a small section of the phase was removed by adhering to the Inconel 718 during peeling.

FIGURE 13: PHOTOGRAPH SHOWING THE SURFACE OF 321 STAINLESS STEEL AFTER PEELING FROM THE INCONEL 718 ALLOY

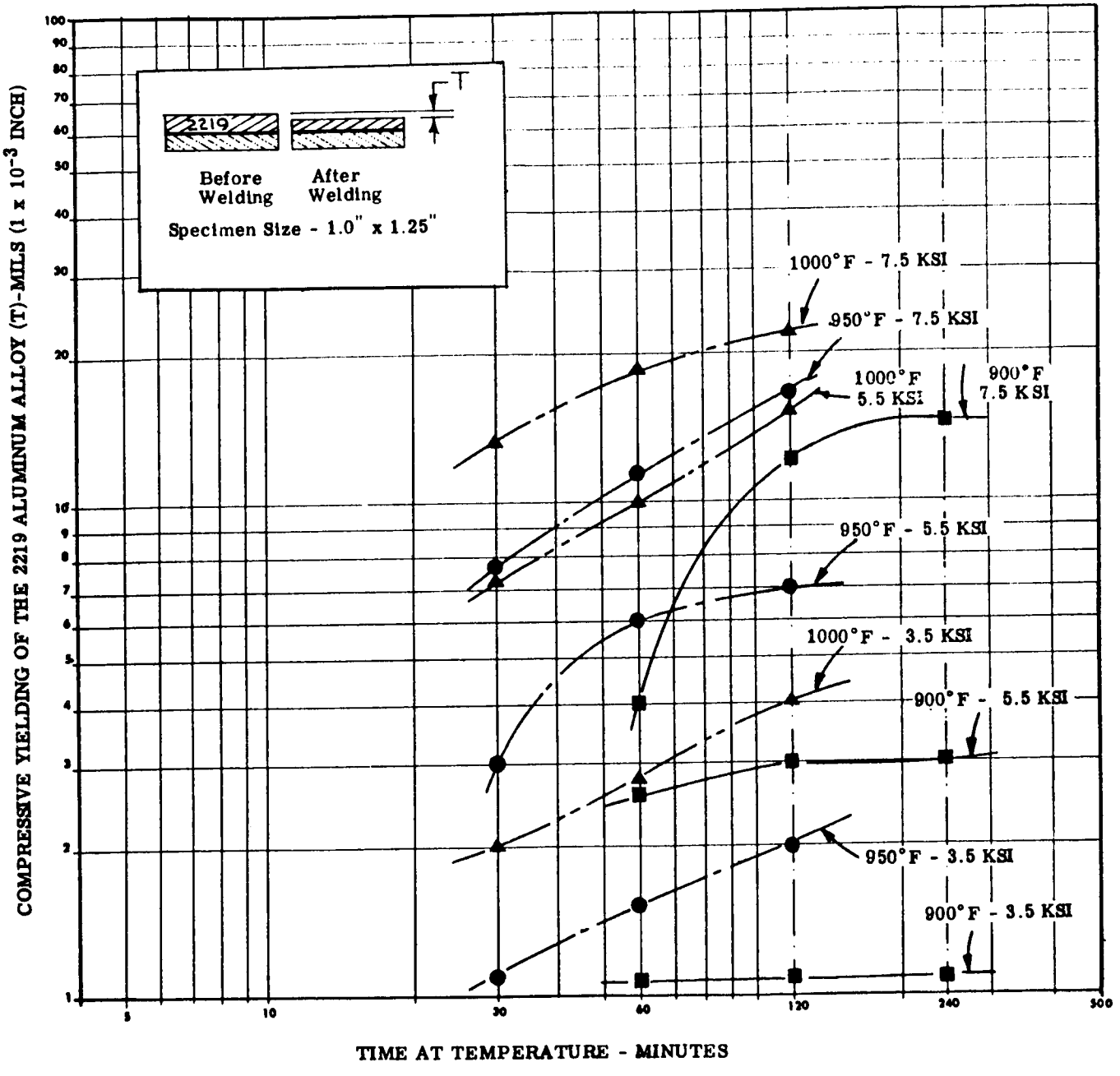


FIGURE 14: EFFECT OF TIME, TEMPERATURE AND PRESSURE ON THE COMPRESSIVE YIELDING OF 2219 ALUMINUM ALLOY DURING DIFFUSION WELDING
(2219 Aluminum Alloy to 321 Stainless Steel)
(2219 Aluminum Alloy to Ti-5Al-2.5Sn Alloy)

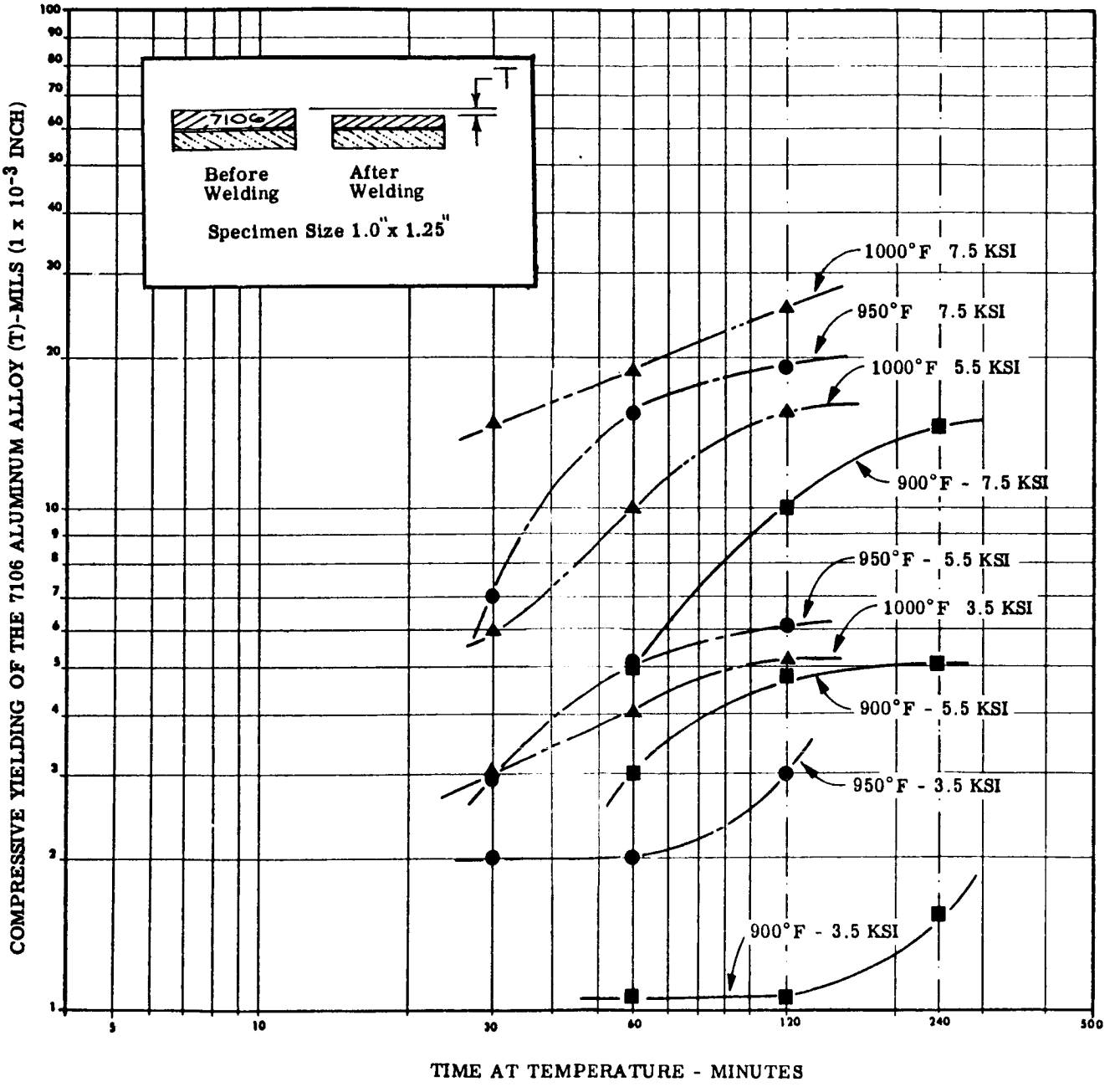


FIGURE 15: EFFECT OF TIME, TEMPERATURE AND PRESSURE ON THE COMPRESSIVE YIELDING OF 7106 ALUMINUM ALLOY DURING DIFFUSION WELDING (7106 Aluminum Alloy to 321 Stainless Steel)

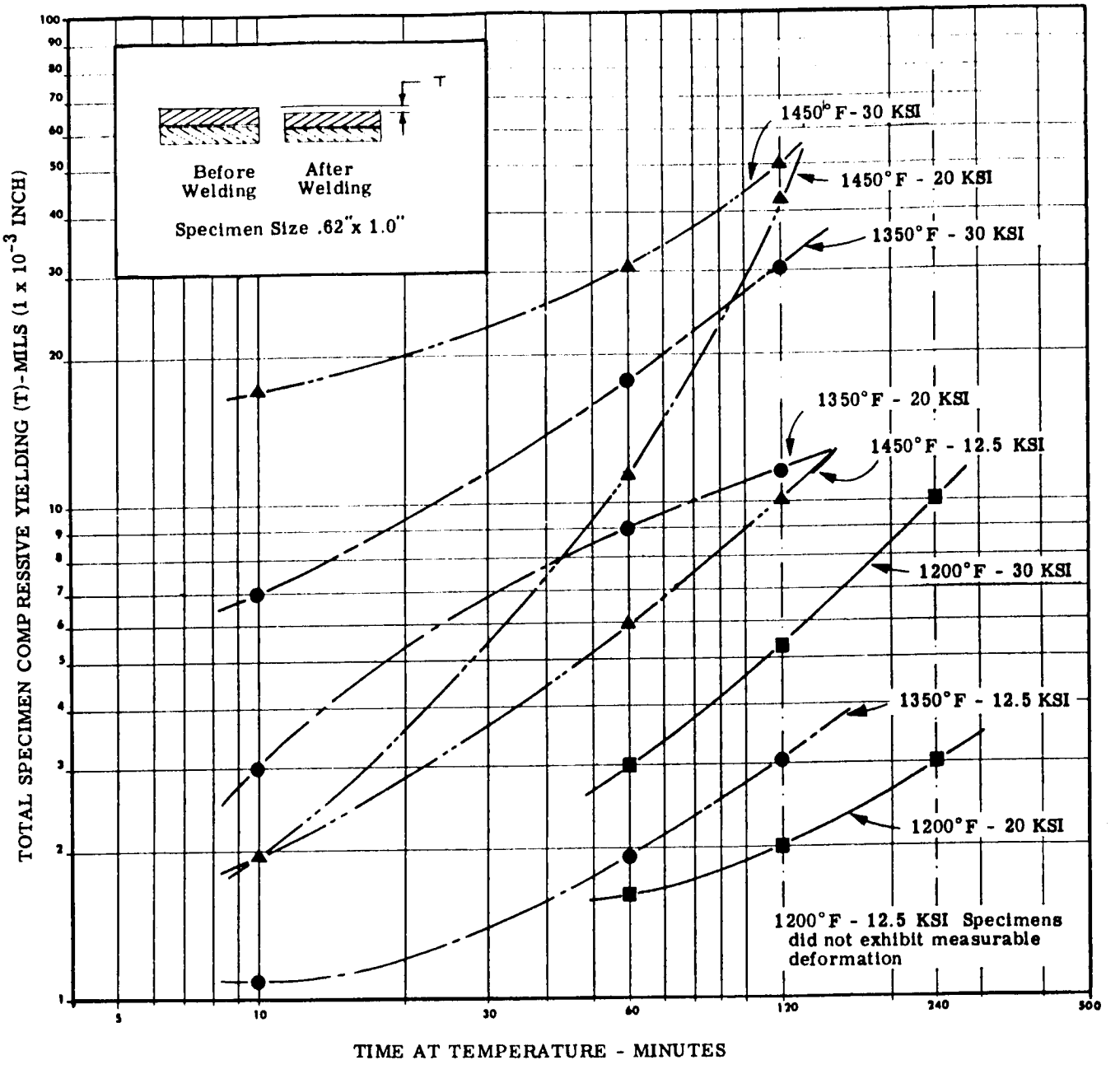


FIGURE 16: EFFECT OF TIME, TEMPERATURE AND PRESSURE ON SPECIMEN COMPRESSIVE YIELDING DURING DIFFUSION WELDING (321 Stainless Steel to Ti-8Al-1Mo-1V Alloy)

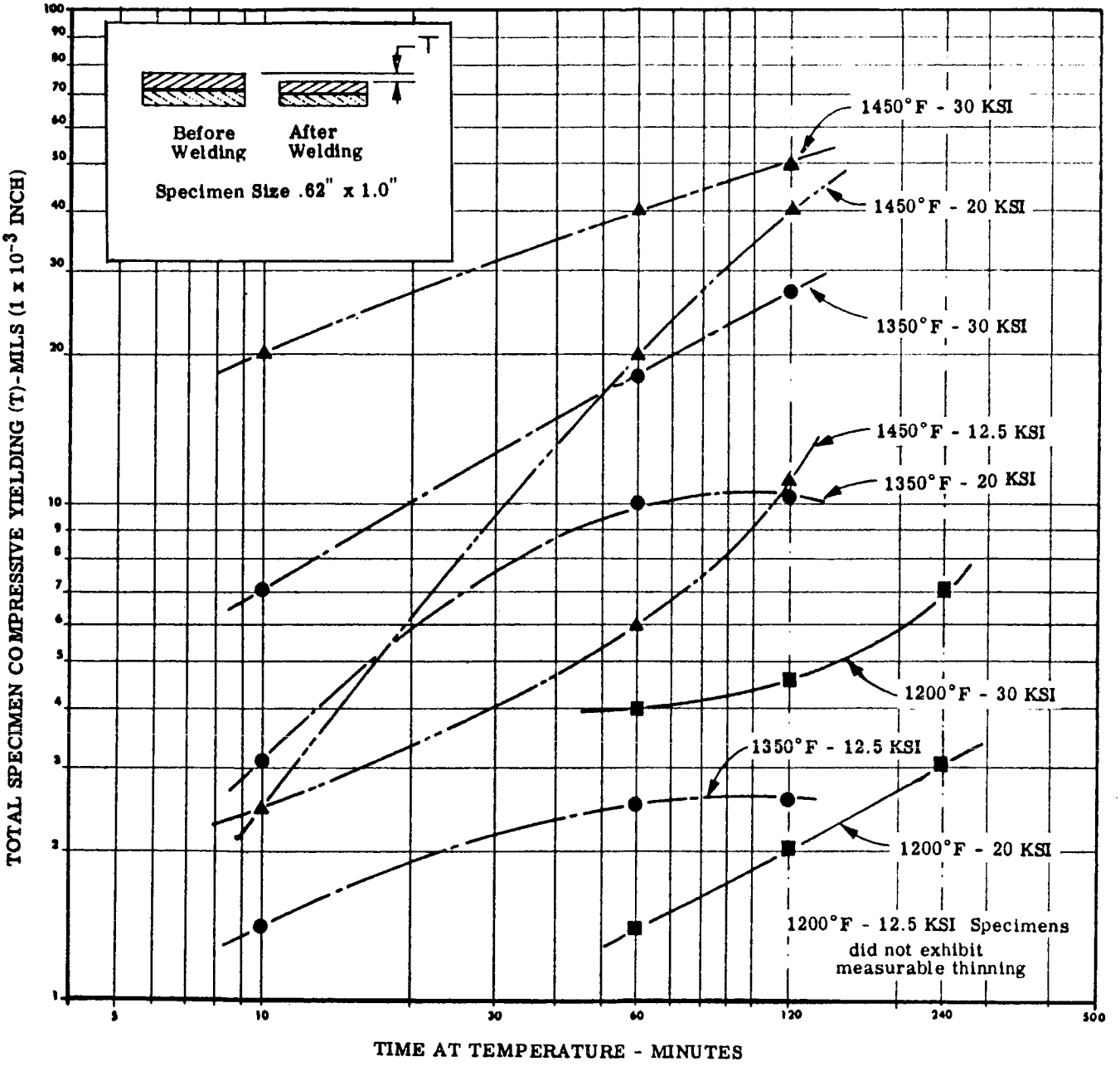


FIGURE 17: EFFECT OF TIME, TEMPERATURE AND PRESSURE ON SPECIMEN COMPRESSIVE YIELDING DURING DIFFUSION WELDING (Inconel 600 Alloy to Ti-8 Al-1 Mo-1 V)

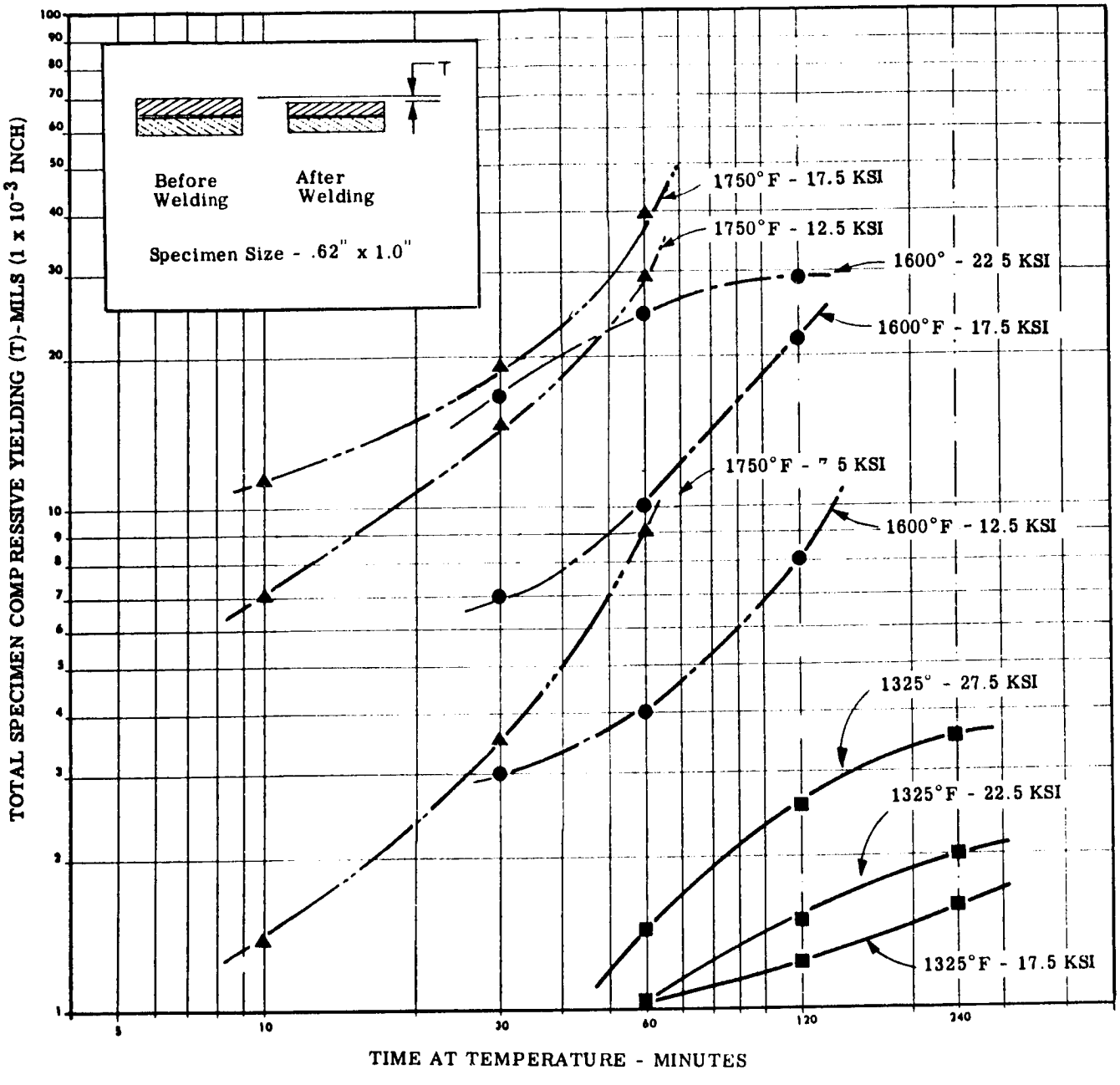
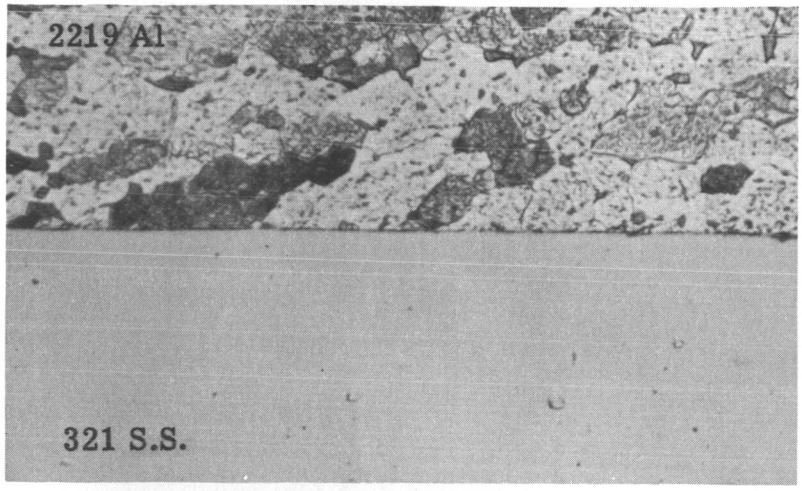
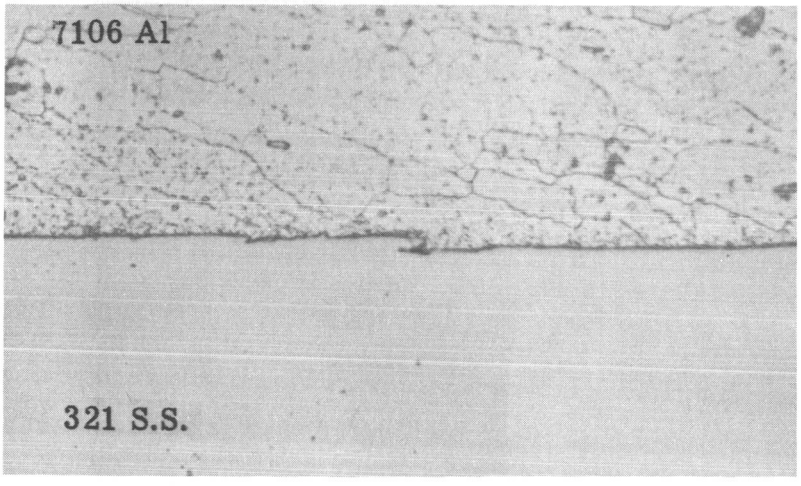


FIGURE 18: EFFECT OF TIME, TEMPERATURE AND PRESSURE ON SPECIMEN COMPRESSIVE YIELDING DURING DIFFUSION WELDING (Inconel 718 Alloy to 321 Stainless Steel)



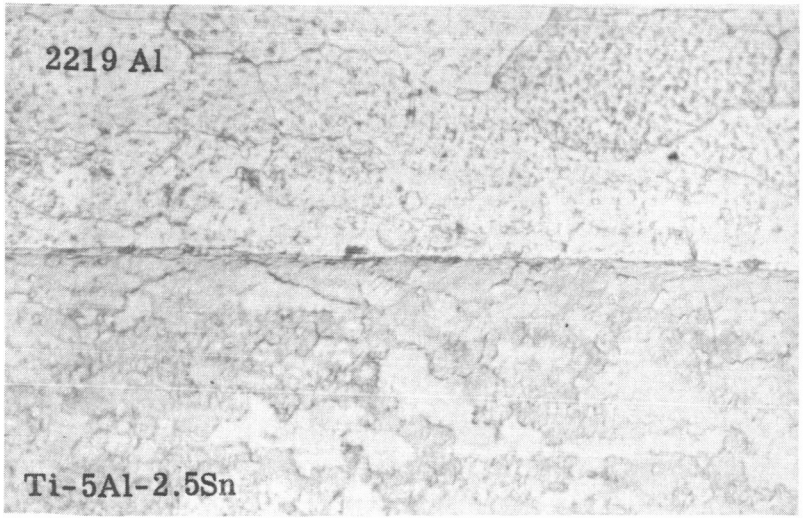
500X 2A206808

(a) 2219 Al/321 S.S.
#159
950°F/7.5 ksi/120 min.
90°Cross-Section
Etched



500X 2A206809

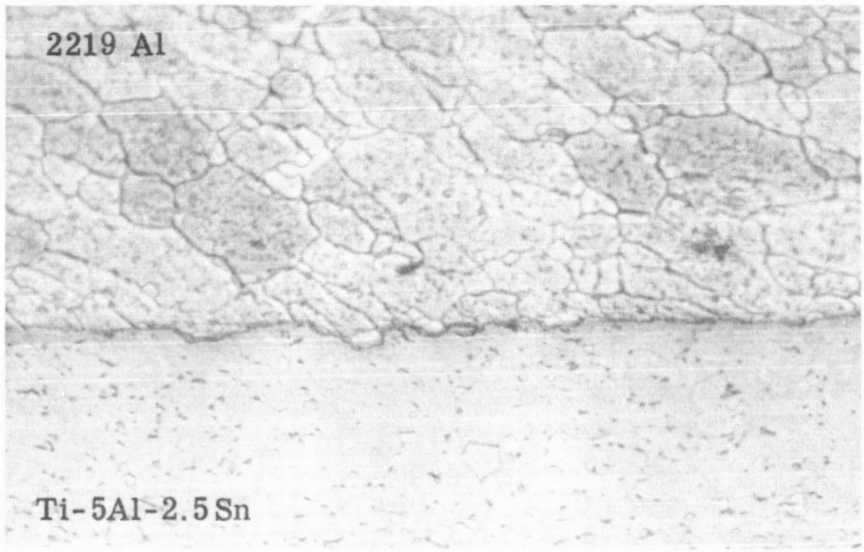
(b) 7106 Al/321 S.S.
#166
950°F/7.5 ksi/60 min.
90° Cross-Section
Etched



500X 2A206807

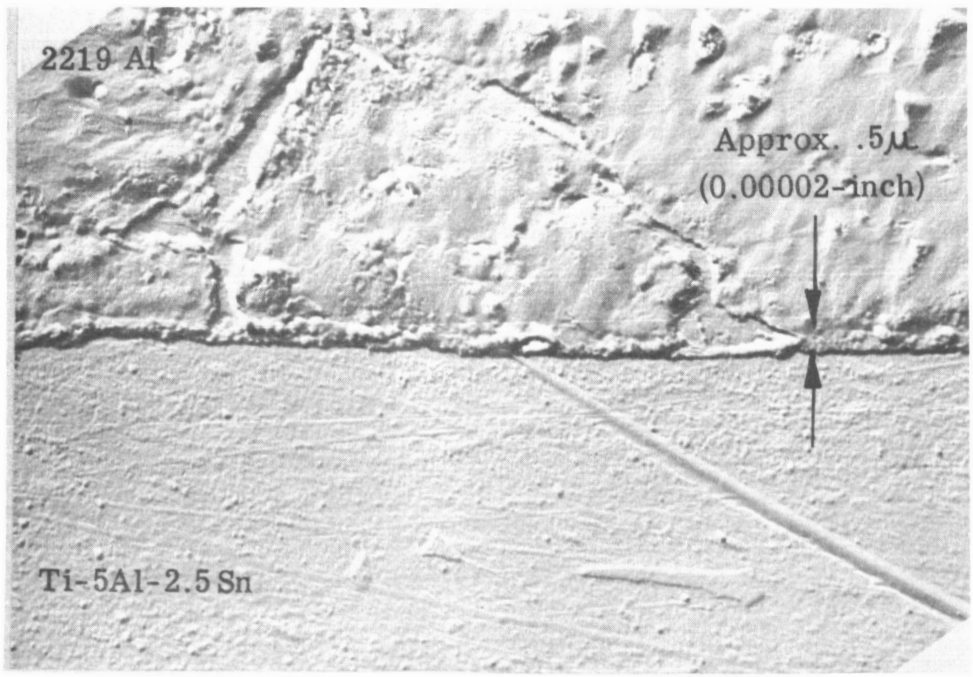
(c) 2219 Al/Ti-5Al-2.5Sn
#167
950°F/7.5 ksi/60 min.
90° Cross-Section
Etched

FIGURE 19: MICROSTRUCTURE OF DIFFUSION WELDS OF 2219 Al ALLOY TO 321 STAINLESS STEEL, 7106 Al ALLOY TO 321 STAINLESS STEEL AND 2219 Al ALLOY TO Ti-5Al-2.5Sn ALLOY.



500X 2A206952

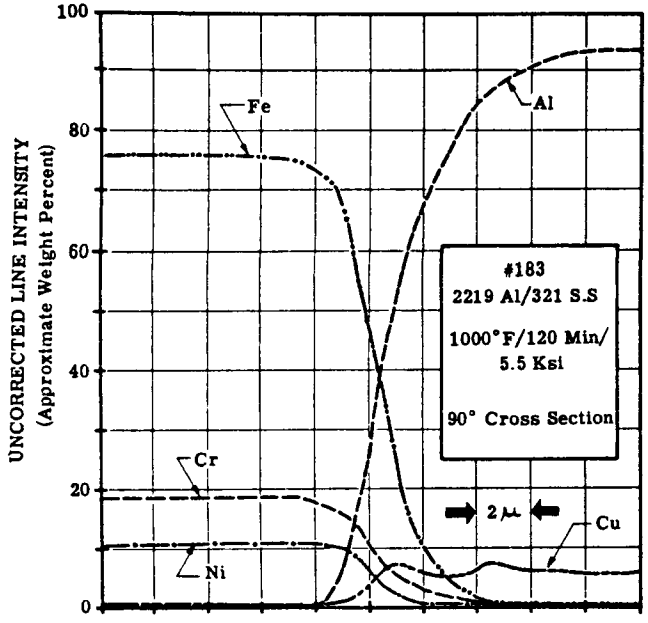
(a) #182 1000°F/120 min/7.5 ksi
OPTICAL MICROGRAPH

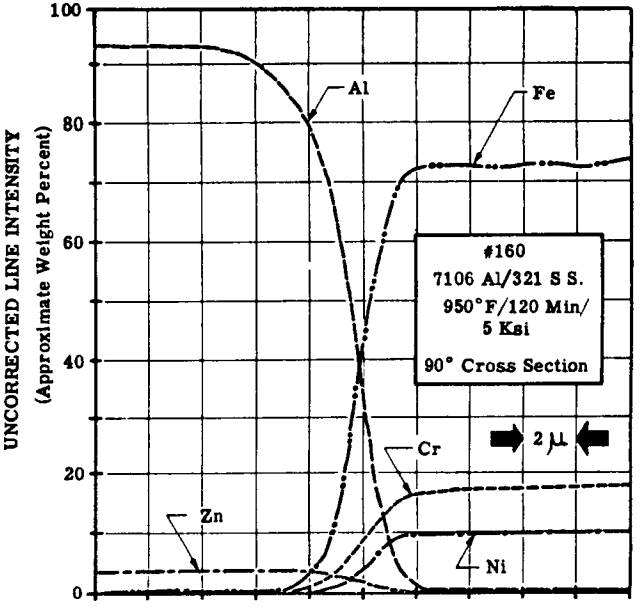


8500X 1-20-66-10

(b) ELECTRON MICROGRAPH
(Titanium not etched)

FIGURE 20: MICROSTRUCTURE OF DIFFUSION ZONE OF 2219 Al To Ti-5Al-2.5Sn





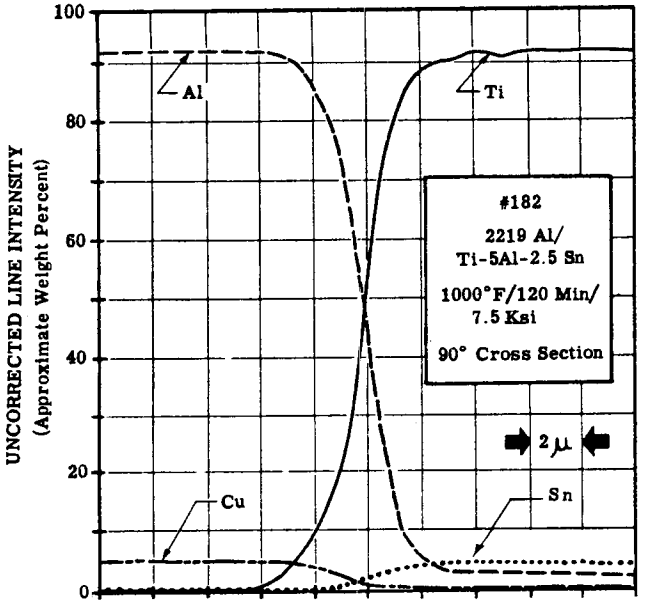
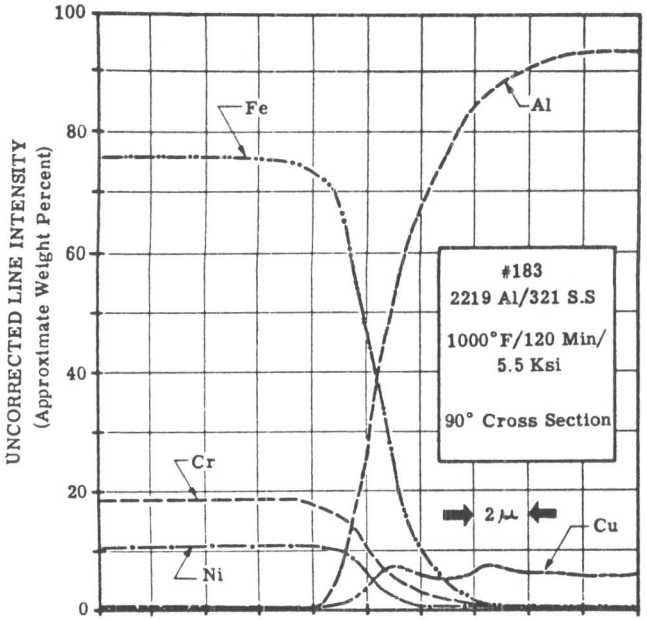
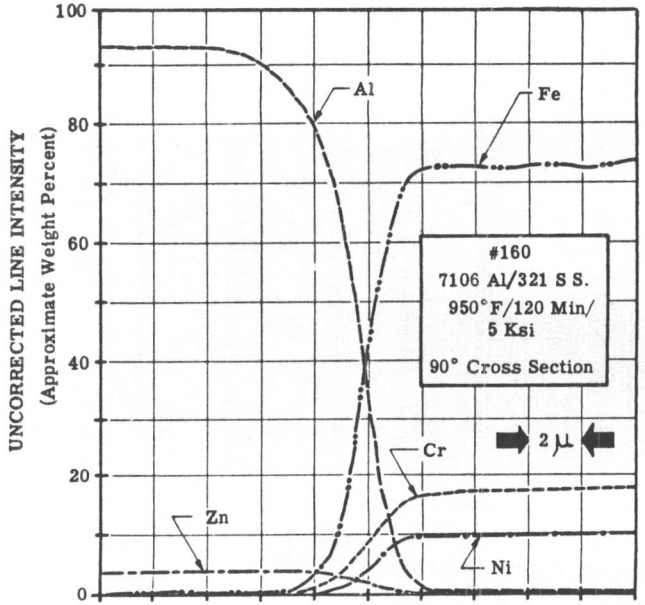


FIGURE 21: MICROPROBE ANALYSIS OF 2219 Al/321 S.S., 7106 Al/321 S.S. AND 2219 Al/Ti-5 Al-2.5 Sn DIFFUSION WELDS.





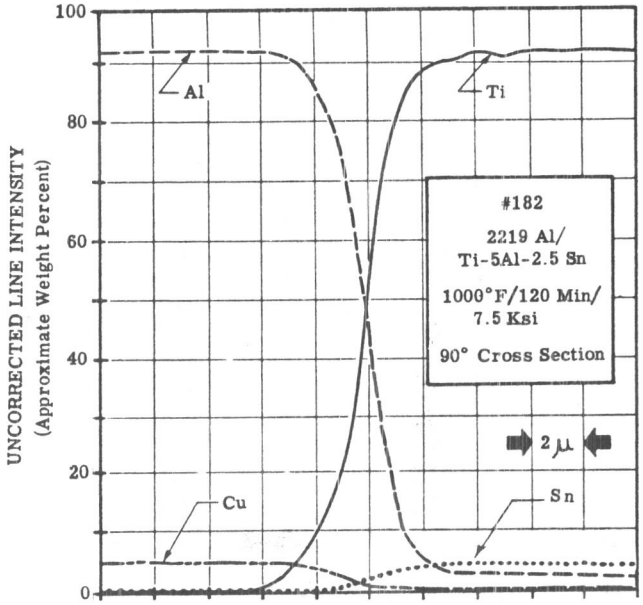
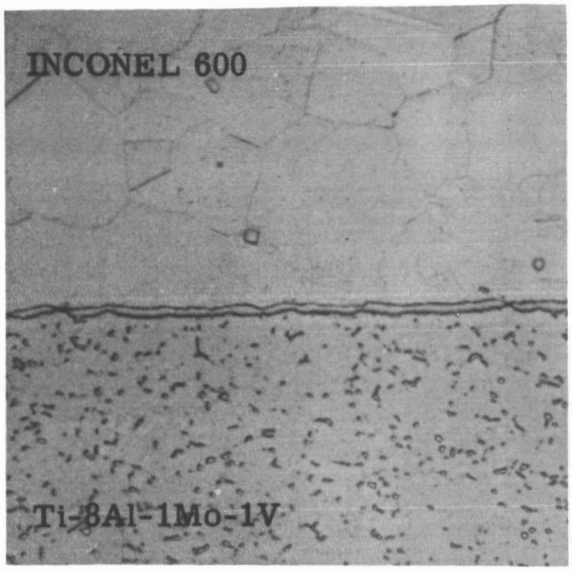
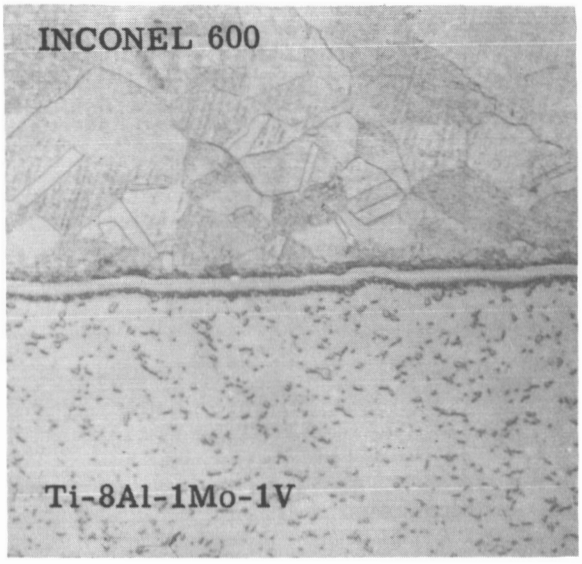


FIGURE 21: MICROPROBE ANALYSIS OF 2219 Al/321 S.S., 7106 Al/321 S.S. AND 2219 Al/Ti-5 Al-2.5 Sn DIFFUSION WELDS.



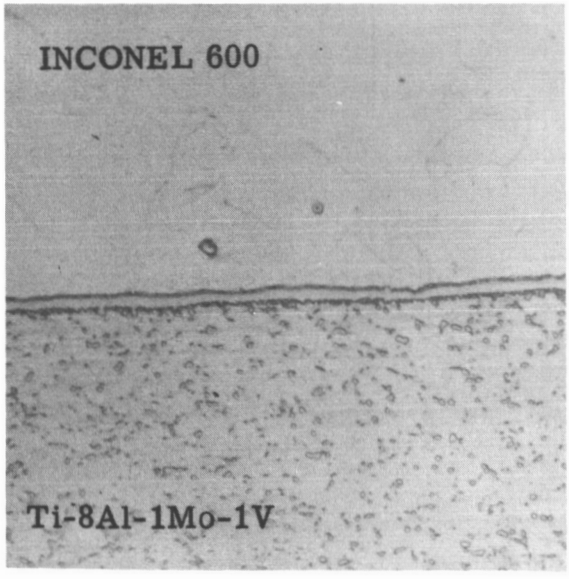
500X 2A206742

(a) #69 1200°F/20 ksi/60 min.



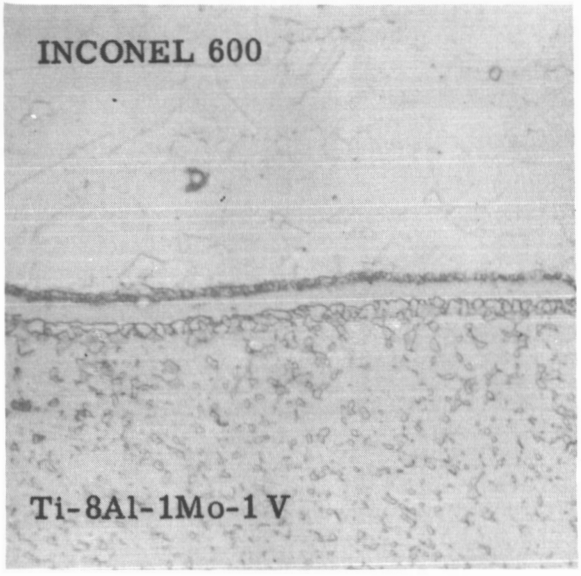
500X 2A206772

(b) #87 1350°F/20 ksi/120 min.



500X 2A206753

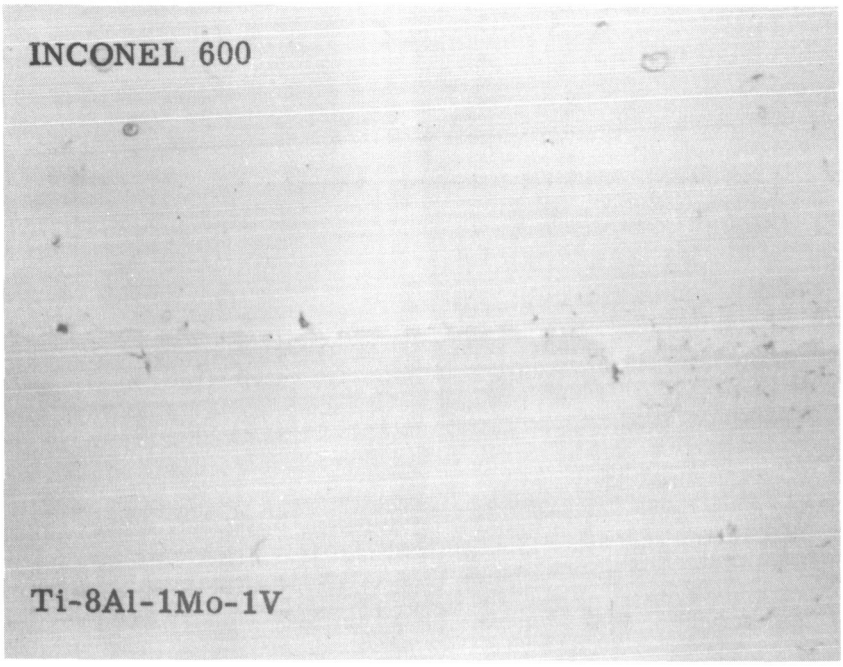
(c) #121 1450°F/20 ksi/10 min.



500X 2A206776

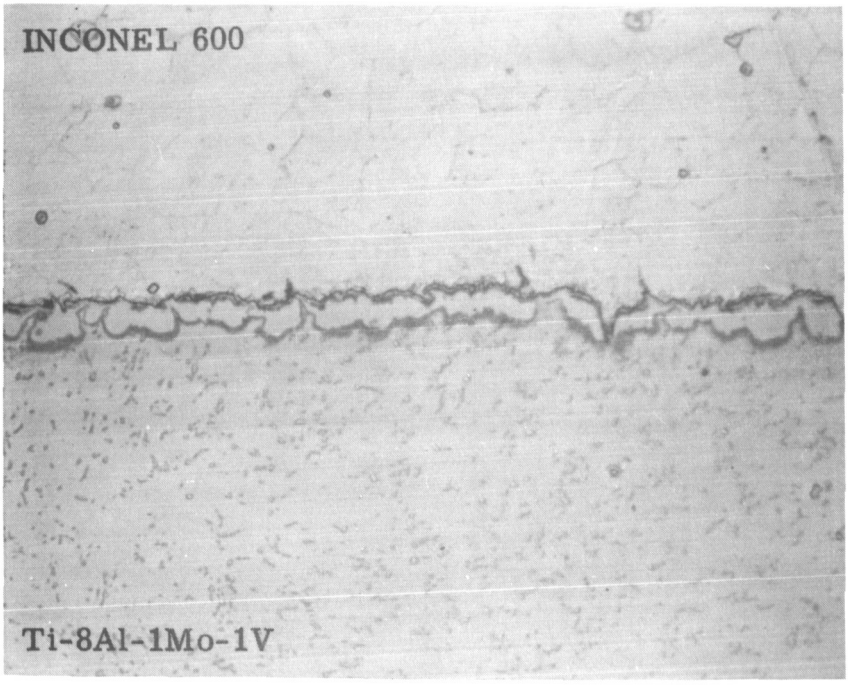
(d) #117 1450°F/20 ksi/120 min.

FIGURE 22: MICROSTRUCTURE OF INCONEL 600 TO Ti-8Al-1Mo-1V DIFFUSION WELDS. 90° CROSS-SECTIONS. ETCHED



500X 2A206550

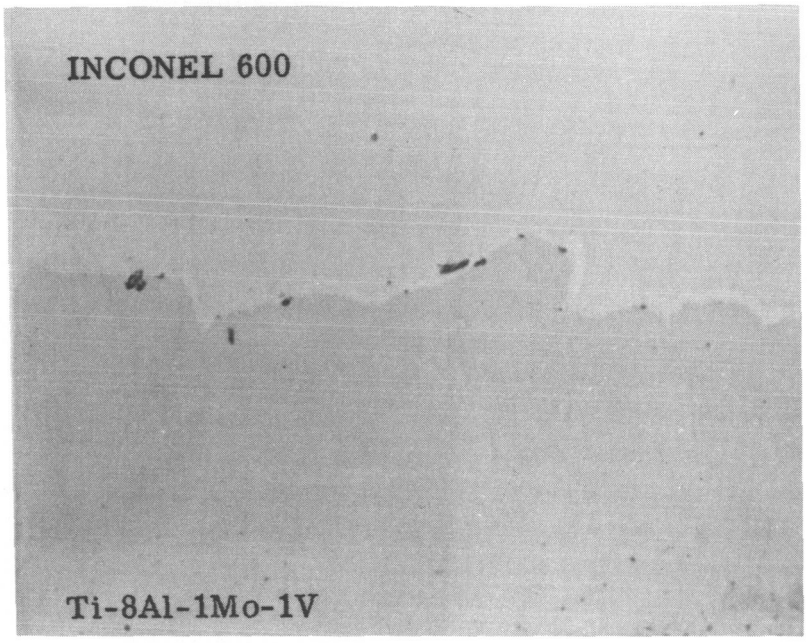
(a) Unetched



500X 2A206562

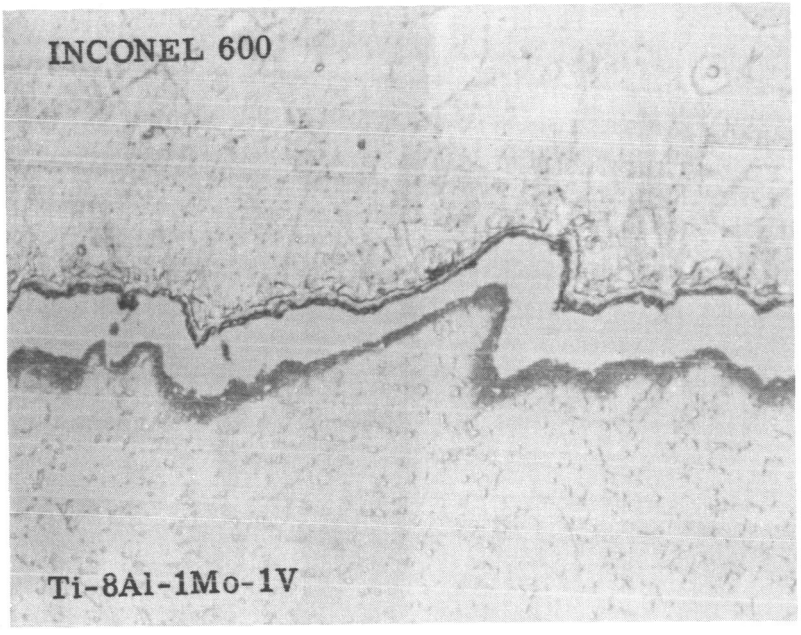
(b) Etched

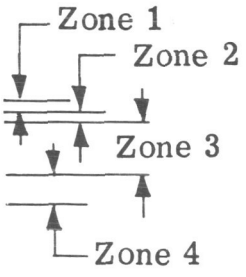
FIGURE 24: MICROSTRUCTURE OF INCONEL 600 TO Ti-8Al-1Mo-1V DIFFUSION WELDS. SPECIMEN #69 DIFFUSION WELDED AT 1200°F/20 KSI/60 MINUTES. 15° TAPER MICROSECTION



500X 2A206552

(a) Unetched

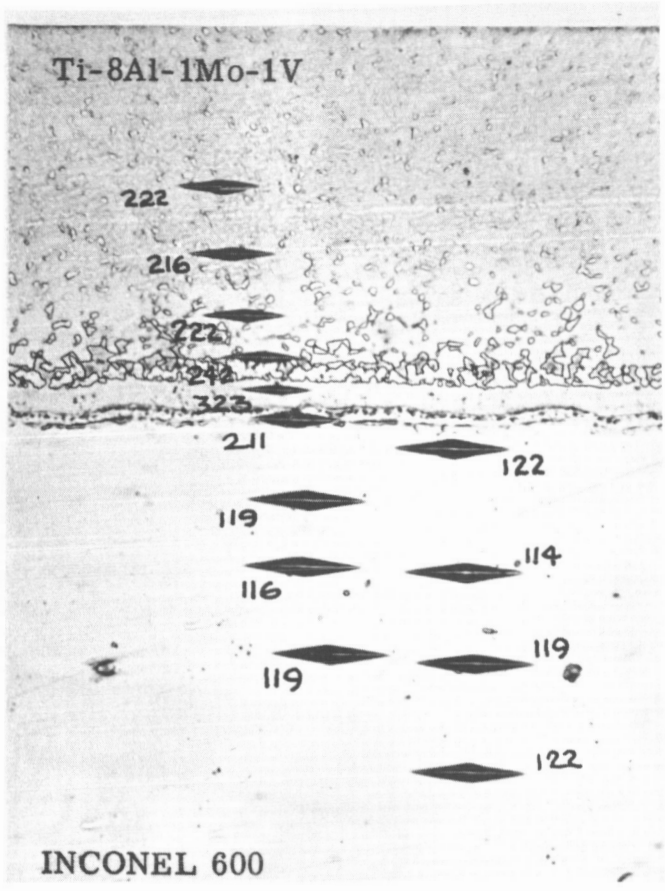




500X 2A206560

(b) Etched

FIGURE 25: MICROSTRUCTURE OF INCONEL 600 TO Ti-8Al-1Mo-1V 15° TAPER SECTION OF SPECIMEN #87 DIFFUSION WELDED AT 1350°F/20 KSI/120 MINUTES

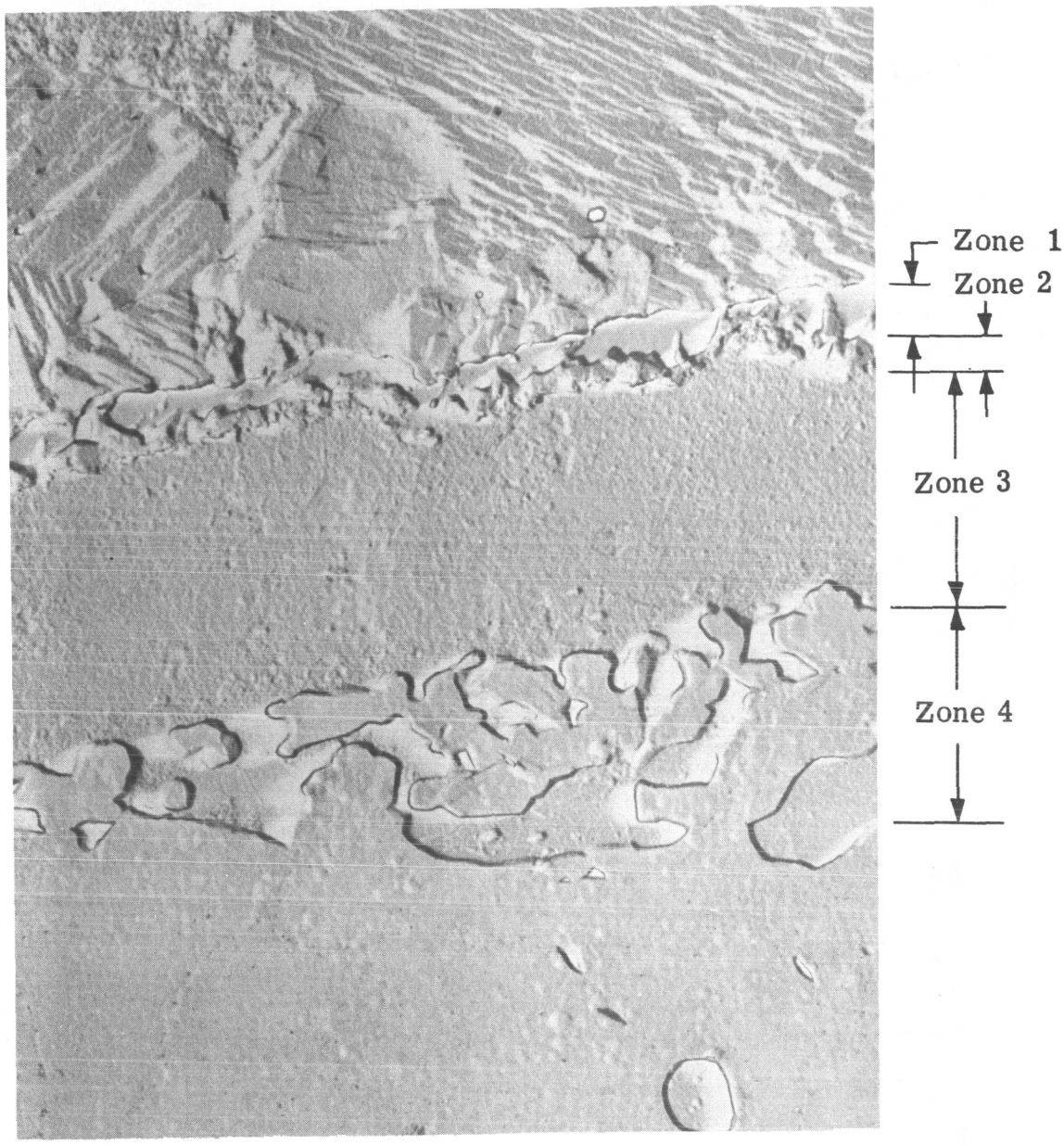


500X 2A206764

#117 1450°F/20 KSI/120 Min.

Reichert Micro-Hardness Tester - Knoop Diamond Indentor With 17 Gram Load - Hardness Values Expressed in KHN.

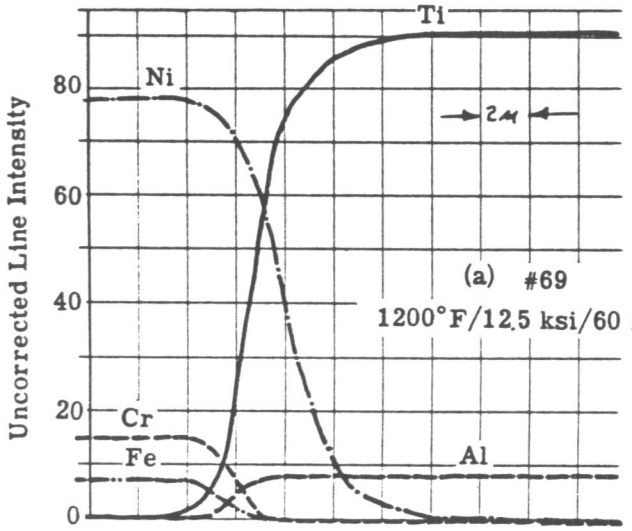
FIGURE 26: MICROHARDNESS TRAVERSE OF INCONEL 600 TO Ti-8Al-1Mo-1V DIFFUSION WELD. 90° CROSS-SECTION. ETCHED FOR TITANIUM.

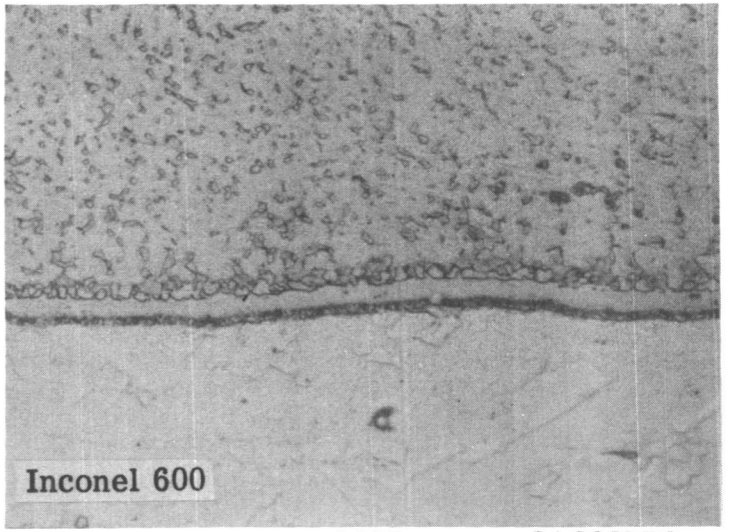


11,700X 11-8-65-3

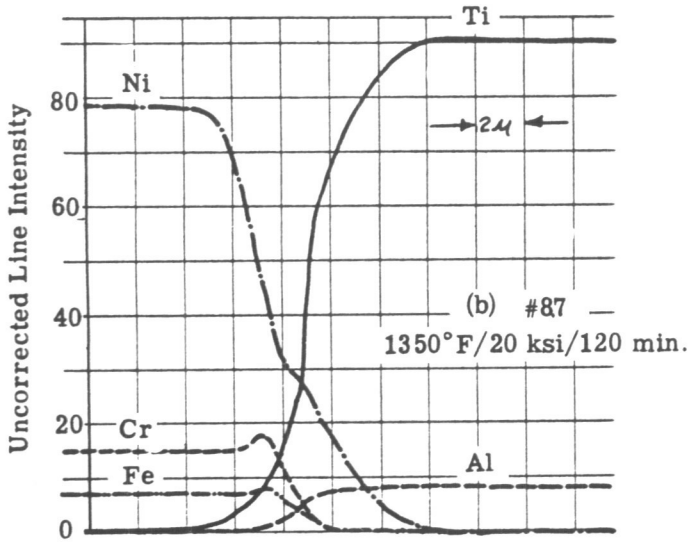
#87 1350°F/20 ksi/120 min.

FIGURE 27: ELECTRON MICROGRAPH OF DIFFUSION ZONE OF INCONEL 600 TO Ti-8Al-1Mo-1V DIFFUSION WELD. CARBON REPLICA. ETCHED





500X #117 2A206776



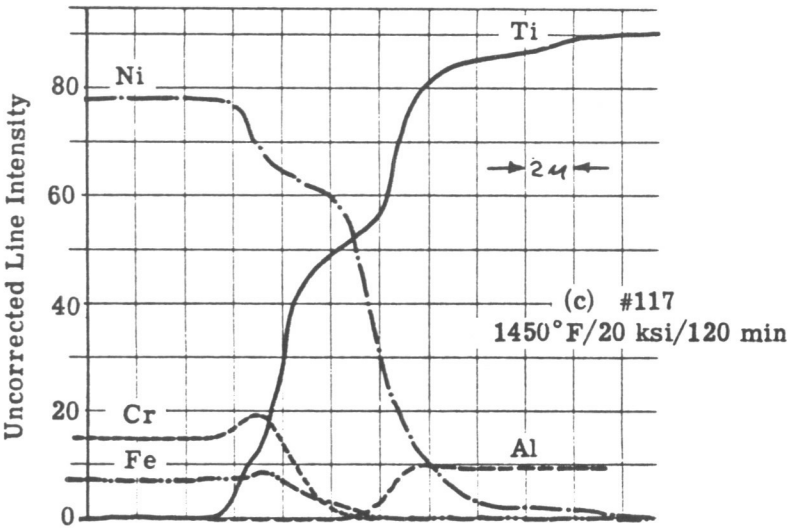
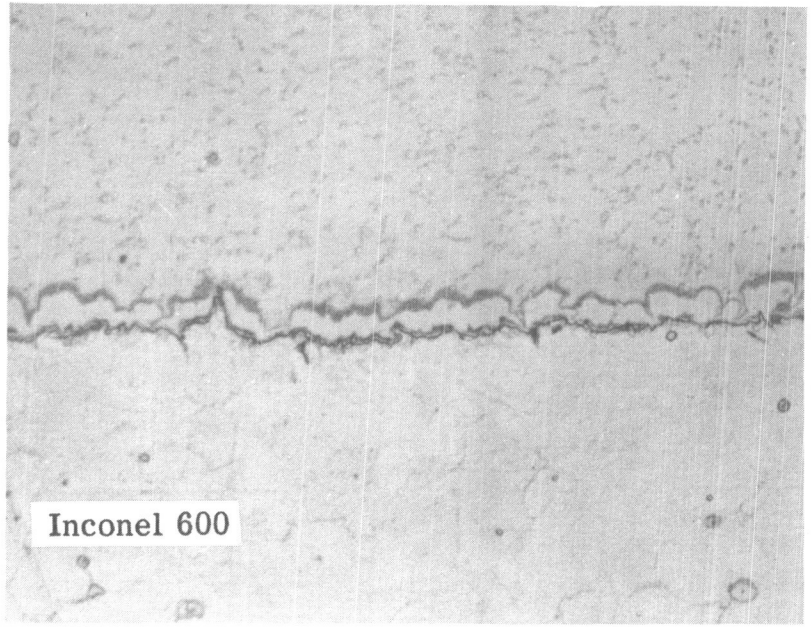
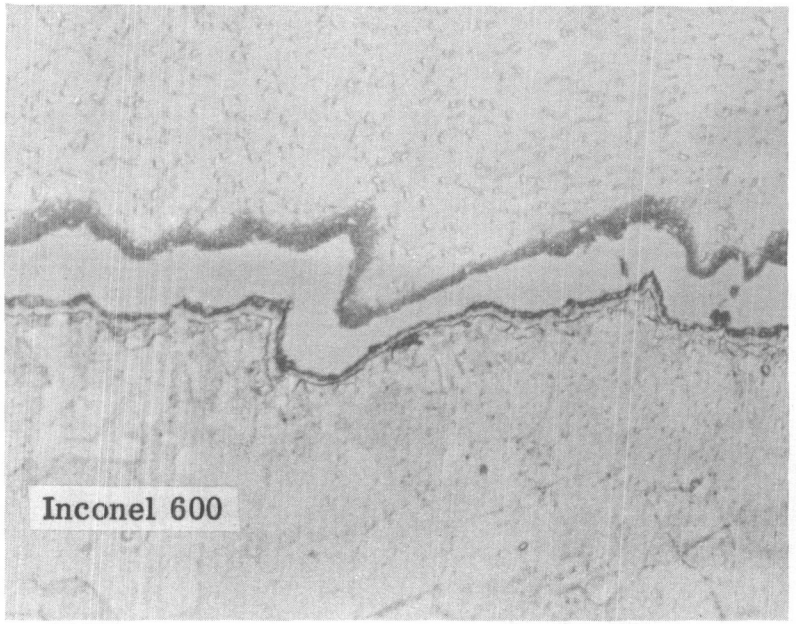


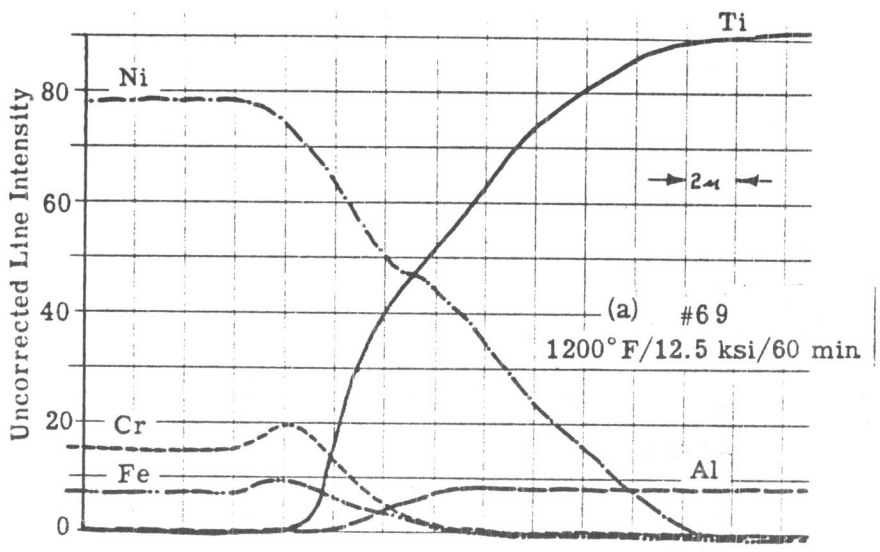
FIGURE 28: MICROPROBE ANALYSIS OF INCONEL 600 TO Ti-8Al-1Mo-1V DIFFUSION WELDS. 90° CROSS-SECTIONS.



500X 2A206562



500X 2A206560



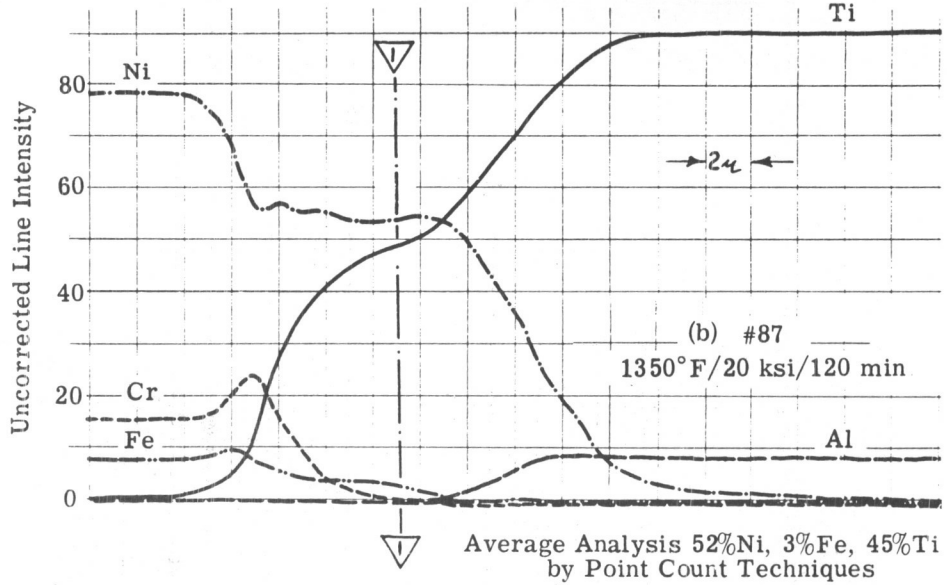


FIGURE 29: MICROPROBE ANALYSIS OF INCONEL 600 to Ti-8 Al-1 Mo-1V DIFFUSION WELDS. 15° TAPER MICROSECTIONS.

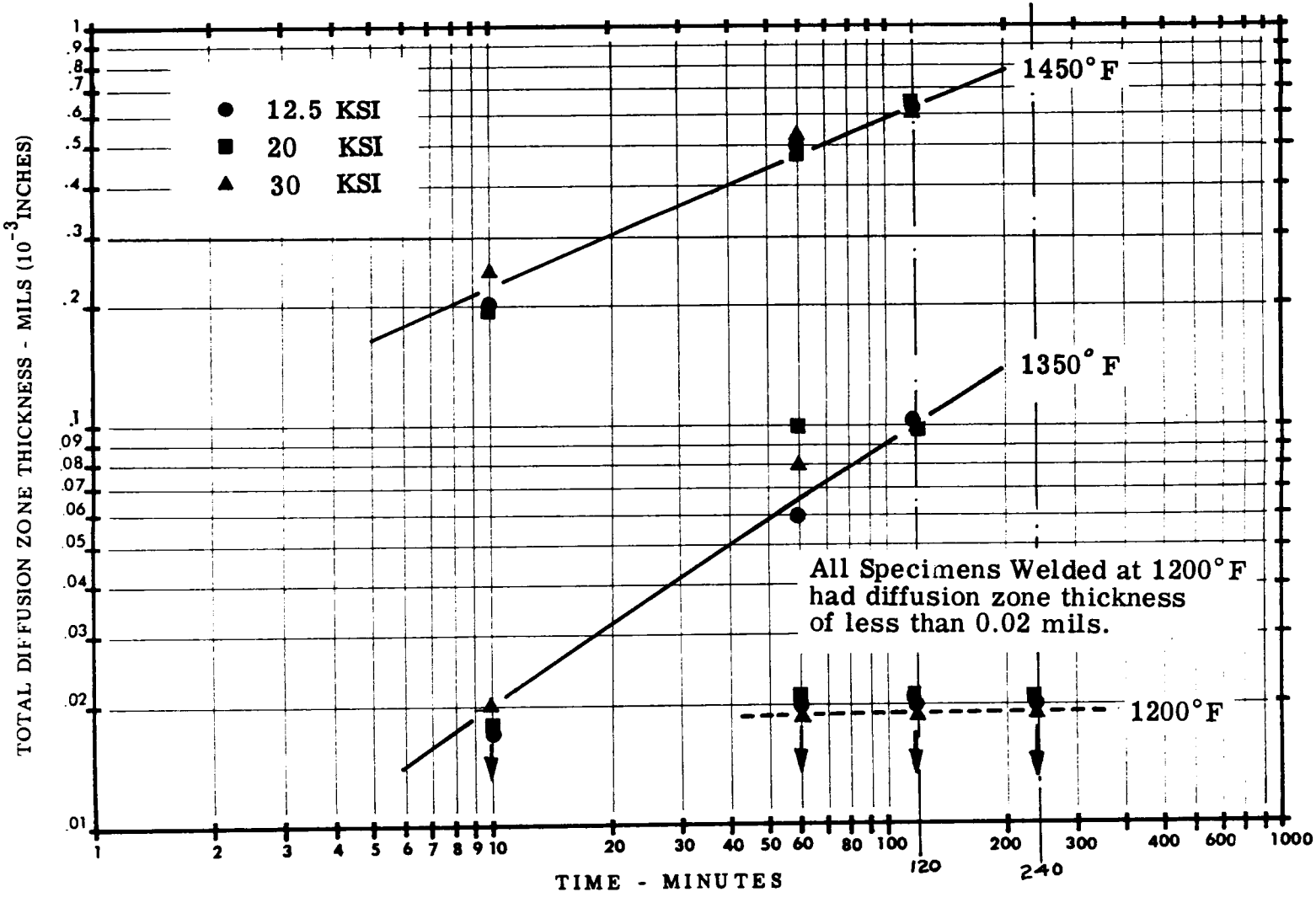
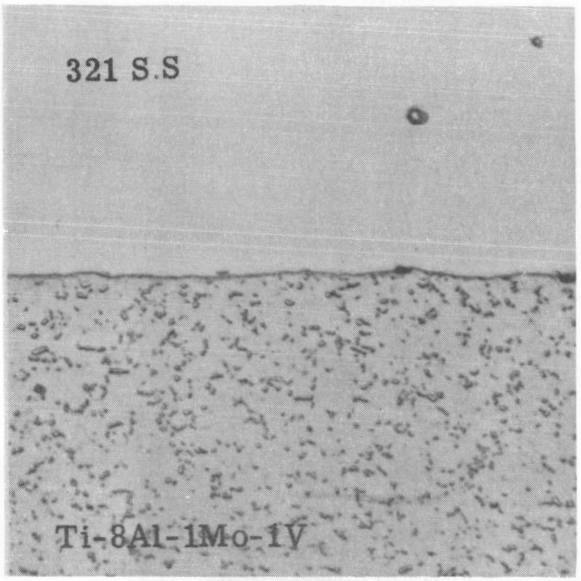
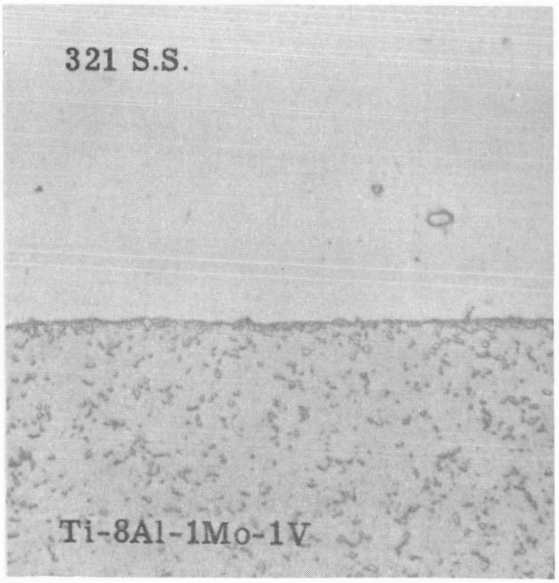


FIGURE 30: EFFECT OF TIME, TEMPERATURE AND PRESSURE ON DIFFUSION ZONE THICKNESS OF 321 STAINLESS STEEL DIFFUSION WELDED TO Ti-8Al-1Mo-1V



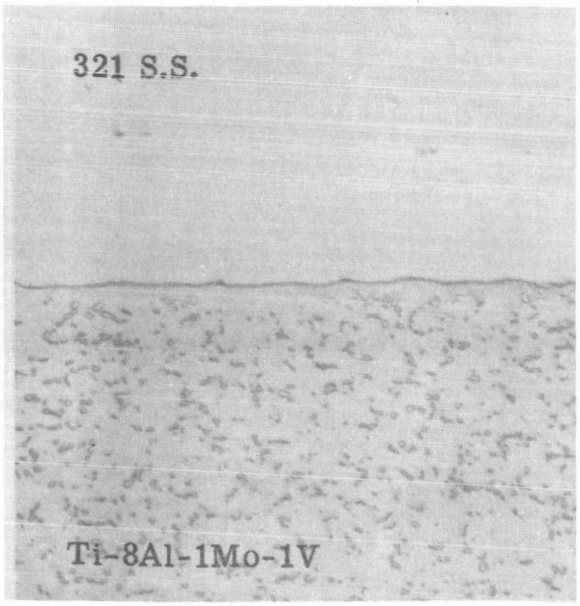
500X 2A206779

(a) #70 1200°F/20 ksi/60 min.



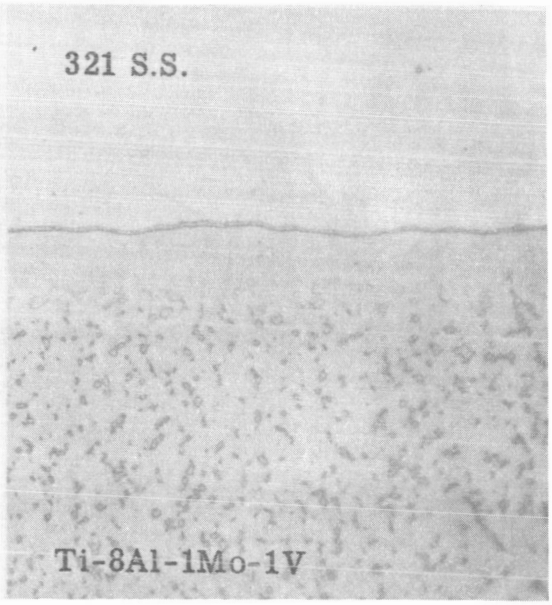
500X 2A206799

(b) #88 1350°F/20 ksi/120 min.



500X 2A206791

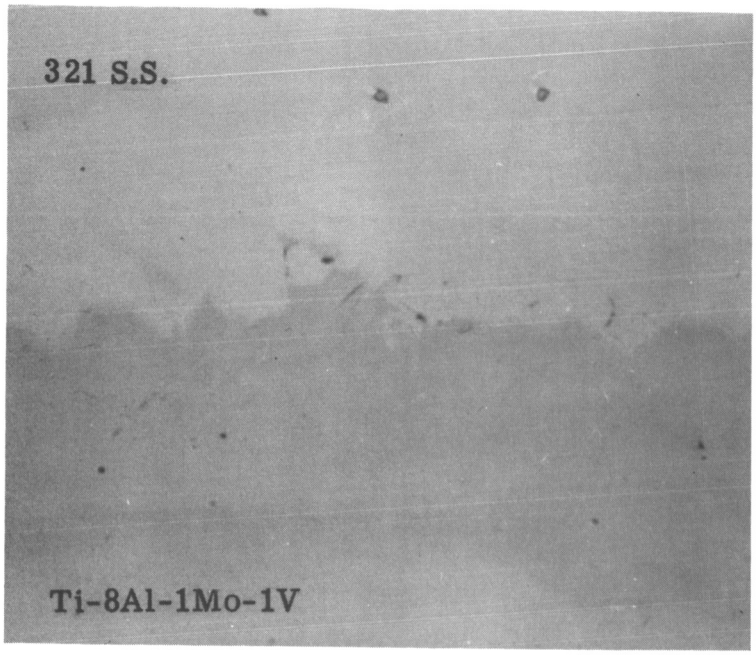
(c) #122 1450°F/20 ksi/10 min.



500X 2A206803

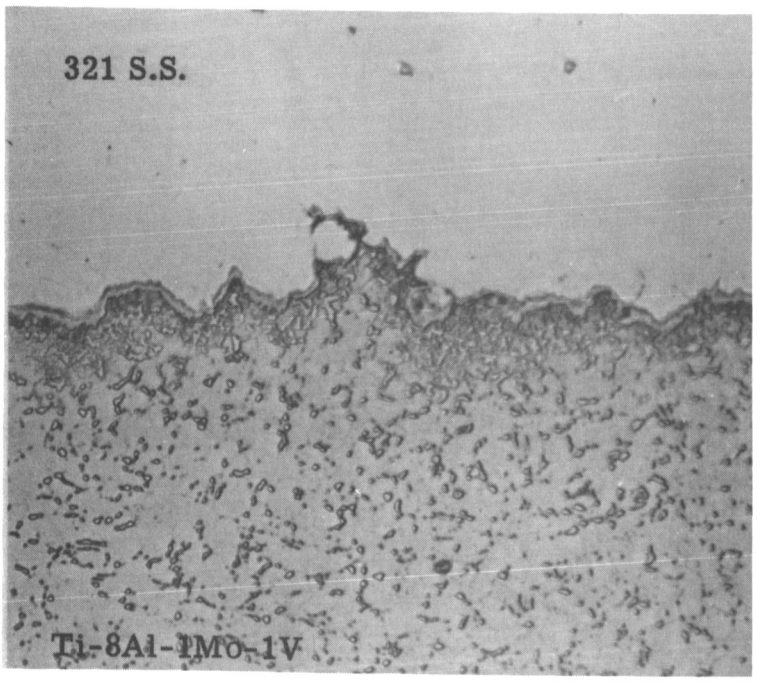
(d) #118 1450°F/20 ksi/120 min.

FIGURE 31: MICROSTRUCTURE OF 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V DIFFUSION WELDS. 90° CROSS-SECTIONS. ETCHED FOR TITANIUM



500X 2A206553

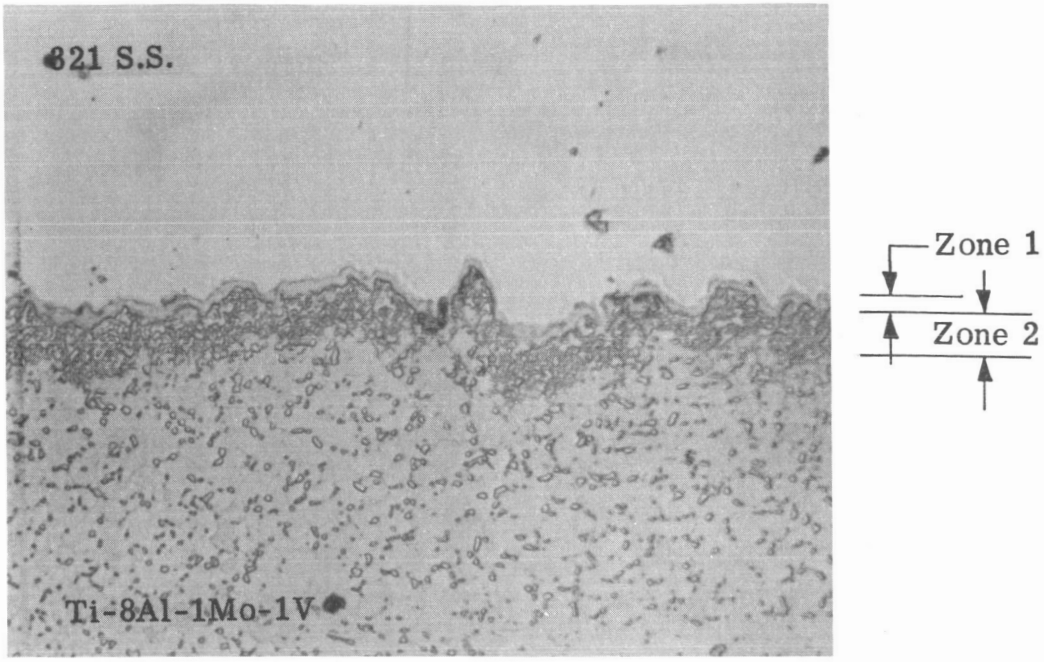
(a) Unetched



500X 2A206561

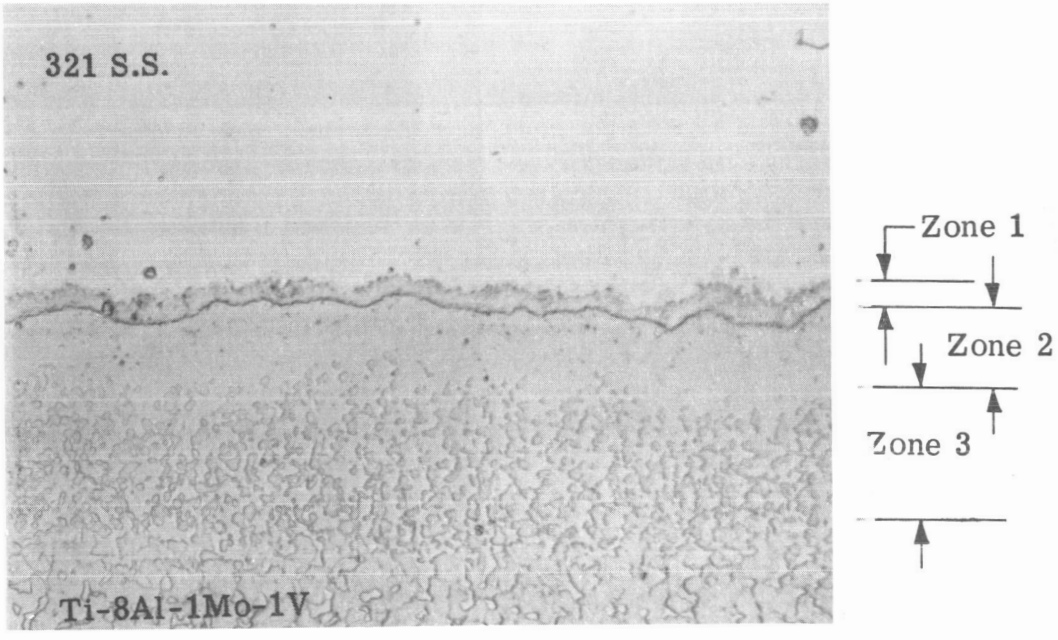
(b) Etched for Titanium

FIGURE 32: MICROSTRUCTURE OF 321 STAINLESS STEEL TO Ti-8A1-1Mo-1V DIFFUSION WELDS. SPECIMEN #88 WELDED AT 1350°F/20 KSI/120 MINUTES. 15°TAPER MICROSECTION



500X 2A206559

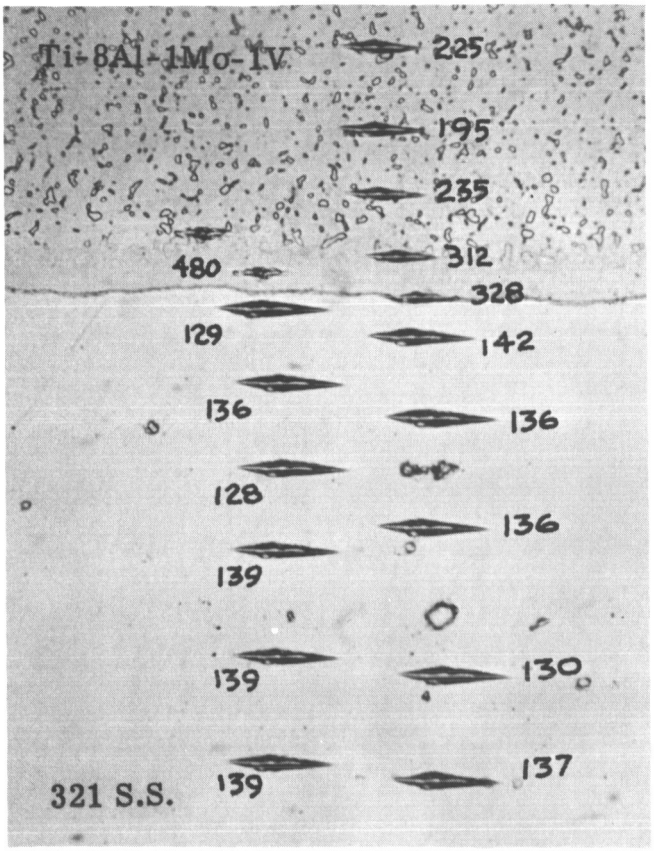
(a) #122 1450°F/20 ksi/10 min. Etched For Ti



500X 2A206557

(b) #118 1450°F/20 ksi/120 min. Etched For Ti

FIGURE 33: MICROSTRUCTURE OF 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V DIFFUSION WELDS. 15° TAPER MICROSECTIONS.



500X 2A206762

#118 1450°F/20 ksi/120 min.

Reichert Micro-Hardness Tester- Knoop Diamond Indentor With 17 Gram Load- Hardness Values Expressed in KHN.

FIGURE 34: MICROHARDNESS TRAVERSE OF 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V DIFFUSION WELD. 90° CROSS-SECTION. Etched for Titanium.

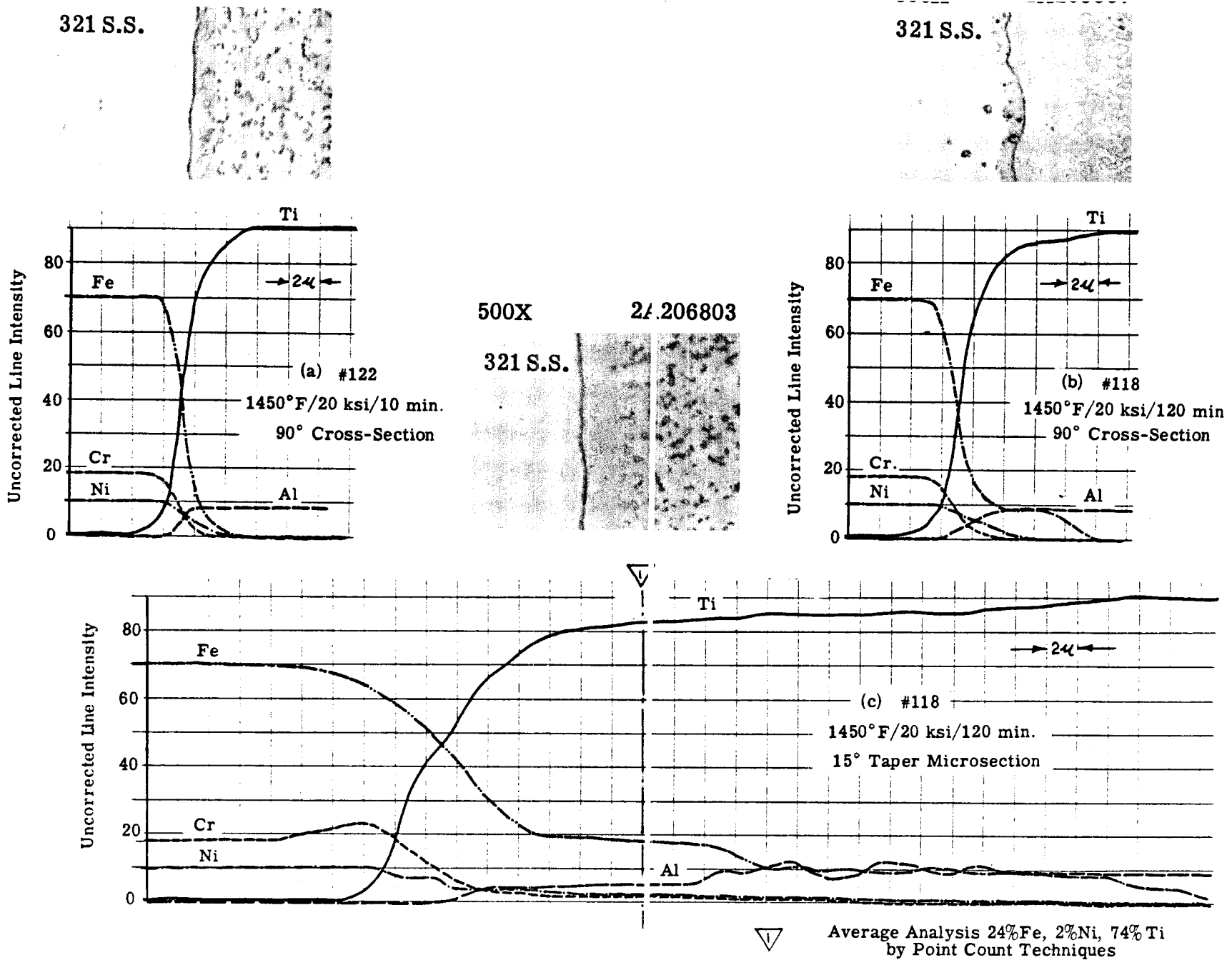
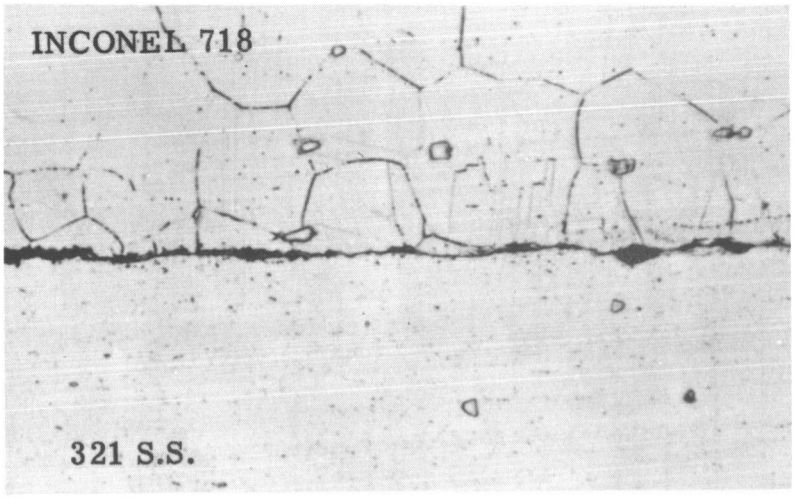


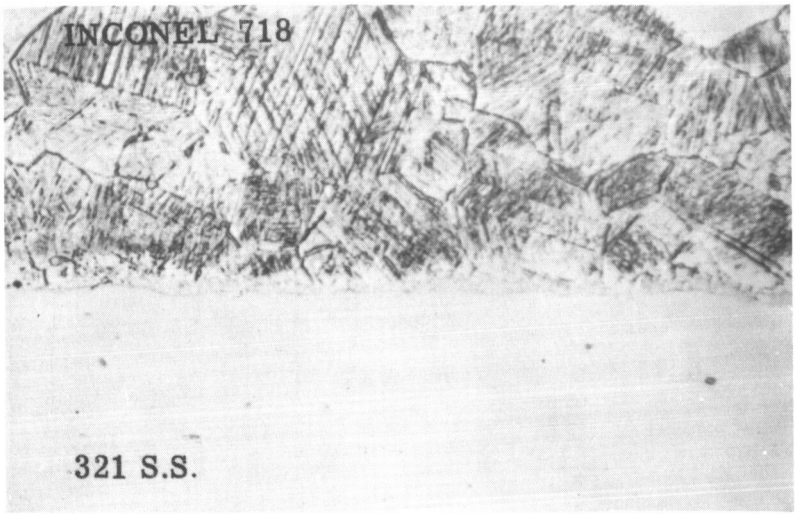
FIGURE 35: MICROPROBE ANALYSIS OF STAINLESS STEEL TO Ti-8 Al-1 Mo-1V DIFFUSION WELDS.



500X 2A206812

(a) #220

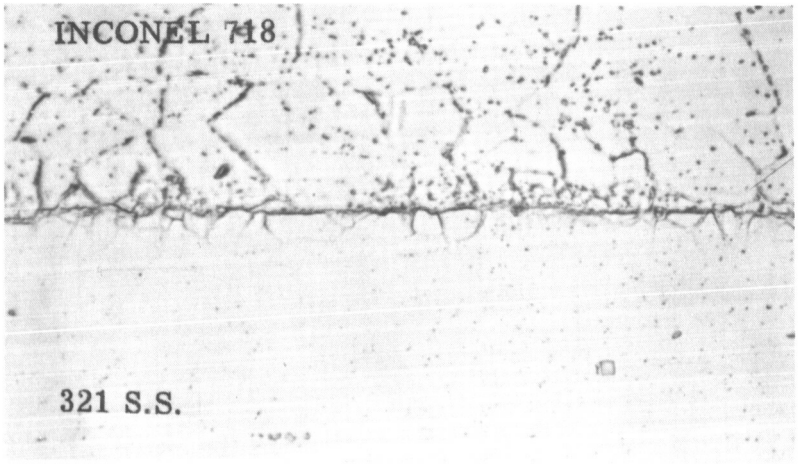
1325°F/22.5 ksi/
120 min.



500X 2A206811

(b) #214

1600°F/17.5 ksi/
120 min.



500X 2A206810

(c) #232

1750°F/12.5 ksi/
60 min.

FIGURE 36: MICROSTRUCTURE OF 321 STAINLESS STEEL TO INCONEL 718 DIFFUSION WELDS. 90° CROSS-SECTION. ETCHED FOR INCONEL 718.

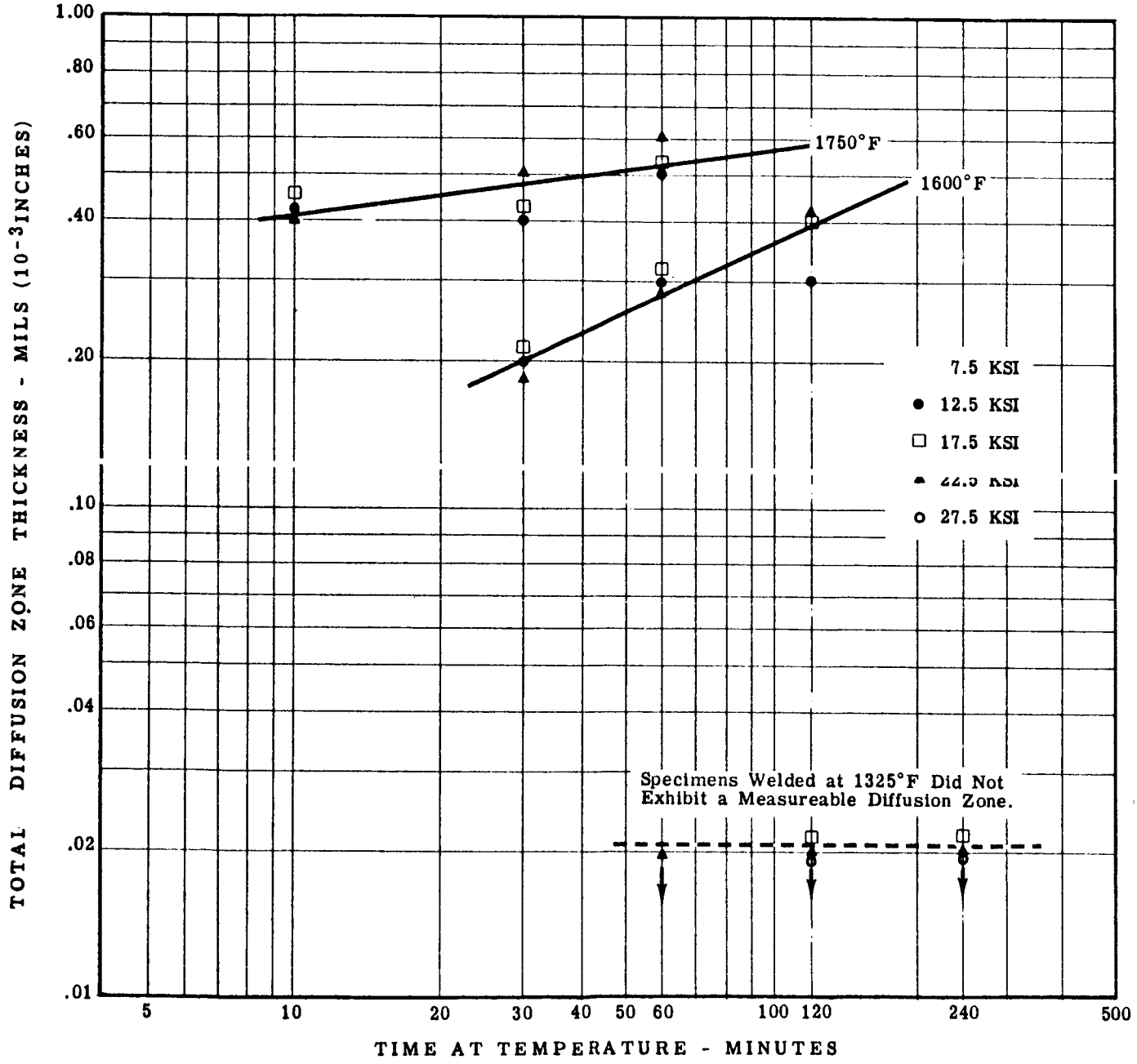
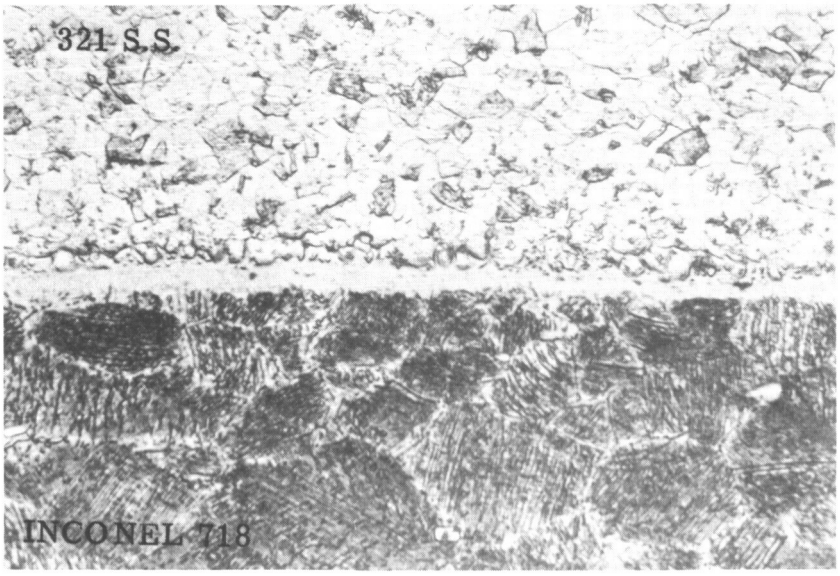
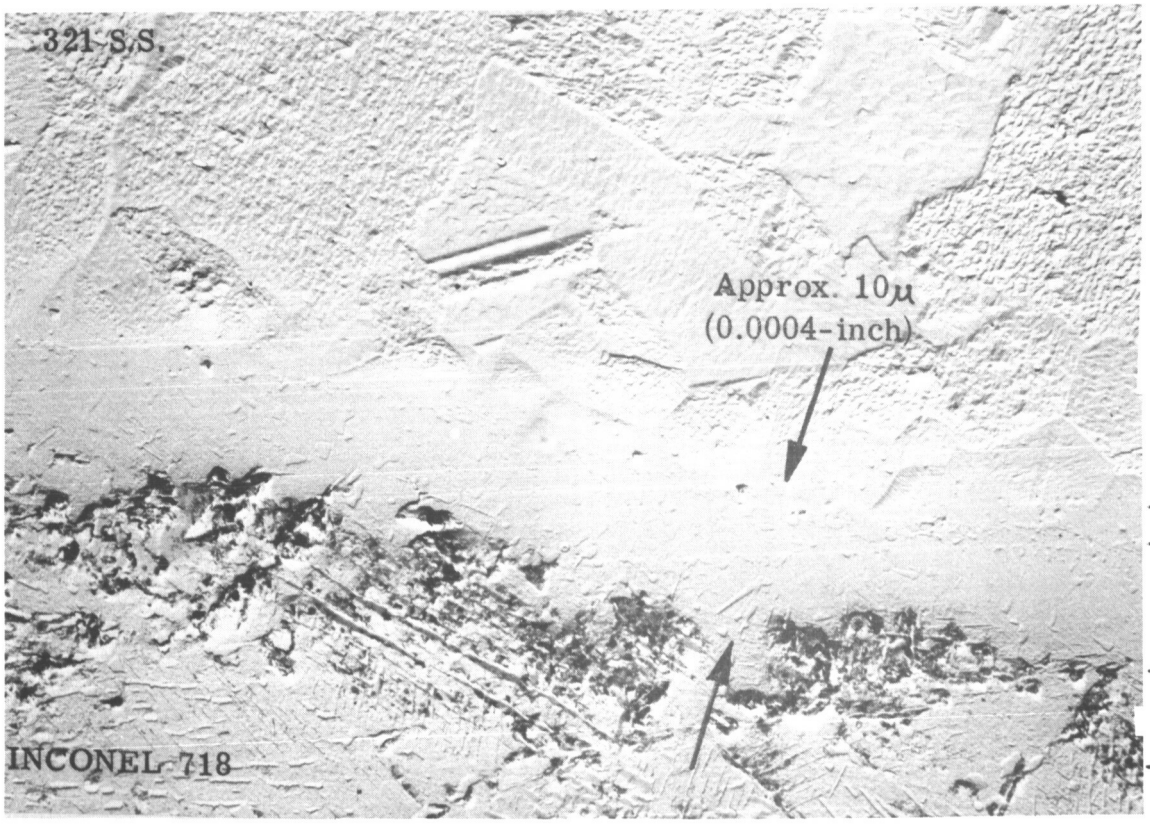


FIGURE 37: EFFECT OF TIME, TEMPERATURE AND PRESSURE ON DIFFUSION ZONE THICKNESS OF 321 STAINLESS STEEL DIFFUSION WELDED TO INCONEL 718.



500X 2A206853

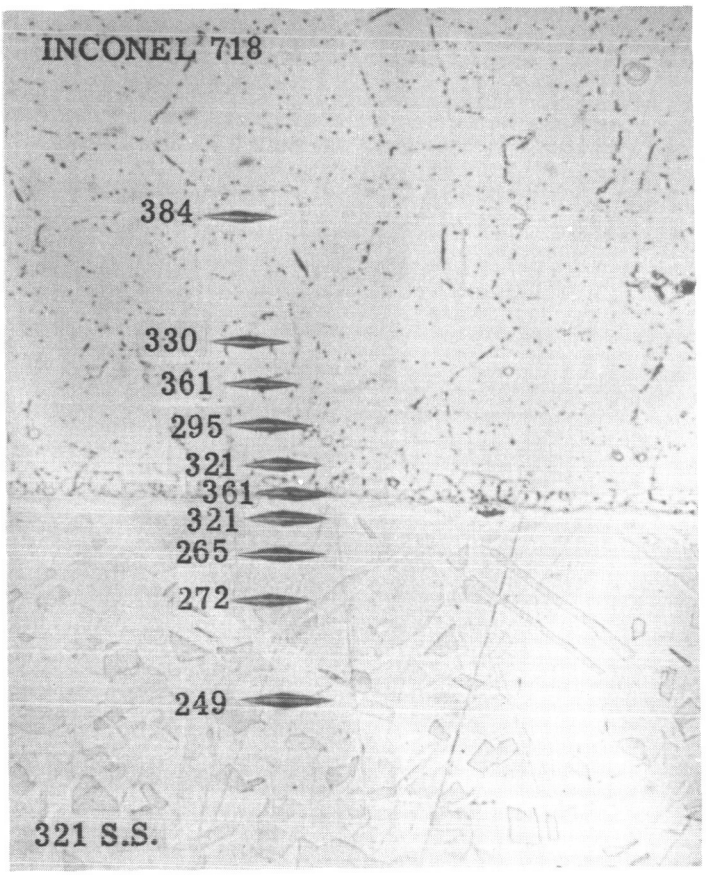
(a) #214 1600°F/120 min/17.5 ksi
OPTICAL MICROGRAPH
(Etched for 321 S.S. and Inconel 718)



2000X 1-20-66-12

(b) ELECTRON MICROGRAPH

FIGURE 38: MICROSTRUCTURE OF DIFFUSION ZONE OF 321 S.S. TO INCONEL 718

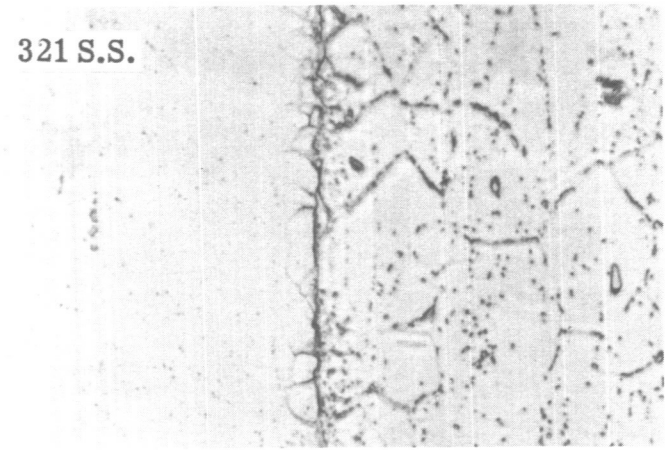


500X 2A223300

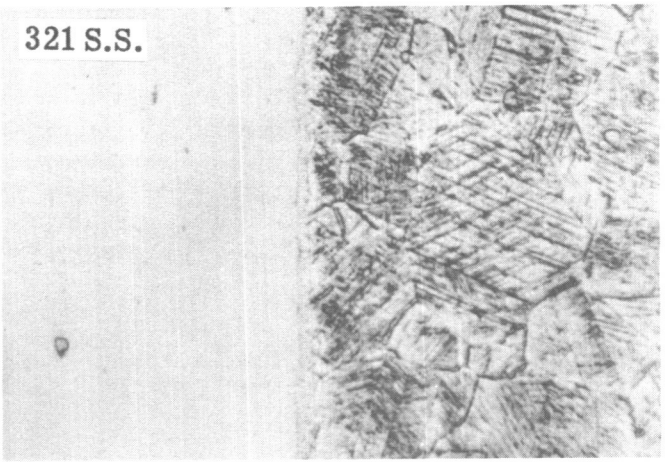
#232 1750°F/12.5 ksi/60 min

Reichert Micro-Hardness Tests - Knoop Diamond Indentor With 12 Gram Load- Hardness Values Expressed in KHN.

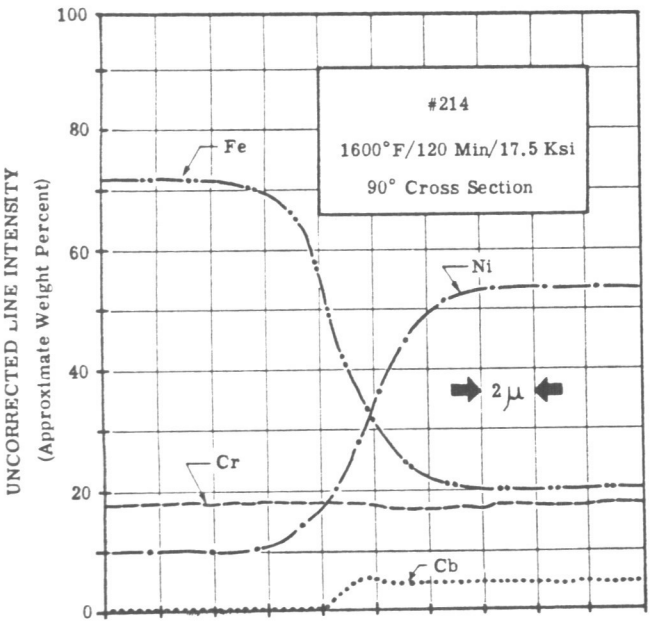
FIGURE 39: MICROHARDNESS TRAVERSE OF 321 STAINLESS STEEL TO INCONEL 718 DIFFUSION WELD. 90° CROSS-SECTION. ETCHED



2A206811



2A206810



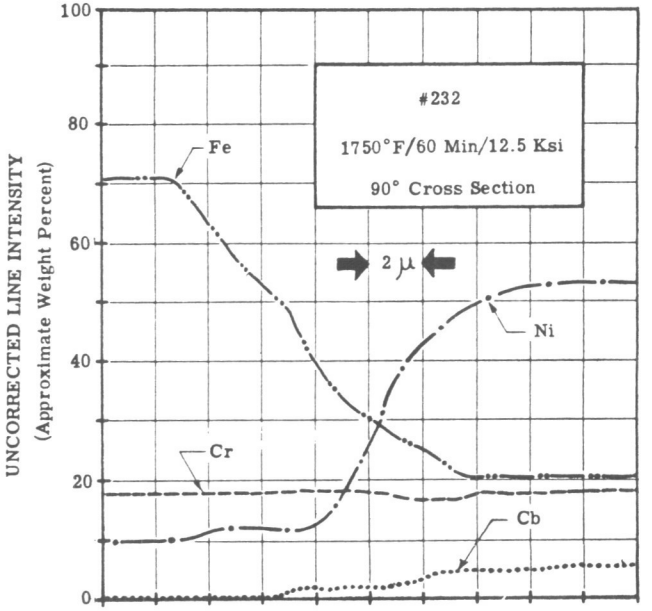
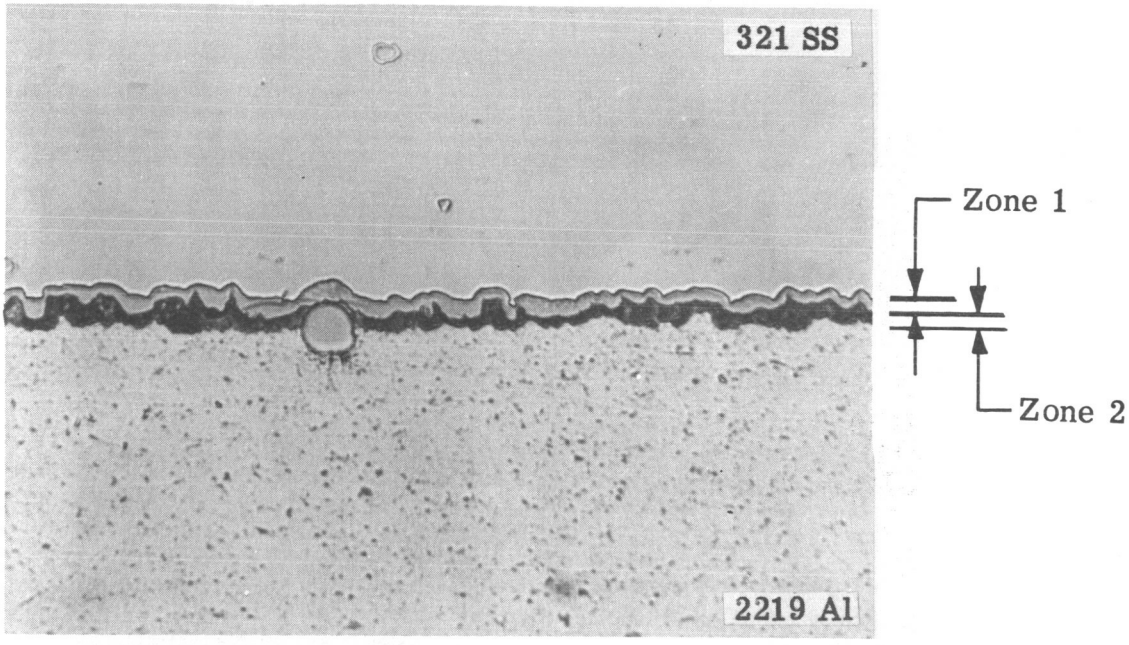
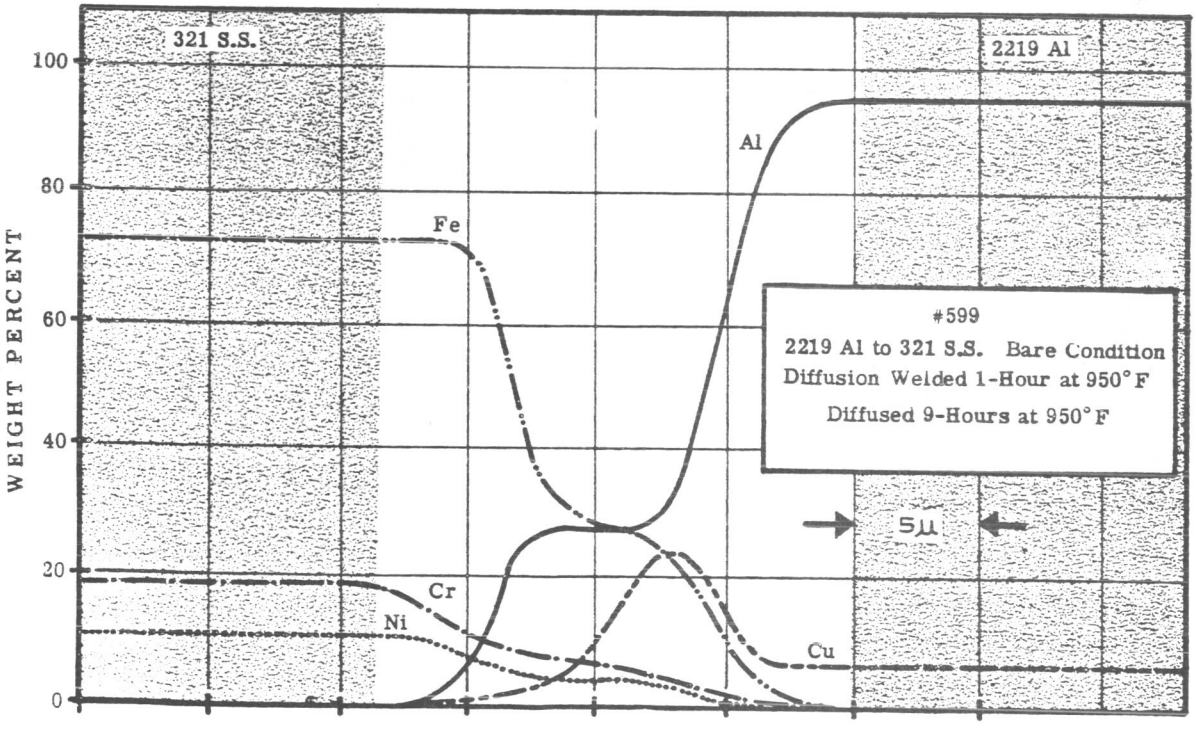


FIGURE 40: MICROPROBE OF 321 S.S./Inconel 718 DIFFUSION WELDS.



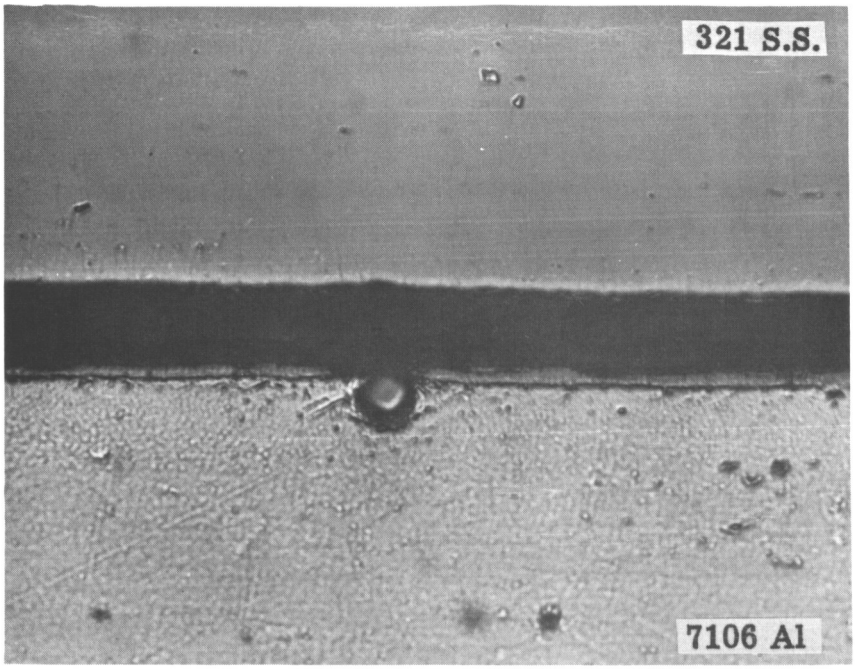
500X Etched 2A223649

(a) Microstructure Showing Tungsten Marker
90° Cross Section



(b) Microprobe Analysis
90° Cross Section

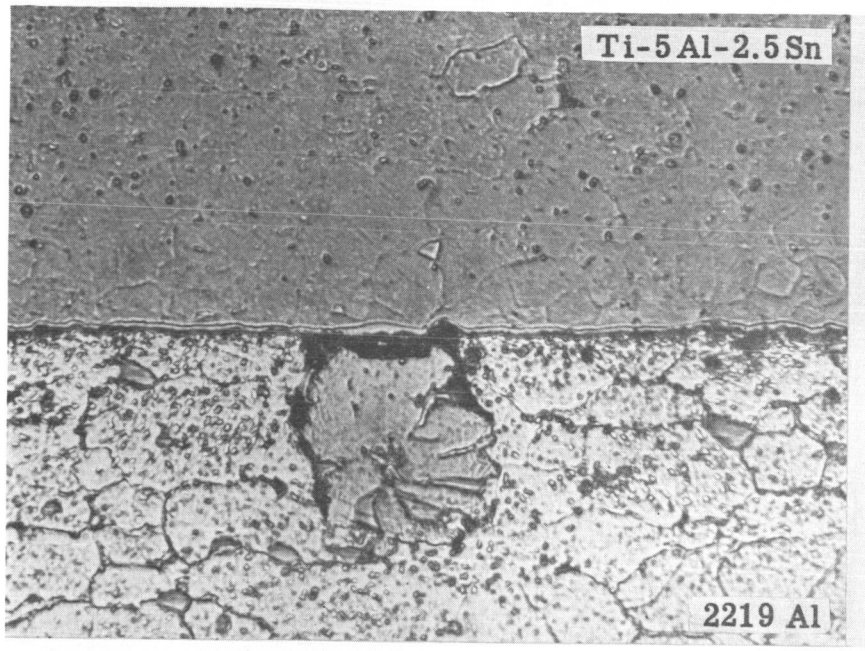
FIGURE 41: MICROSTRUCTURE AND MICROPROBE ANALYSIS OF 2219 ALUMINUM ALLOY TO 321 STAINLESS STEEL DIFFUSION SPECIMEN AFTER 10 HOURS AT 950°F



500X Unetched 2A223654

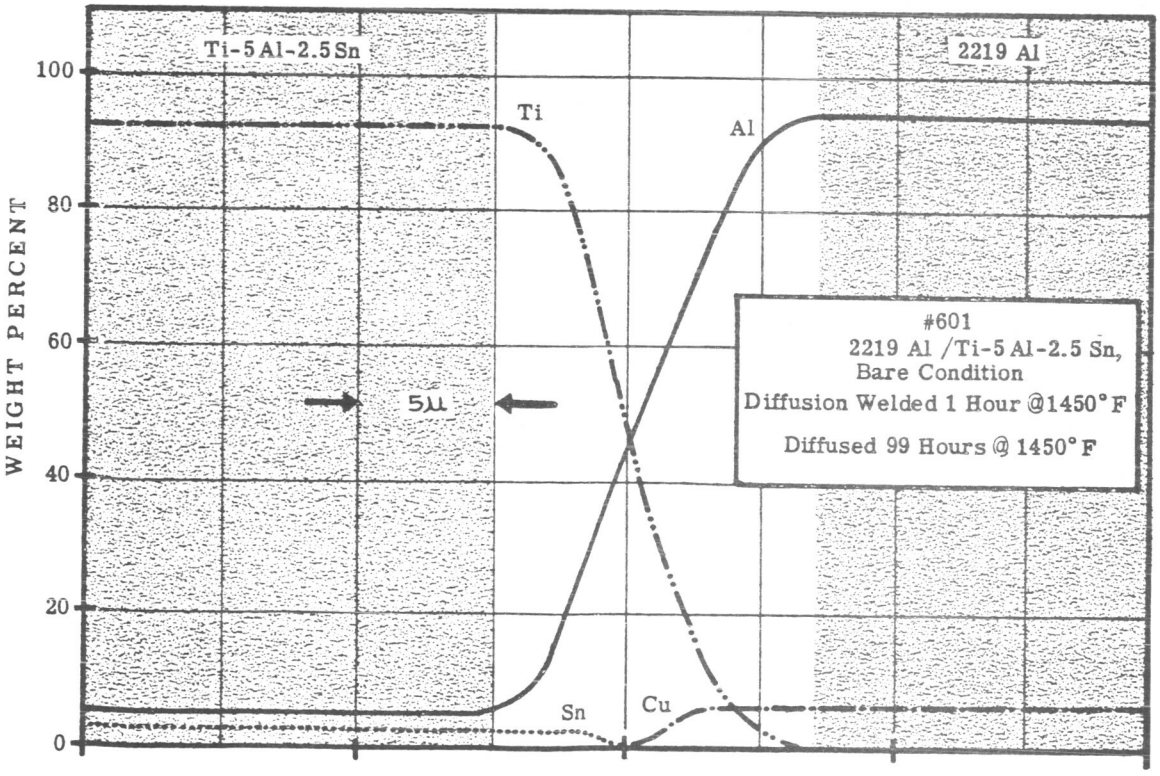
#600 Diffusion Welded 1 Hour at 950°F
Diffused 99 Hours at 860°F

FIGURE 42: MICROSTRUCTURE OF FRACTURED 7106 ALUMINUM ALLOY TO 321 STAINLESS STEEL DIFFUSION SPECIMEN



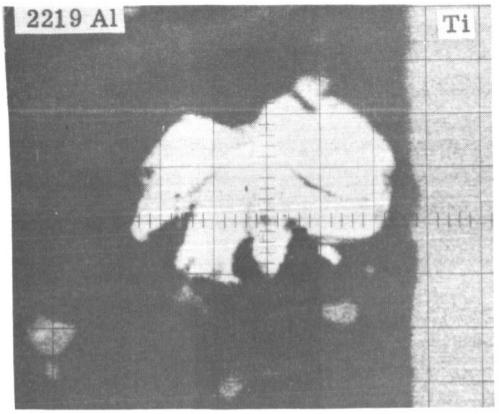
500X Etched 2A223655

(a) Microstructure Showing Tungsten Marker
90° Cross Section

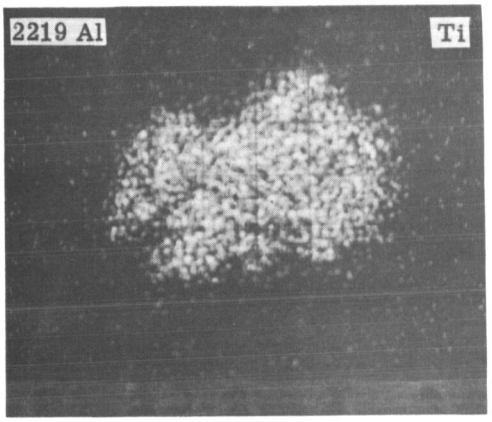


(b) Microprobe Analysis
90° Cross Section

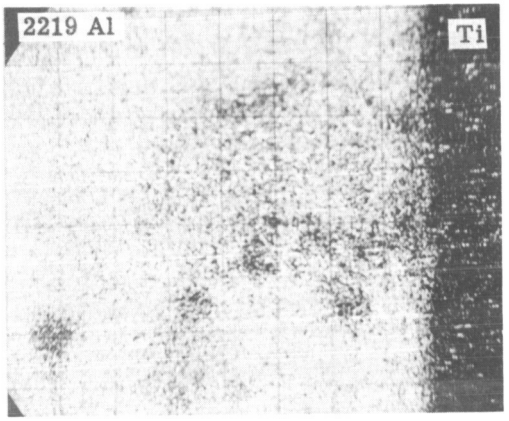
FIGURE 43: MICROSTRUCTURE AND MICROPROBE ANALYSIS OF 2219 ALUMINUM ALLOY TO Ti-5Al-2.5Sn ALLOY DIFFUSION SPECIMEN AFTER 100-HOURS AT 950°F



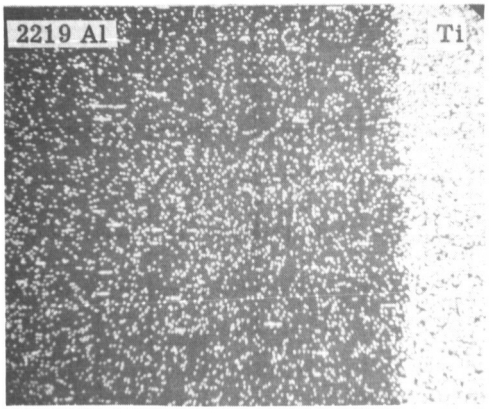
Back Scattered Electrons



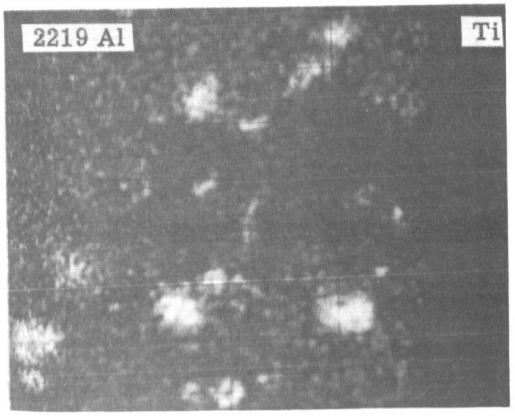
Tungsten X-Ray Fluorescence



Aluminum X-Ray Fluorescence



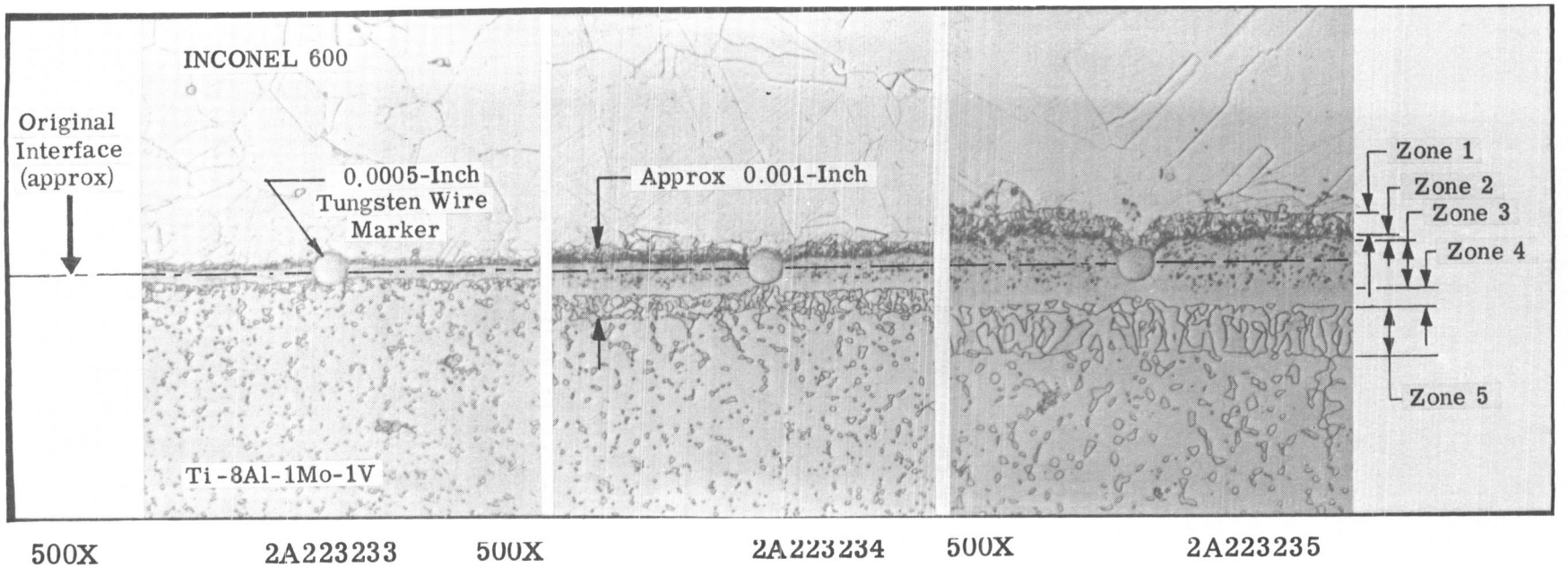
Tin X-Ray Fluorescence



Copper X-Ray Fluorescence

All Photos at 800X

FIGURE 44: MICROPROBE PHOTOGRAPHS OF TUNGSTEN MARKER IN 2219 ALUMINUM ALLOY TO Ti 5Al-2.5 Sn ALLOY DIFFUSION SPECIMEN AFTER 100 HOURS AT 950°F



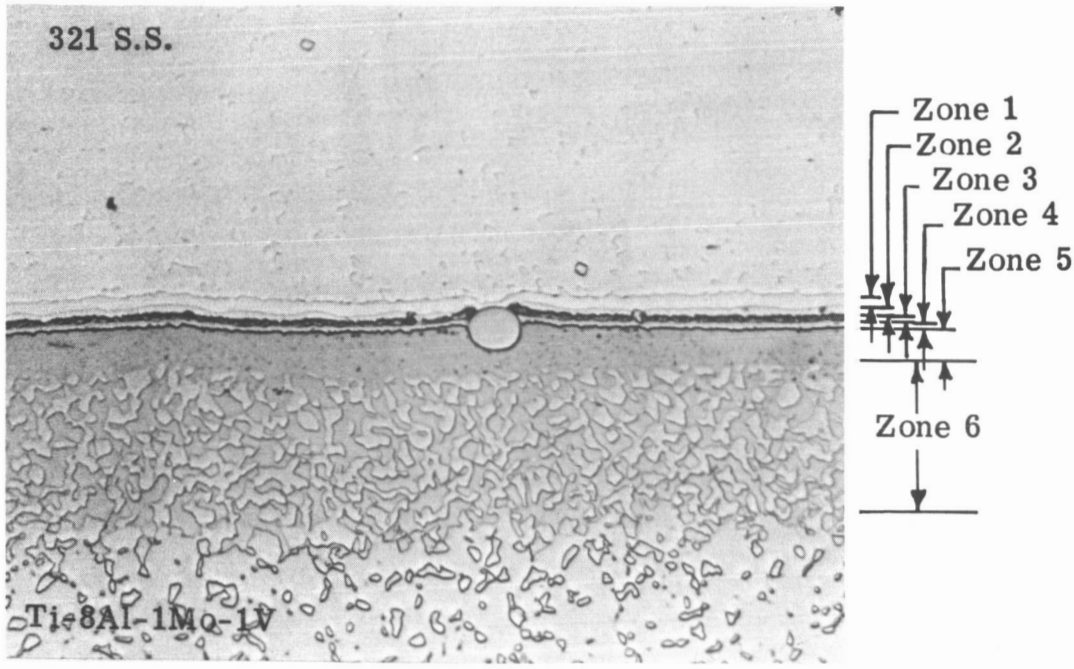
(a) As-Welded

(b) Diffusion Treated 1450°F/ 9 Hr.

(c) Diffusion Treated 1450°F/ 99 Hr.

#483 Diffusion Welded 1450°F/ 20 ksi/ 1 Hr.

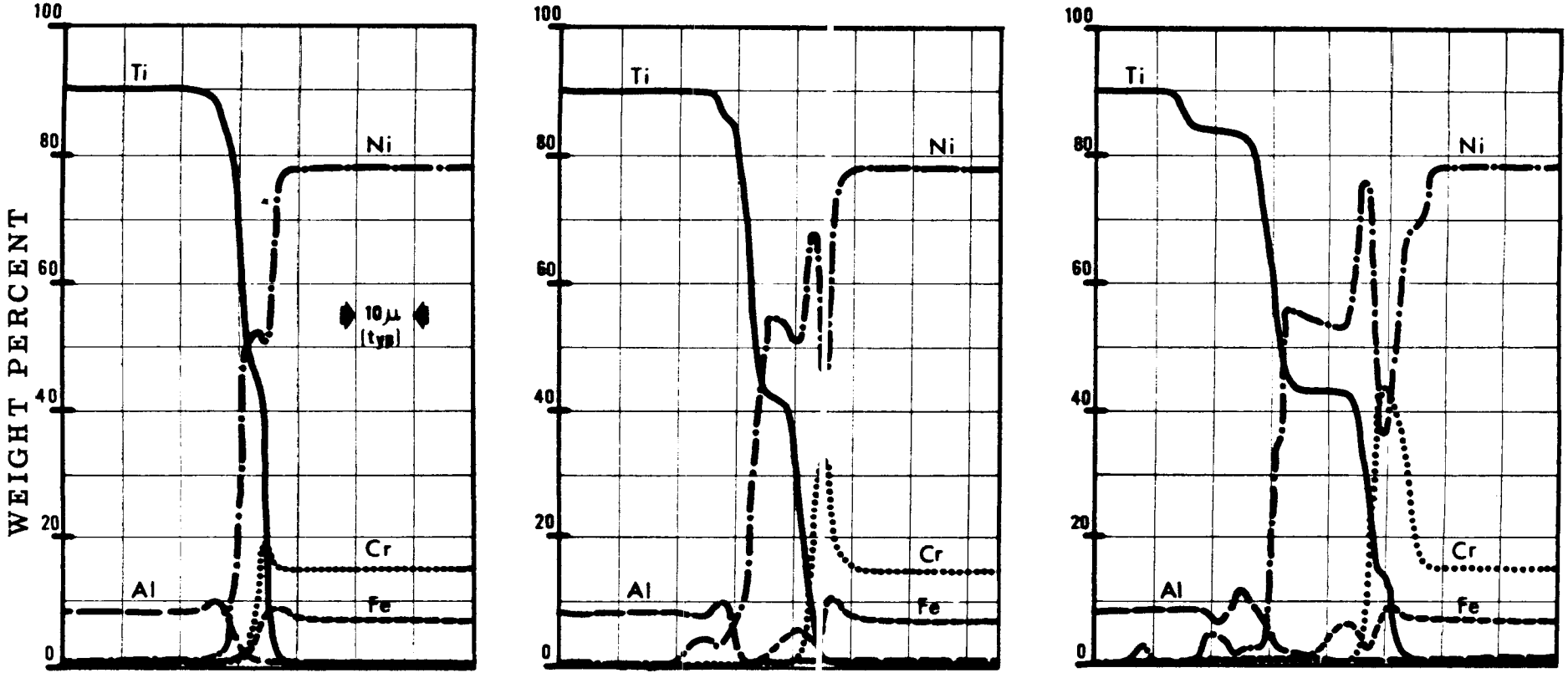
FIGURE 45: MICROSTRUCTURES OF INCONEL 600 to Ti-8Al-1Mo-1V DIFFUSION WELDS CONTAINING TUNGSTEN WIRE MARKERS



#484 1450°F/20 ksi/60min

Diffusion Treated 1450°F/ 99 hr.

FIGURE 46: MICROSTRUCTURE OF 321 STAINLESS STEEL TO Ti-8Al-1 Mo-1V DIFFUSION WELD CONTAINING TUNGSTEN WIRE MARKERS.

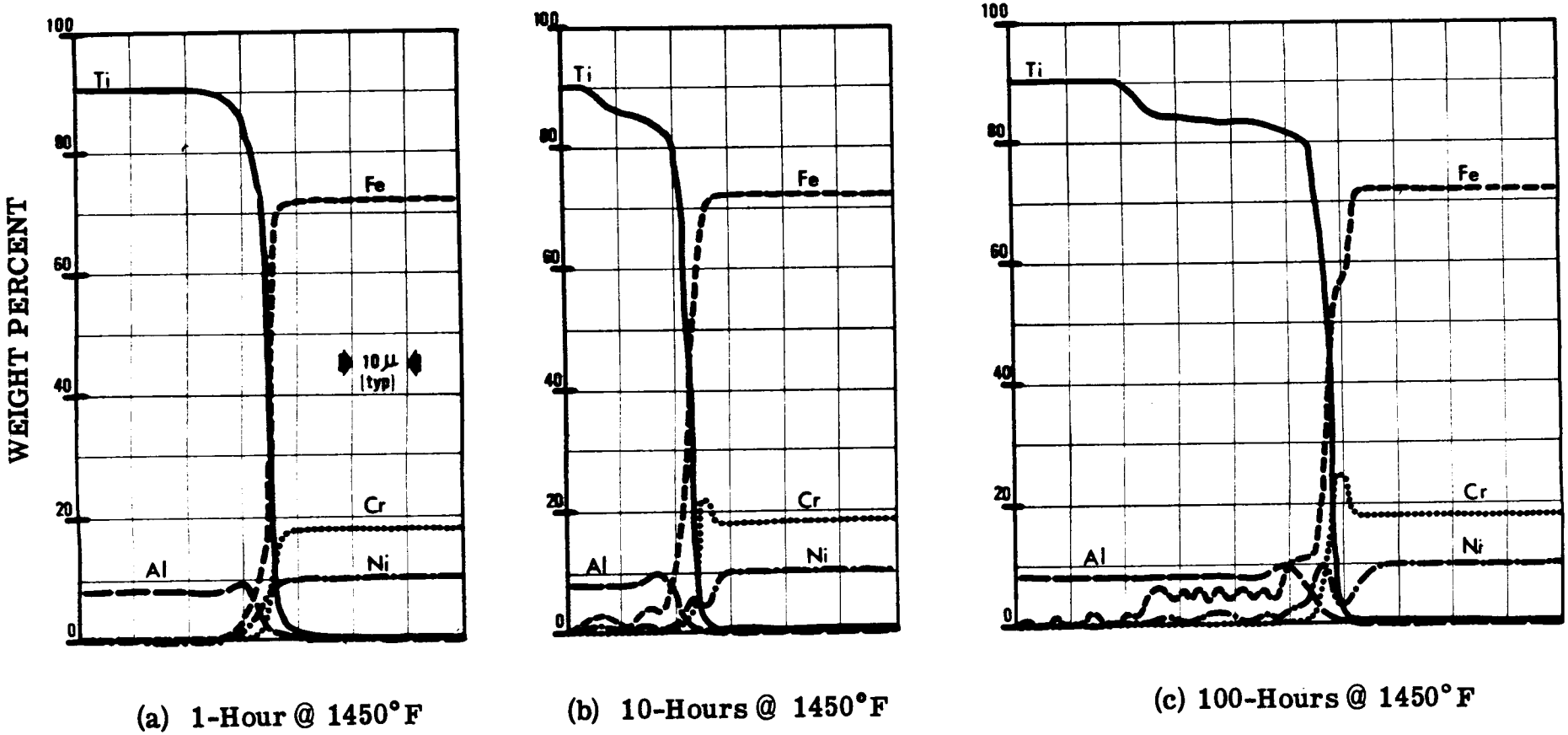


(a) 1-Hour @ 1450°F

(b) 10-Hours @ 1450°F

(c) 100-Hours @ 1450°F

FIGURE 47: MICROPROBE ANALYSES OF INCONEL 600 TO Ti-8Al-1Mo-1V DIFFUSION SPECIMENS

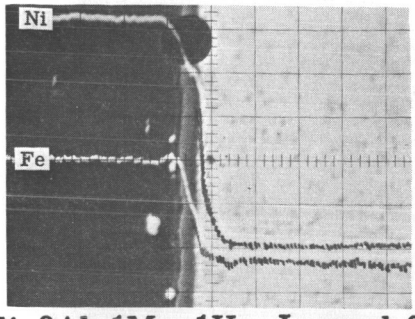


(a) 1-Hour @ 1450°F

(b) 10-Hours @ 1450°F

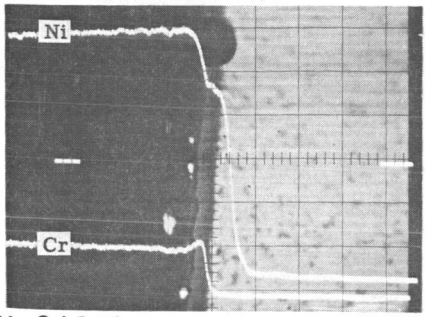
(c) 100-Hours @ 1450°F

FIGURE 48: MICROPROBE ANALYSES OF 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V DIFFUSION SPECIMENS

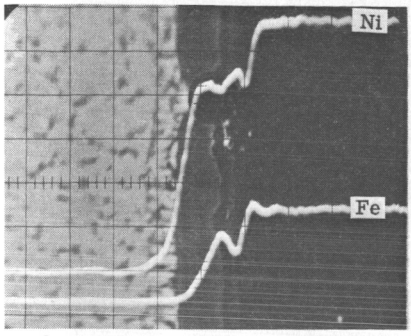


Ti-8Al-1Mo-1V Inconel 600

1-Hour @ 1450°F

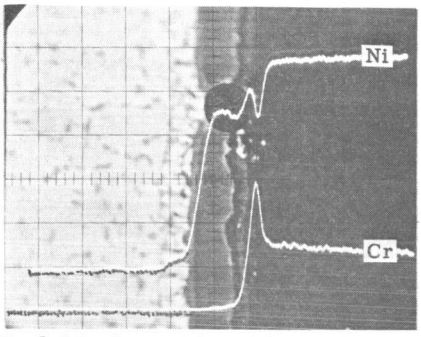


Ti-8Al-1Mo-1V Inconel 600

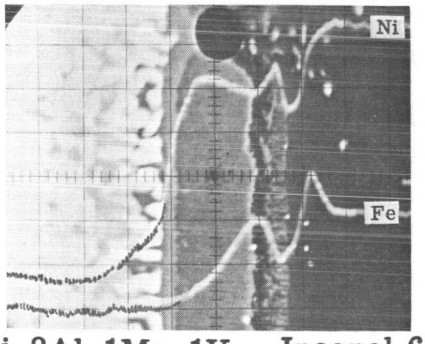


Ti-8Al-1Mo-1V Inconel 600

10 Hours @ 1450°F

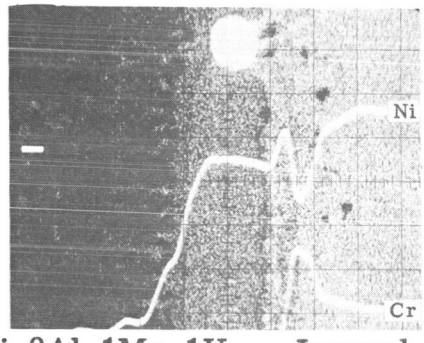


Ti-8Al-1Mo-1V Inconel 600



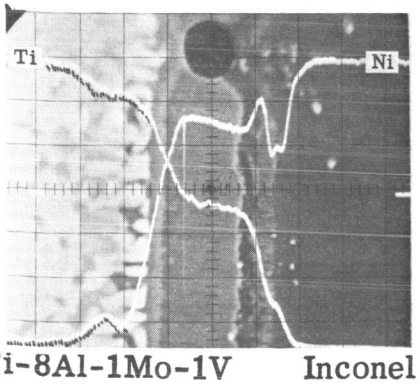
Ti-8Al-1Mo-1V Inconel 600

100-Hours @ 1450°F



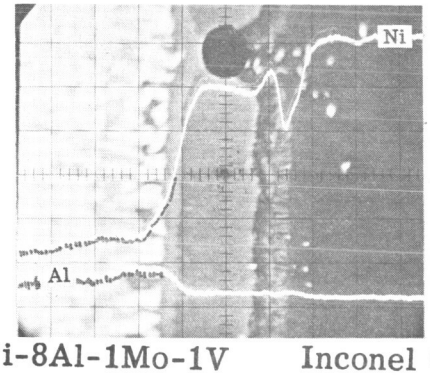
Ti-8Al-1Mo-1V Inconel 600

Back Scattered Electrons



Ti-8Al-1Mo-1V Inconel 600

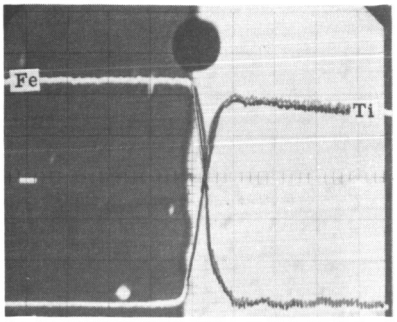
100-Hours @ 1450°F



Ti-8Al-1Mo-1V Inconel 600

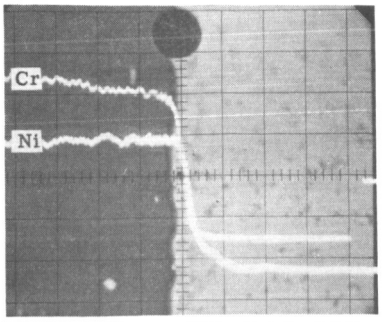
Photos Show Sample Current (Collected Electrons) Scans and Superimposed Concentration Profiles Except as Noted. All Photos at 800X

FIGURE 49: MICROPROBE PHOTOGRAPHS OF INCONEL 600 TO Ti-8Al-1Mo-1V DIFFUSION SPECIMENS

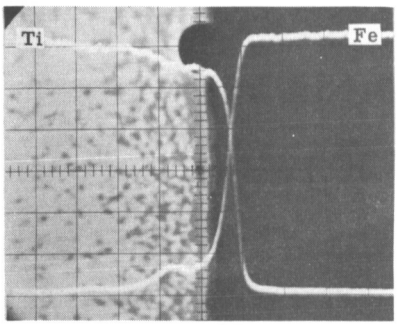


321 S.S. Ti-8Al-1Mo-1V

1-Hour
@ 1450°F

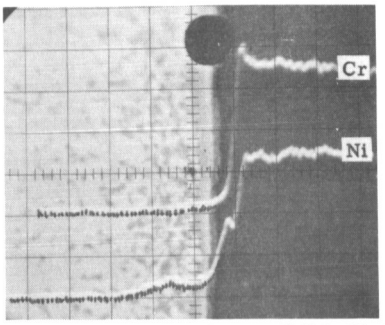


321 S.S. Ti-8Al-1Mo-1V

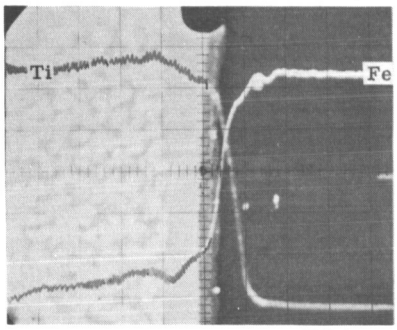


Ti-8Al-1Mo-1V 321 S.S.

10-Hours
@ 1450°F

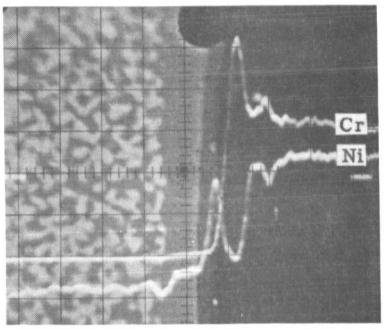


Ti-8Al-1Mo-1V 321 S S

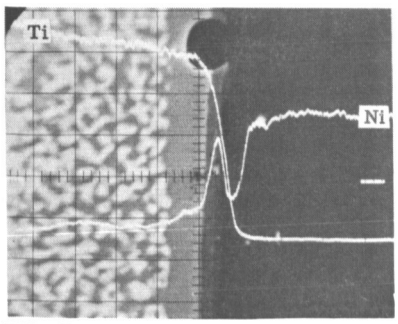


Ti-8Al-1Mo-1V 321 S.S.

100-Hours
@ 1450°F

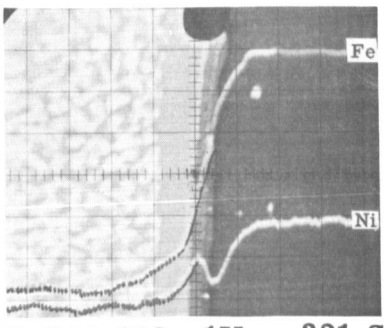


Ti-8Al-1Mo-1V 321S S



Ti-8Al-1Mo-1V 321 S S

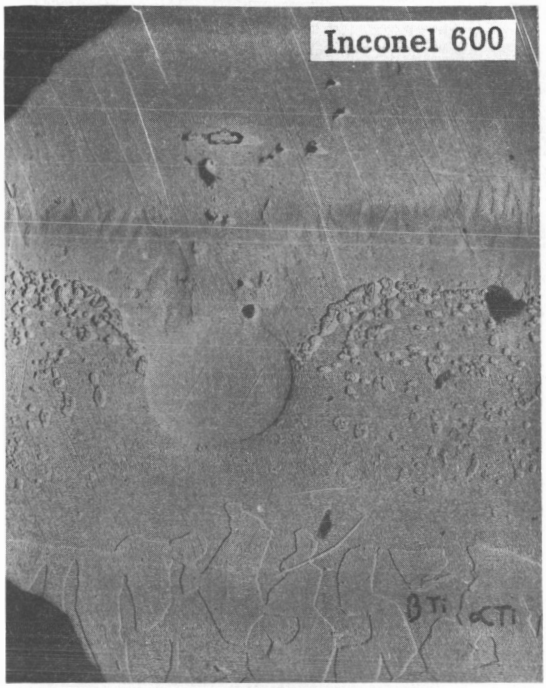
100-Hours
@ 1450°F



Ti-8Al-1Mo-1V 321 S S

Photos Show Sample Current (Collected electrons) Scans and Superimposed Concentration Profiles All Photos @ 800X

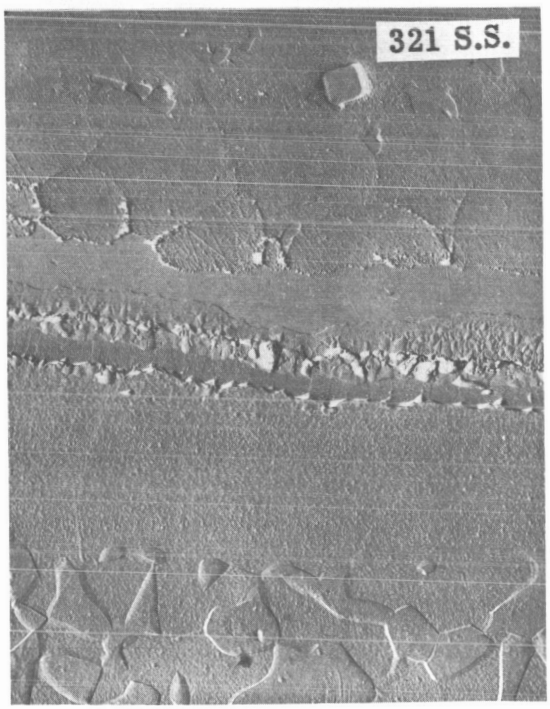
FIGURE 50: MICROPROBE PHOTOGRAPHS OF 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V DIFFUSION SPECIMENS



Zone 1
Zone 2
Zone 3 Ti Ni
Zone 4
Zone 5 Ni- rich βTi+
Al-rich αTi

1570X 4-5-66-1

(a) Inconel 600 to Ti-8Al-1Mo-1V

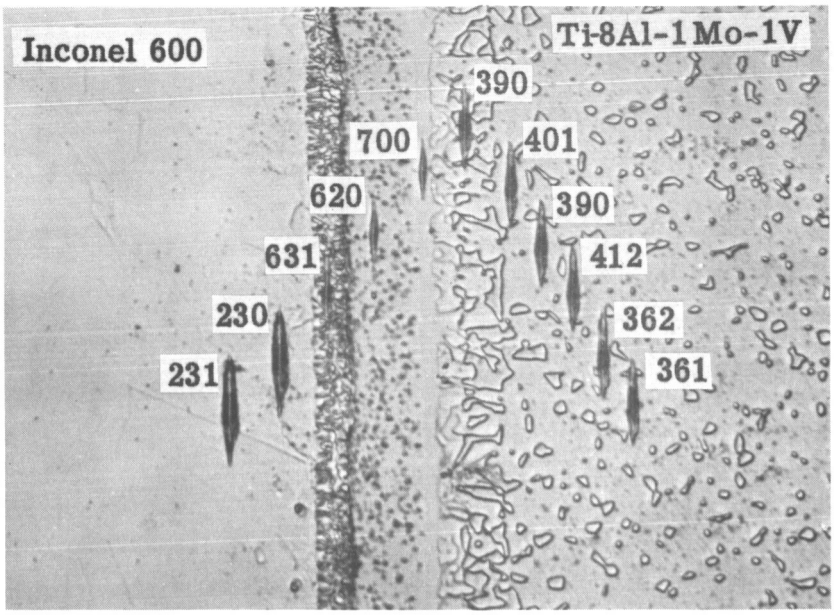


Zone 1
Zone 2
Zone 3
Zone 4
Zone 5 Fe-rich β Ti
Zone 6 Fe-rich βTi+
Al-rich α Ti

2160X 4-20-66-3

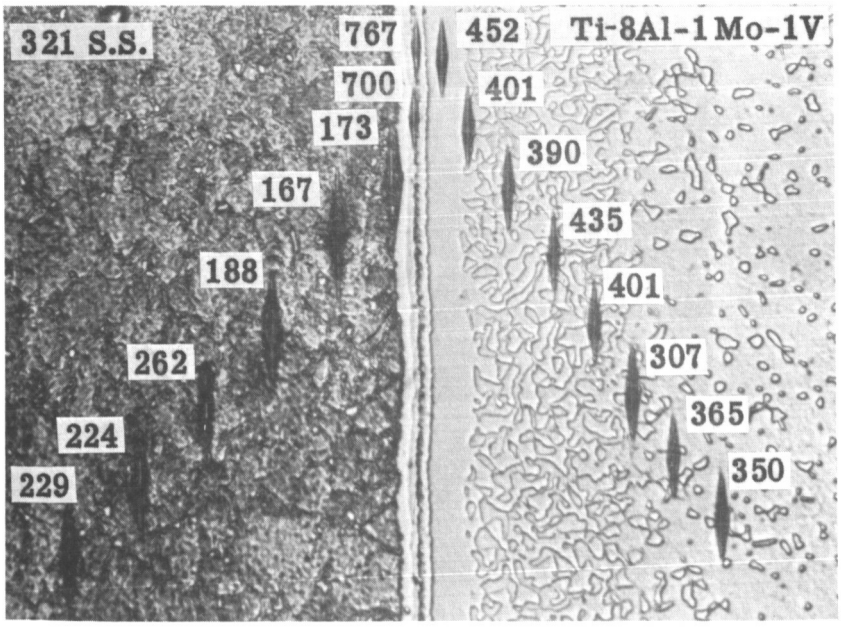
(b) 321 S.S. to Ti-8Al-1Mo-1V

FIGURE 51: ELECTRON MICROSCOPE PHOTOGRAPHS OF INCONEL 600 TO Ti-8Al-1Mo-1V AND 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V DIFFUSION SPECIMENS AFTER 100 HOURS AT 1450°F



500X Etched 2A230088

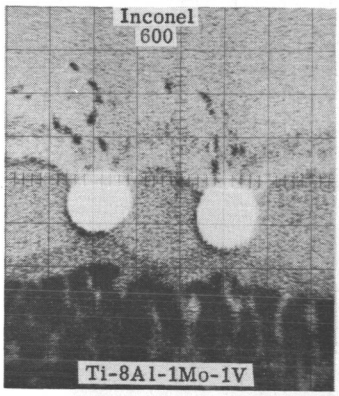
(a) #483 Inconel 600 To Ti 8Al-1Mo-1V
90° Cross Section



500X Etched 2A230087

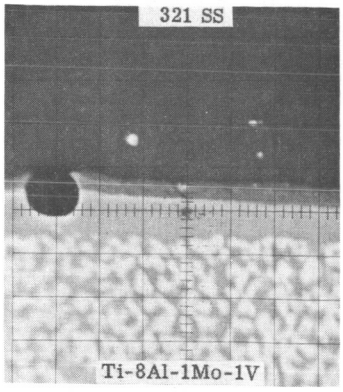
(b) #484 321 S.S. To Ti 8Al-1Mo-1V
90° Cross Section

FIGURE 52: MICROHARDNESS TRAVERSE OF INCONEL 600 TO Ti 8Al-1Mo-1V AND 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V DIFFUSION SPECIMENS EXPOSED 100 HOURS AT 1450°F



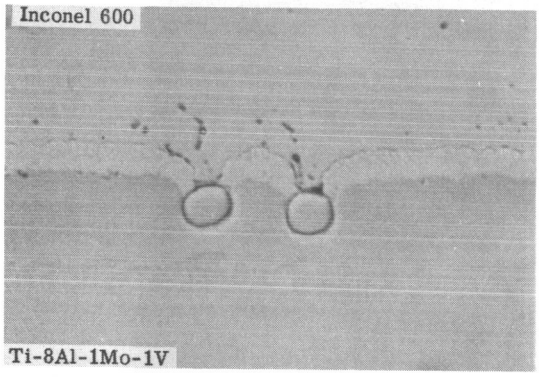
1000X

Back Scattered Electrons
Microprobe Photo

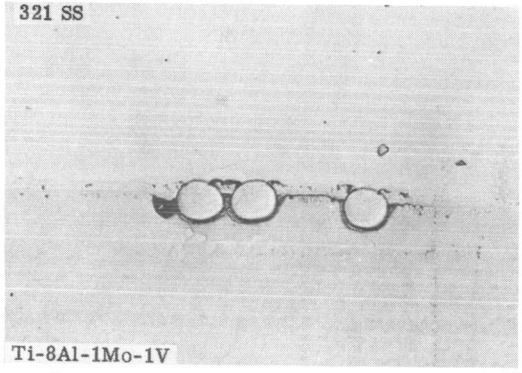


800X

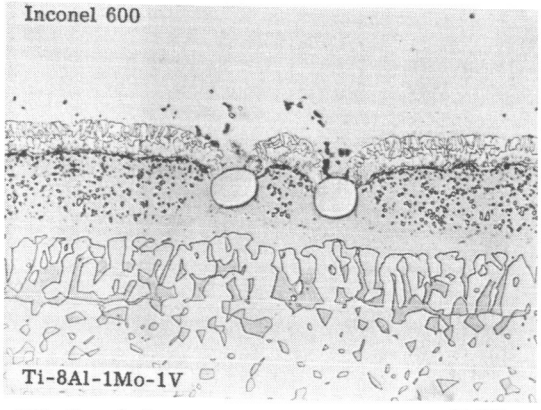
Sample Current
Microprobe Photo



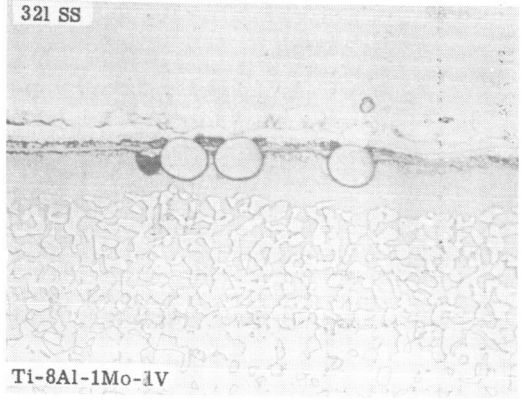
Unetched 750X



Unetched 750X

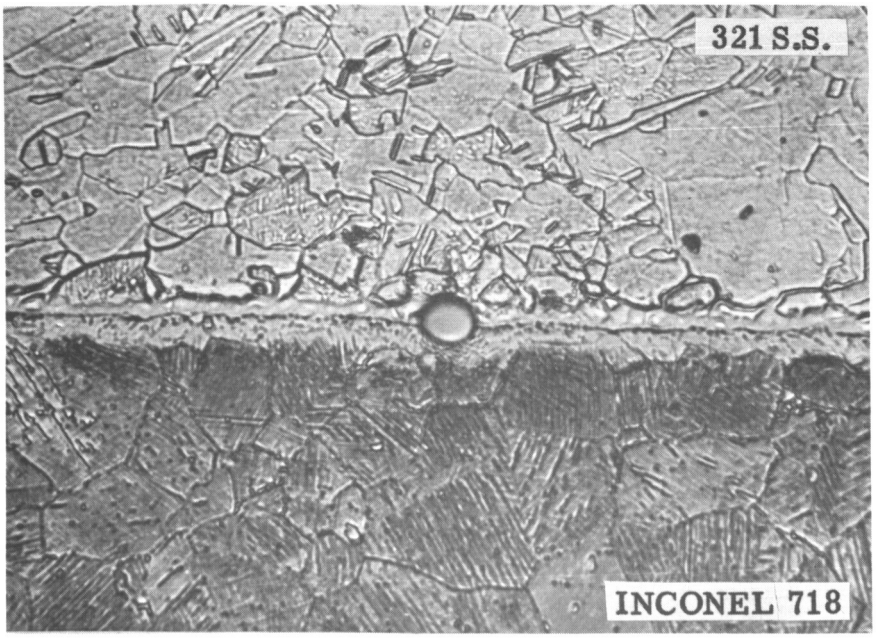


Etched for Titanium 750X



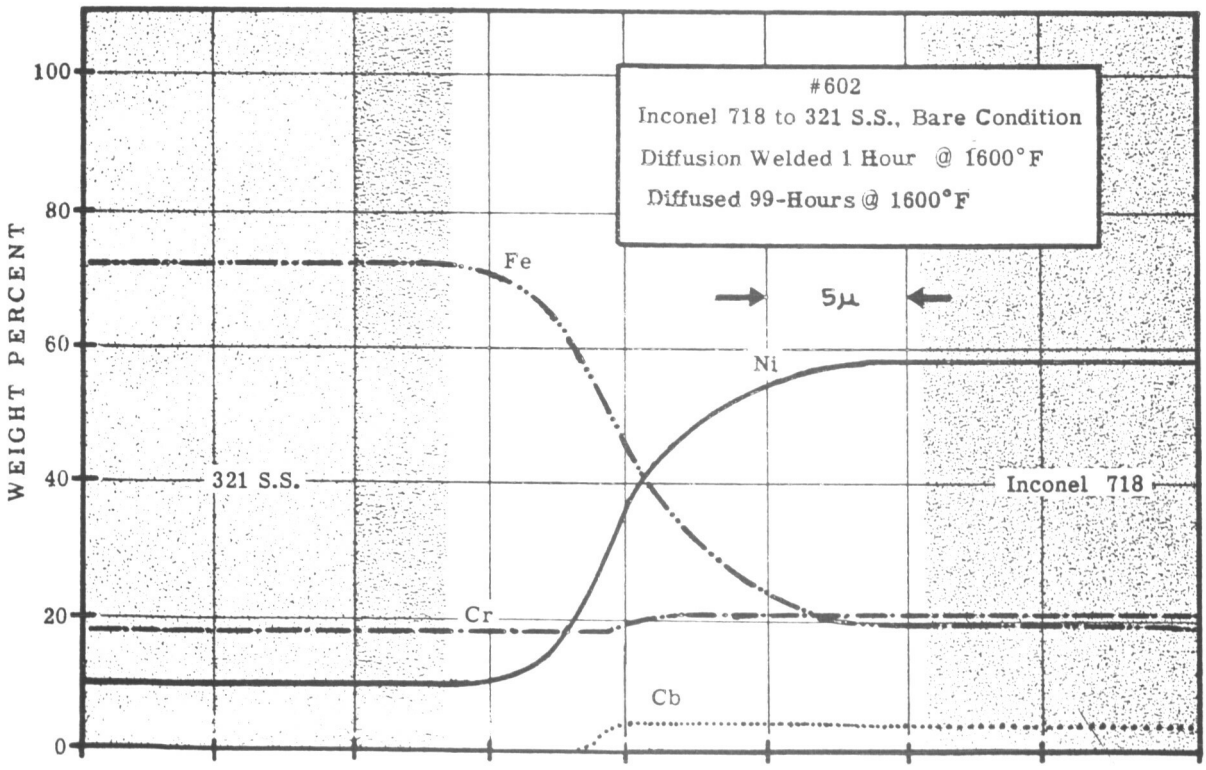
Etched for Titanium 750X

FIGURE 53: INCONEL 600 TO Ti-8Al-1Mo-1V AND 321 S.S. TO Ti-8Al-1Mo-1V DIFFUSION SPECIMENS EXPOSED 100-HOURS AT 1450°F.



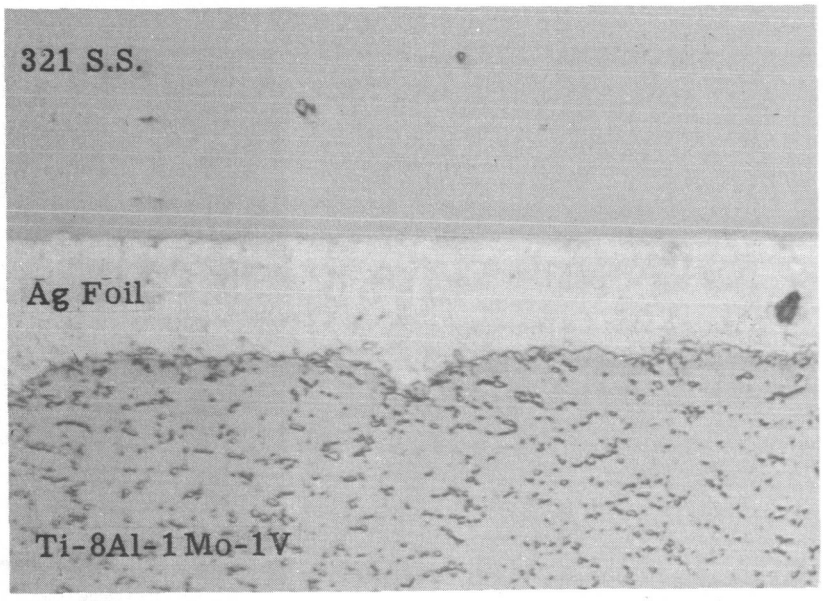
500X Etched 2A223645

(a) Microstructure Showing Tungsten Marker
90° Cross Section



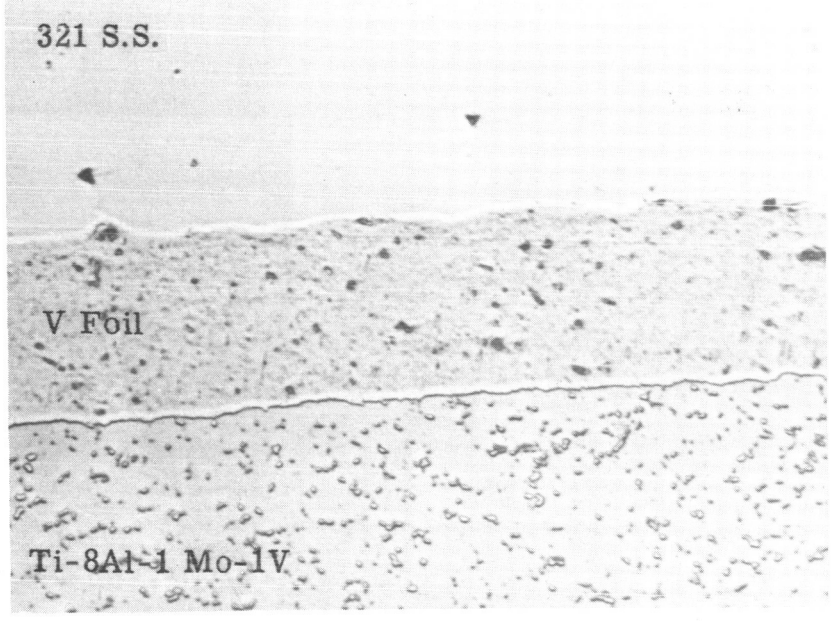
(b) Microprobe Analysis
90°Cross Section

FIGURE 54: MICROSTRUCTURE AND MICROPROBE ANALYSIS OF INCONEL 718 TO 321 STAINLESS STEEL DIFFUSION SPECIMEN AFTER 100 HOURS AT 1600°F



500X 2A223254

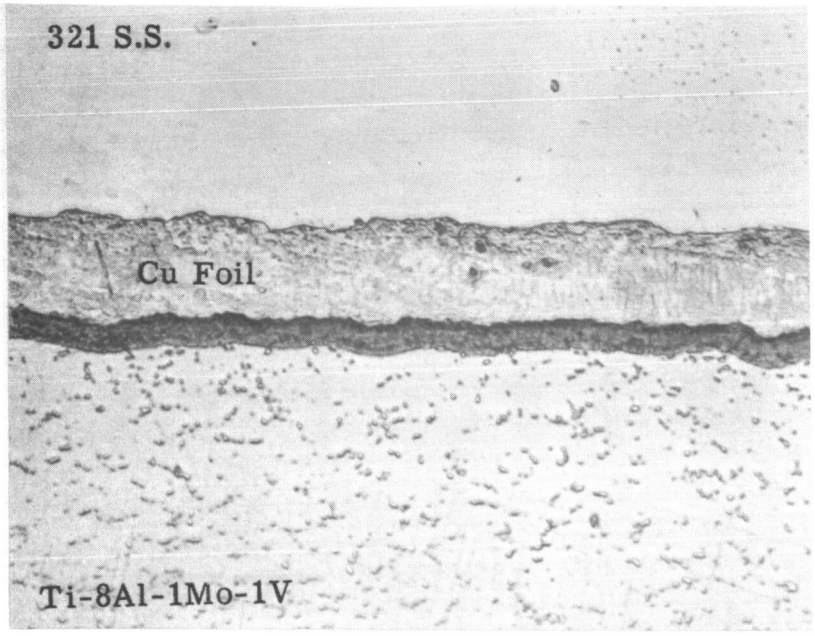
(a) #351 1500°F/20 ksi/10 min Etched for Ti
SILVER FOIL



500X 2A223295

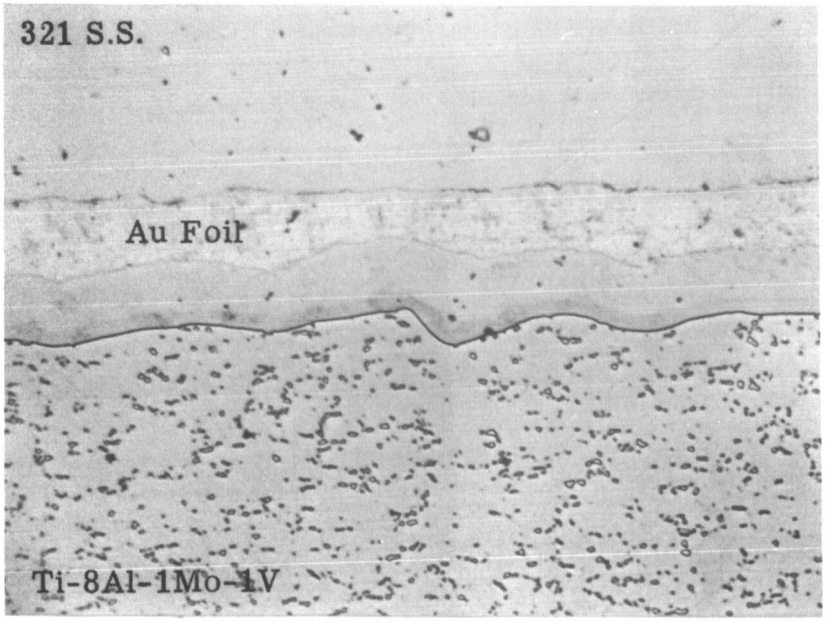
(b) #396 1500°F/20 ksi/10 min Etched For Ti
VANADIUM FOIL

FIGURE 55: PHOTOMICROGRAPHS SHOWING THE APPEARANCE OF DIFFUSION WELD BETWEEN 321 STAINLESS STEEL AND Ti-8Al-1Mo-1V USING SILVER AND VANADIUM FOIL DIFFUSION AIDS.



500X 2A223281

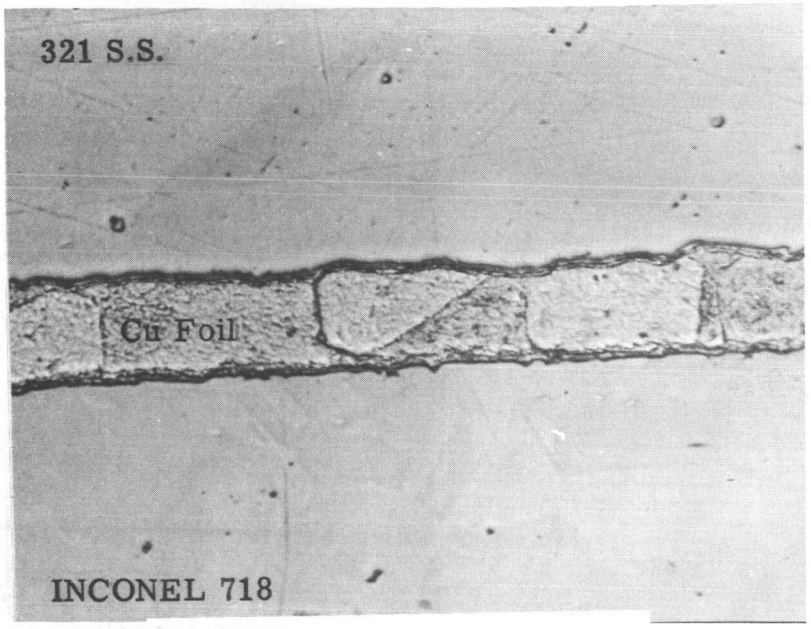
(a) #375 1300°F/20 ksi/60 min. Etched
COPPER FOIL



500X 2A223269

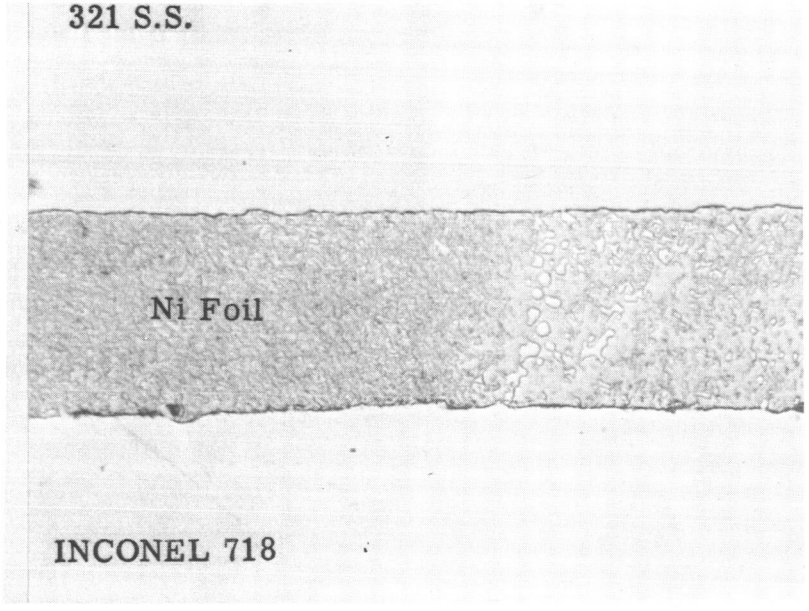
(b) #357 1300°F/20 ksi/10 min. Etched
GOLD FOIL

FIGURE 56: PHOTOMICROGRAPHS SHOWING THE DIFFUSION OF COPPER AND GOLD INTO Ti-8Al-1Mo-1V



500X 2A223282

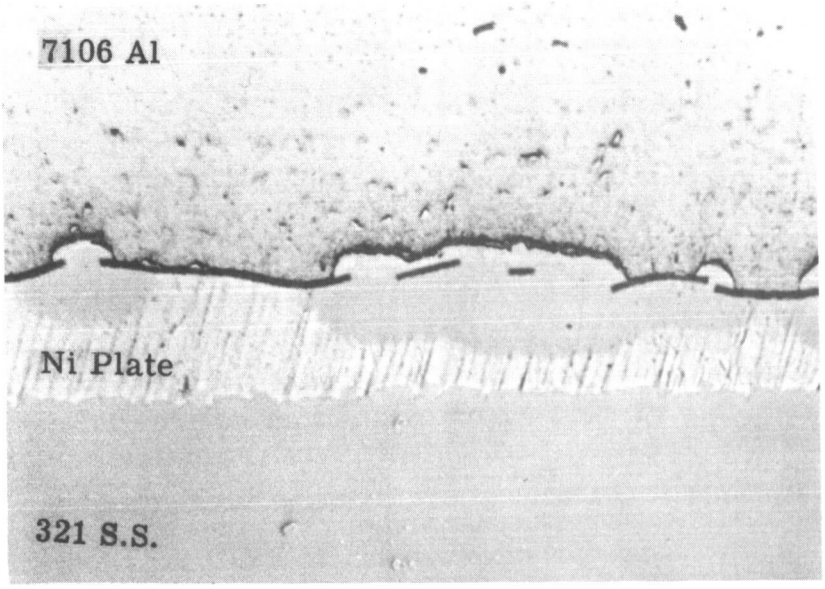
(a) #376 1300°F/20 ksi/60 min. Etched for Cu
COPPER FOIL



500X 2A223278

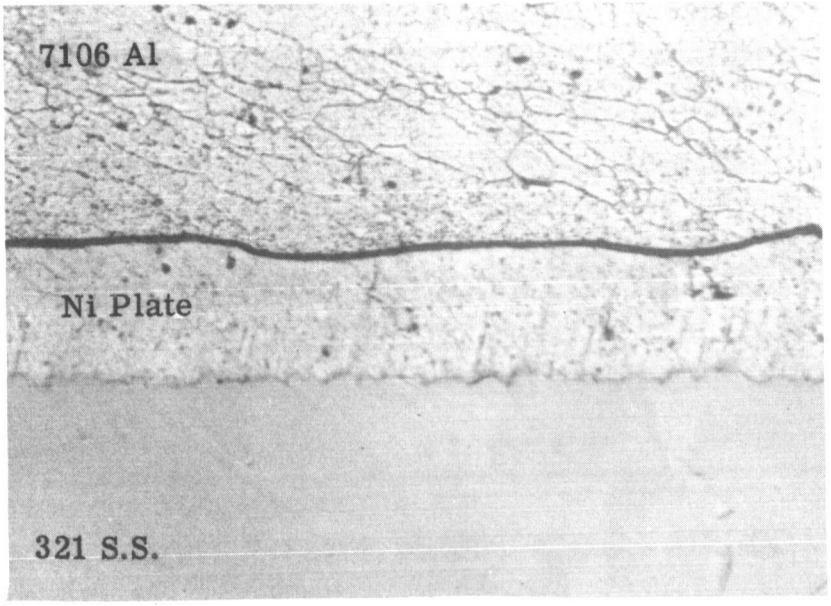
(b) #370 1300°F/20 ksi/60 min. Etched for Ni
NICKEL FOIL

FIGURE 57: PHOTOMICROGRAPHS SHOWING THE APPEARANCE OF DIFFUSION WELD BETWEEN 321 STAINLESS STEEL AND INCONEL 718 WITH COPPER AND NICKEL FOIL DIFFUSION AIDS



500X 2A223335

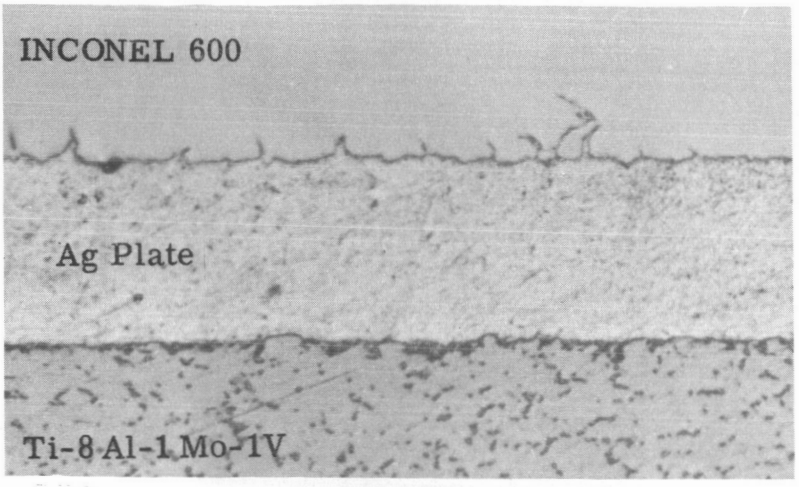
(a) #480 900°F/7.5 ksi/60 min Unetched



500X 2A223339

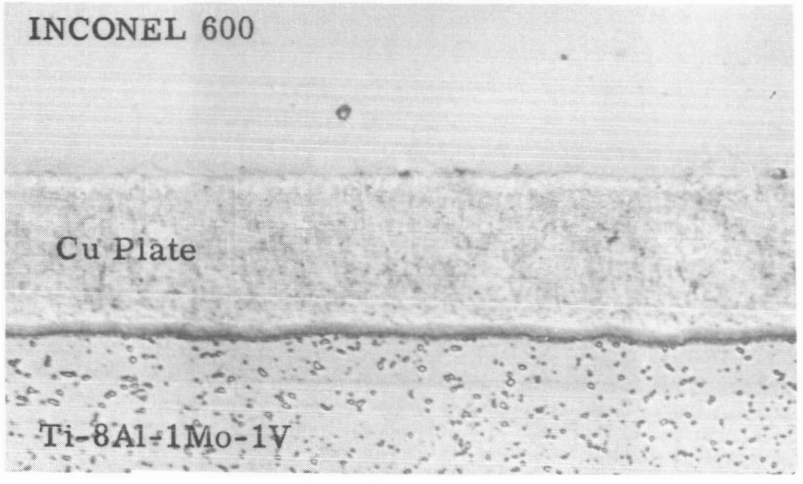
(b) #480 900°/7.5 ksi/60 min Etched for Al

FIGURE 58: PHOTOMICROGRAPH SHOWING THE APPEARANCE OF THE DIFFUSION WELD BETWEEN 7106 ALUMINUM AND 321 STAINLESS STEEL WITH NICKEL PLATING DIFFUSION AID.



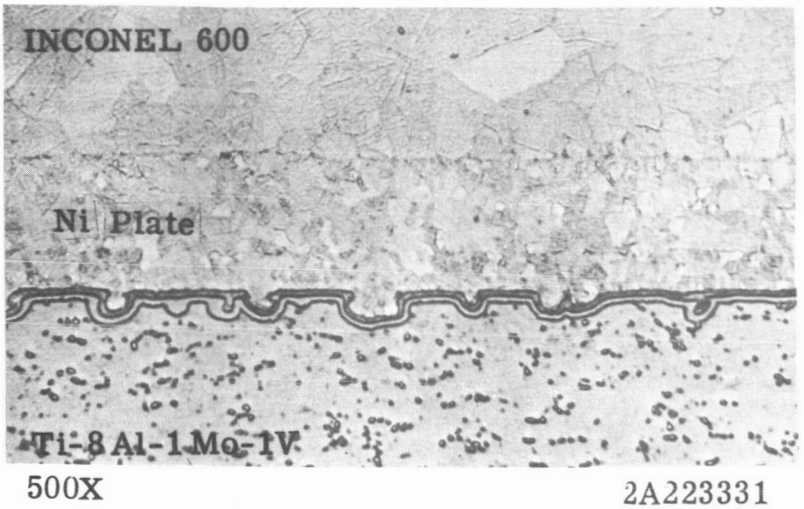
500X 2A223322

(a) #504
1500°F/20 ksi/10 min
SILVER PLATING
Etched for
Ti-8Al-1Mo-1V



500X 2A223324

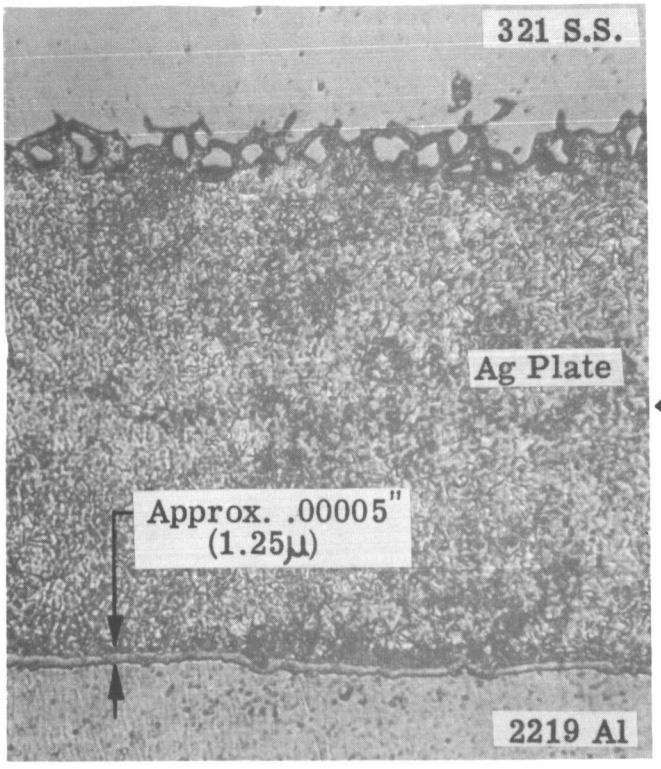
(b) #497
1300°F/20ksi/10 min
COPPER P LATING
Etched for
Ti-8Al-1Mo-1V



500X 2A223331

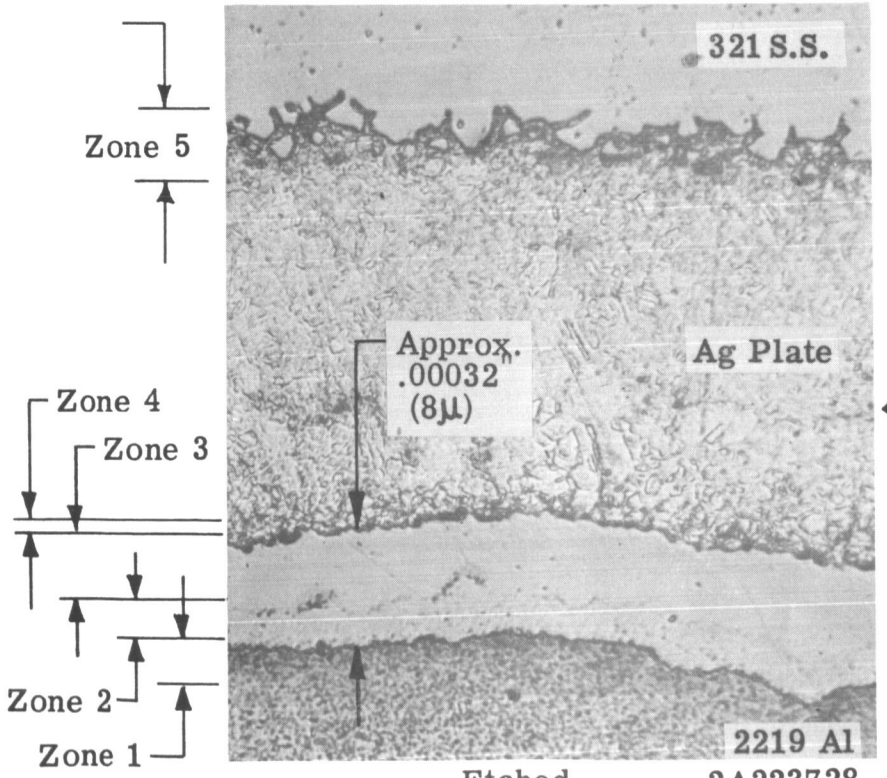
(c) #502
1300°F/20 ksi/10 min
NICKEL PLATING
Etched for
Ti-8Al-1Mo-1V
and
Inconel 600

FIGURE 59: PHOTOMICROGRAPHS SHOWING THE APPEARANCE OF THE DIFFUSION WELDS BETWEEN INCONEL 600 AND Ti-8Al-1Mo-1V WITH SILVER, COPPER AND NICKEL PLATING DIFFUSION AIDS.



500X Etched

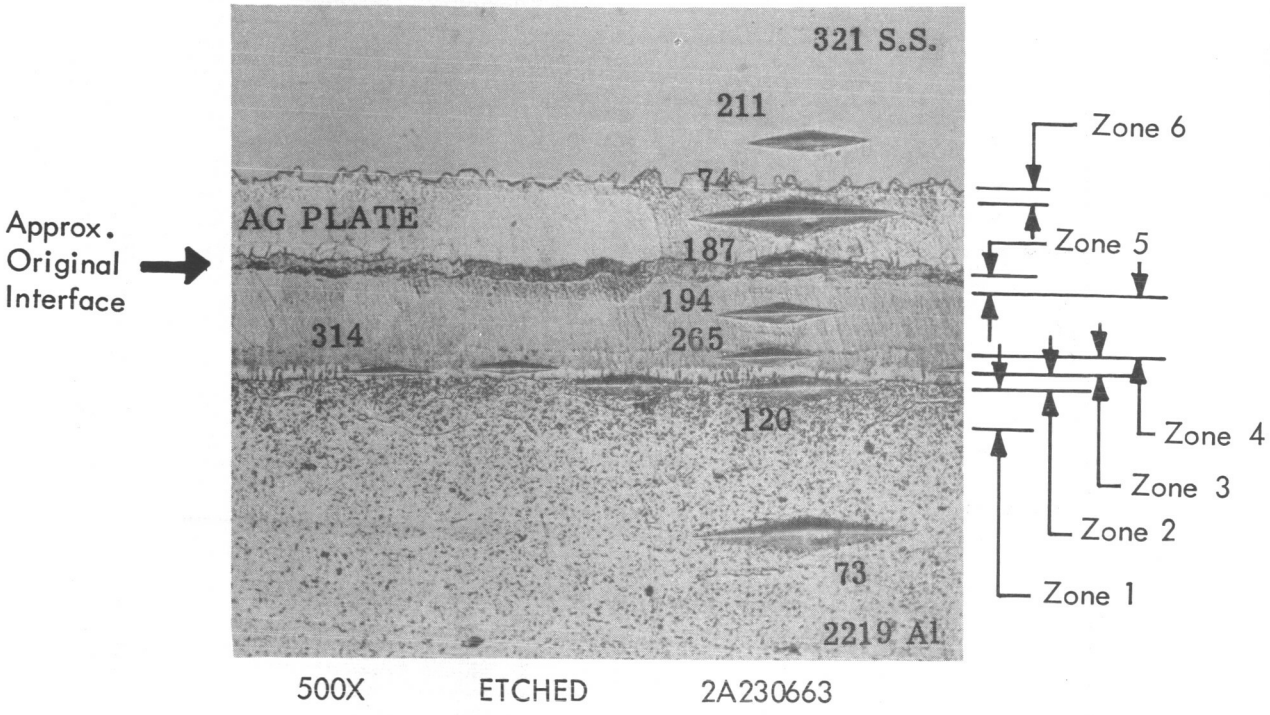
(a) #605 500°F/30 KSI/2 Hours



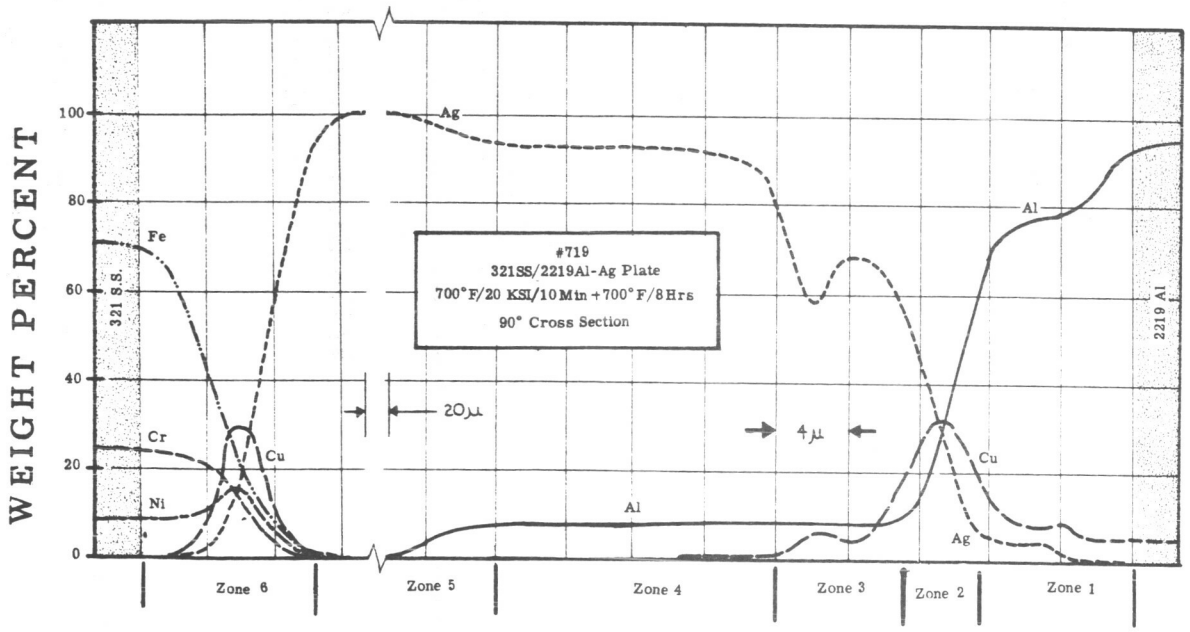
500X Etched 2A223728

(b) #611 700°F/20 KSI/1 Hour

FIGURE 60: MICROSTRUCTURE OF 2219-T6 ALLUMINUM ALLOY TO 321 STAINLESS STEEL DIFFUSION WELDS - SILVER ELECTOPLATED 15° Taper Microsections

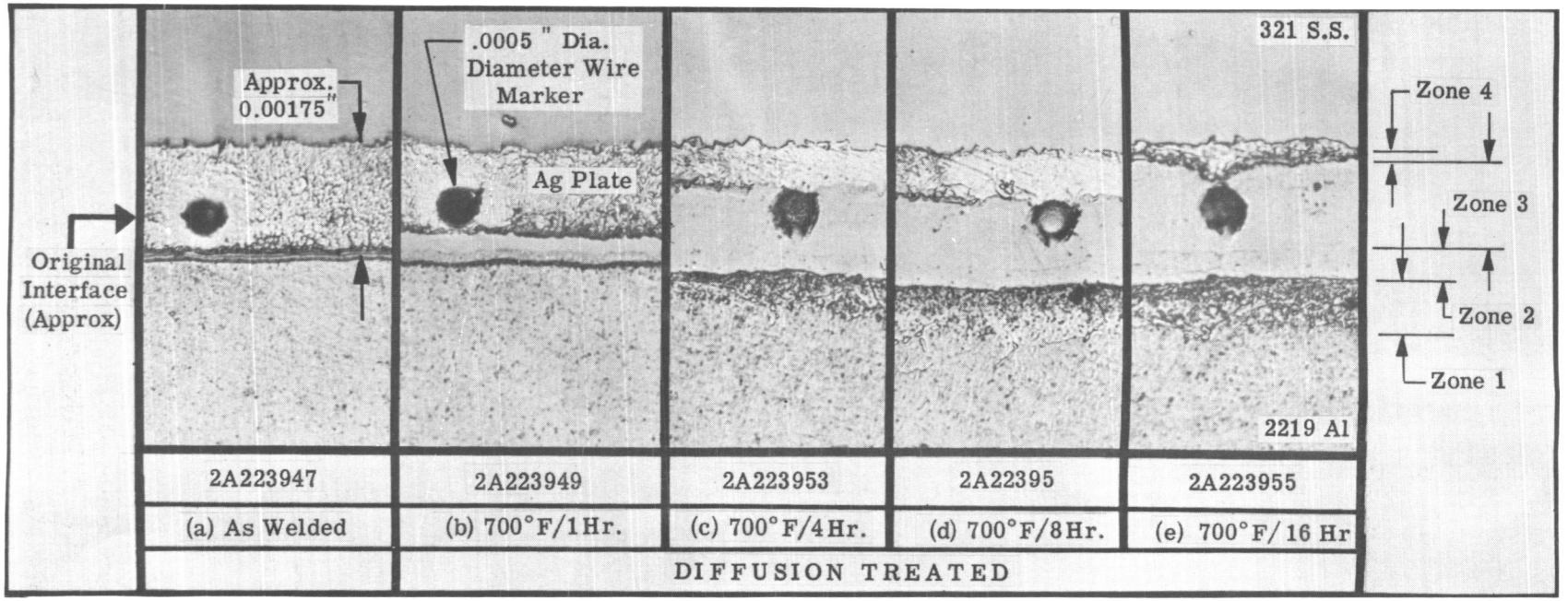


(a) Reichert Microhardness Traverse (KHN) of 321 SS to 2219 Al Diffusion Weld - #719 90° Cross-Section



(b) Microprobe Analysis of 321 SS to 2219 Al Diffusion Weld - #719

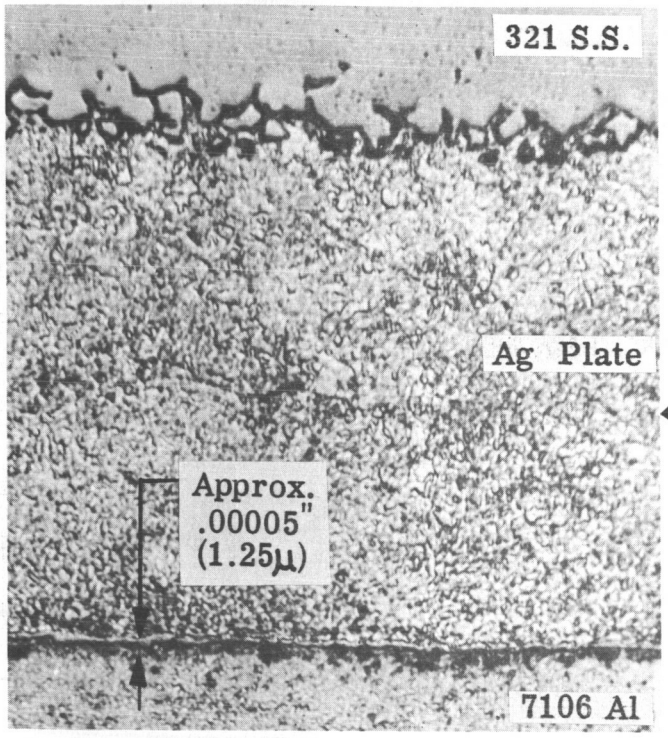
FIGURE 61 - MICROHARDNESS TRAVERSE AND MICROPROBE ANALYSIS OF 321 STAINLESS STEEL TO 2219-T6 ALUMINUM ALLOY DIFFUSION WELDS - SILVER ELECTROPLATED



500X

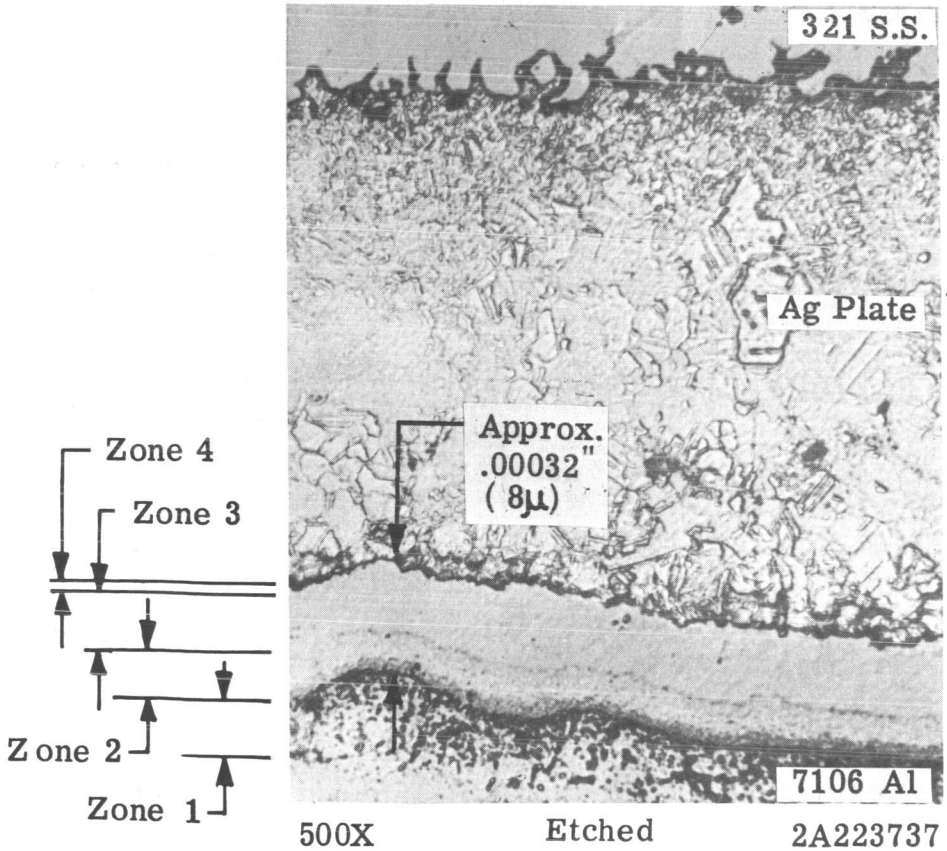
#759 Diffusion Welded 700°F/30 KSI/10 Min.
90° Cross Sections

FIGURE 62: MICROSTRUCTURE OF 321 STAINLESS STEEL TO 2219 - T6 ALUMINUM ALLOY DIFFUSION WELDS CONTAINING TUNGSTEN WIRE MARKERS - SILVER ELECTROPLATED



500X Etched 2A223731

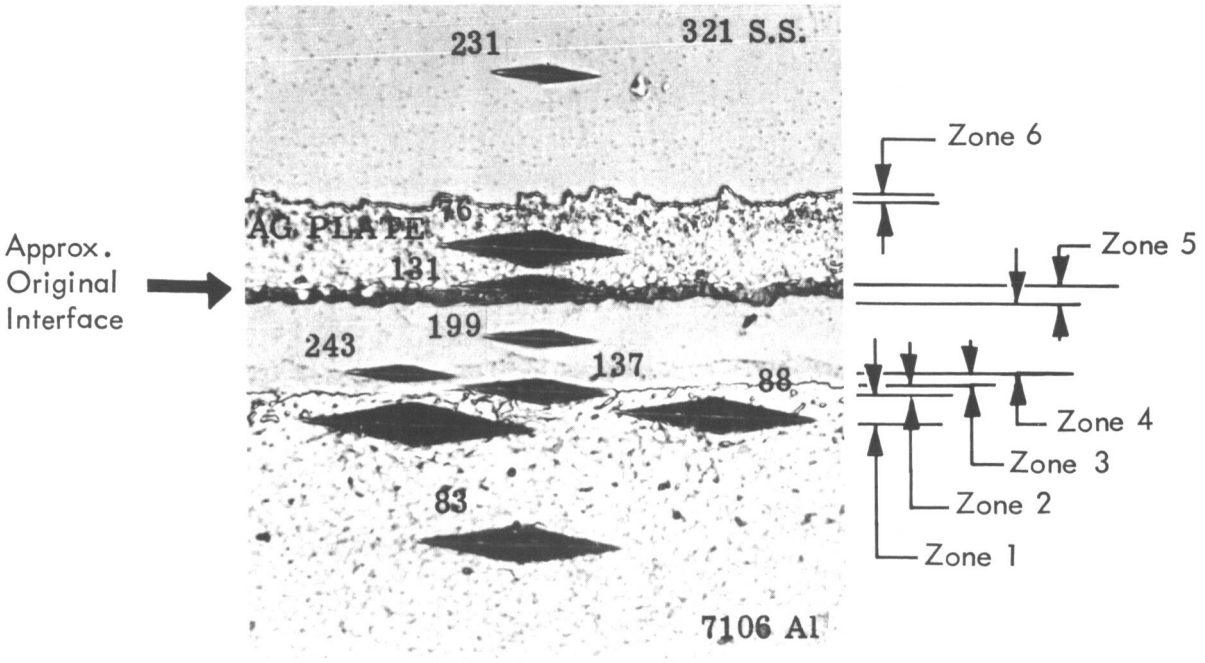
(a) #614 500°F/30 KSI/4-Hours



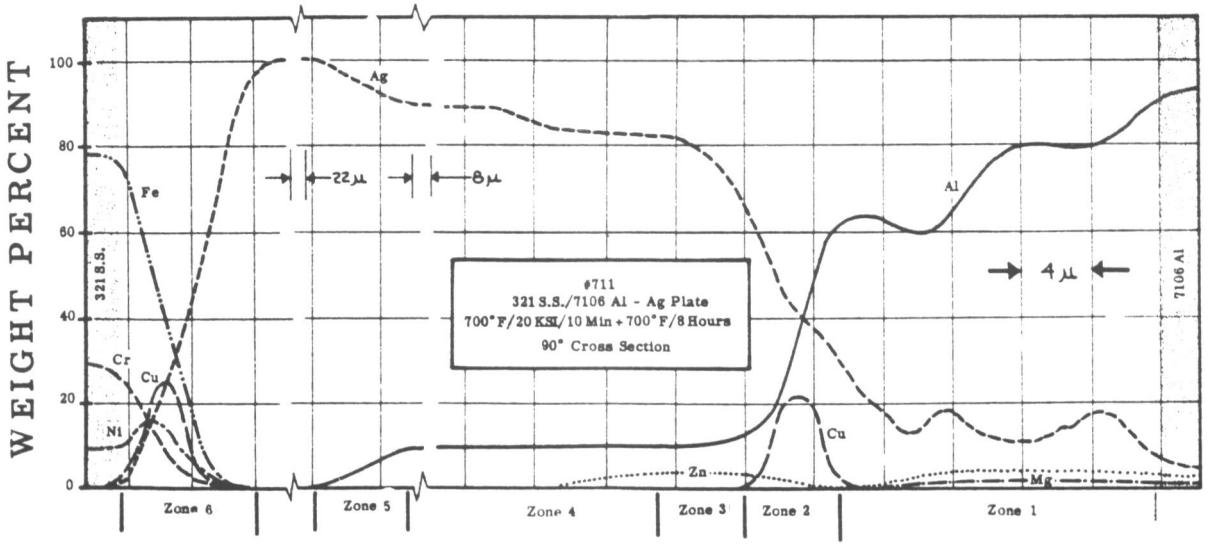
500X Etched 2A223737

(b) #620 700°F/20 KSI/1 Hour

FIGURE 63: MICROSTRUCTURE OF 7106-T6 ALUMINUM ALLOY TO 321 STAINLESS STEEL DIFFUSION WELDS - SILVER ELECTROPLATED 15° TAPER MICROSECTIONS

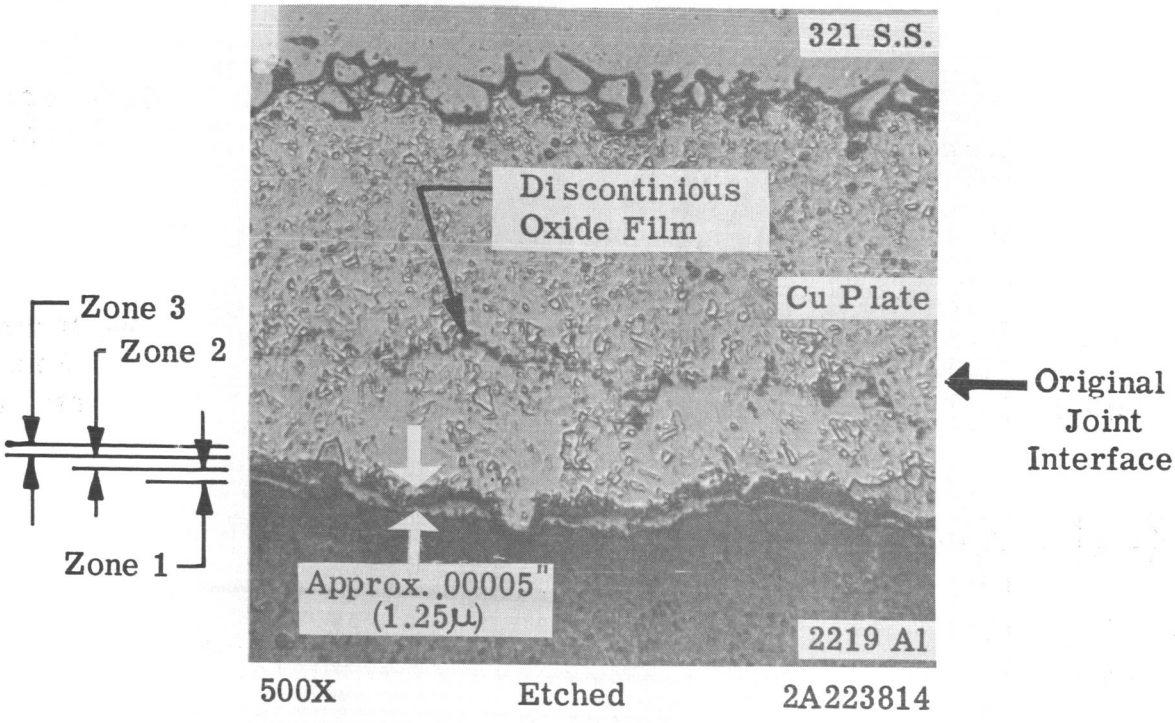


(a) Reichert Microhardness Traverse (KHN) of 321 SS to 7106 Al Diffusion Weld - #711 90° Cross-Section

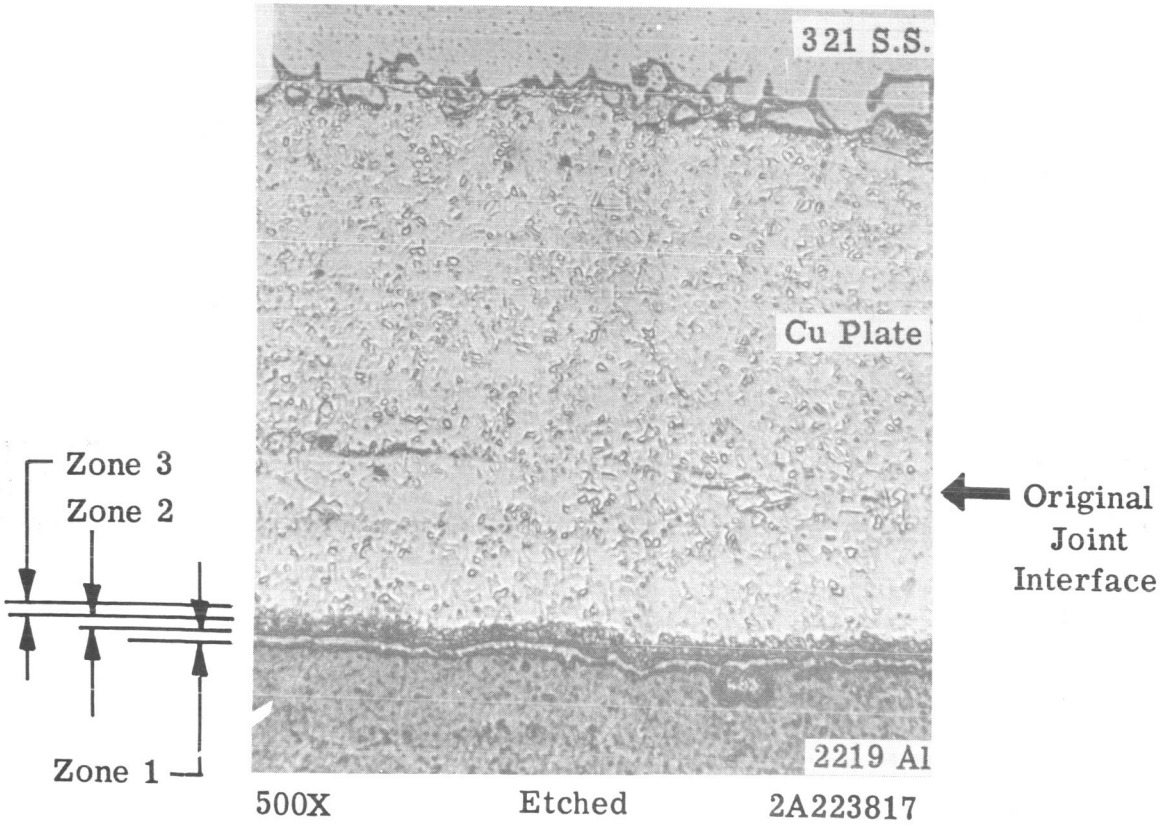


(b) Microprobe Analysis of 321 SS to 7106 Al Diffusion Weld - #711

FIGURE 64: MICROHARDNESS TRAVERSE AND MICROPROBE ANALYSIS OF 321 STAINLESS STEEL TO 7106-T6 ALUMINUM ALLOY DIFFUSION WELD - SILVER ELECTROPLATED

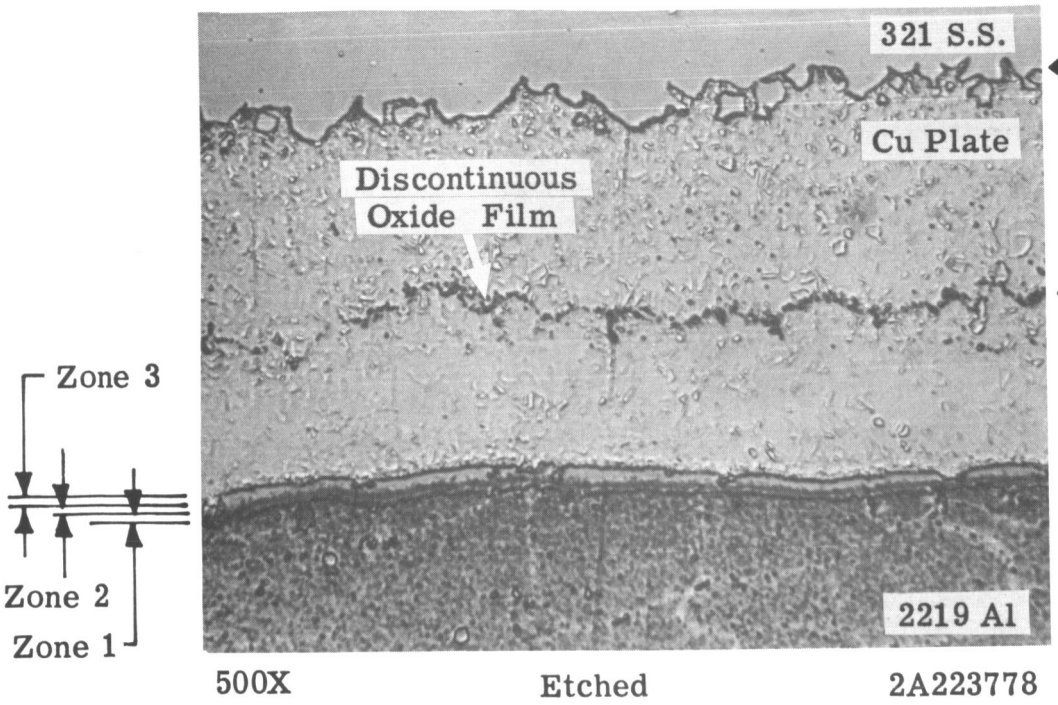


(a) #623 500°F/30KSI/4 Hours

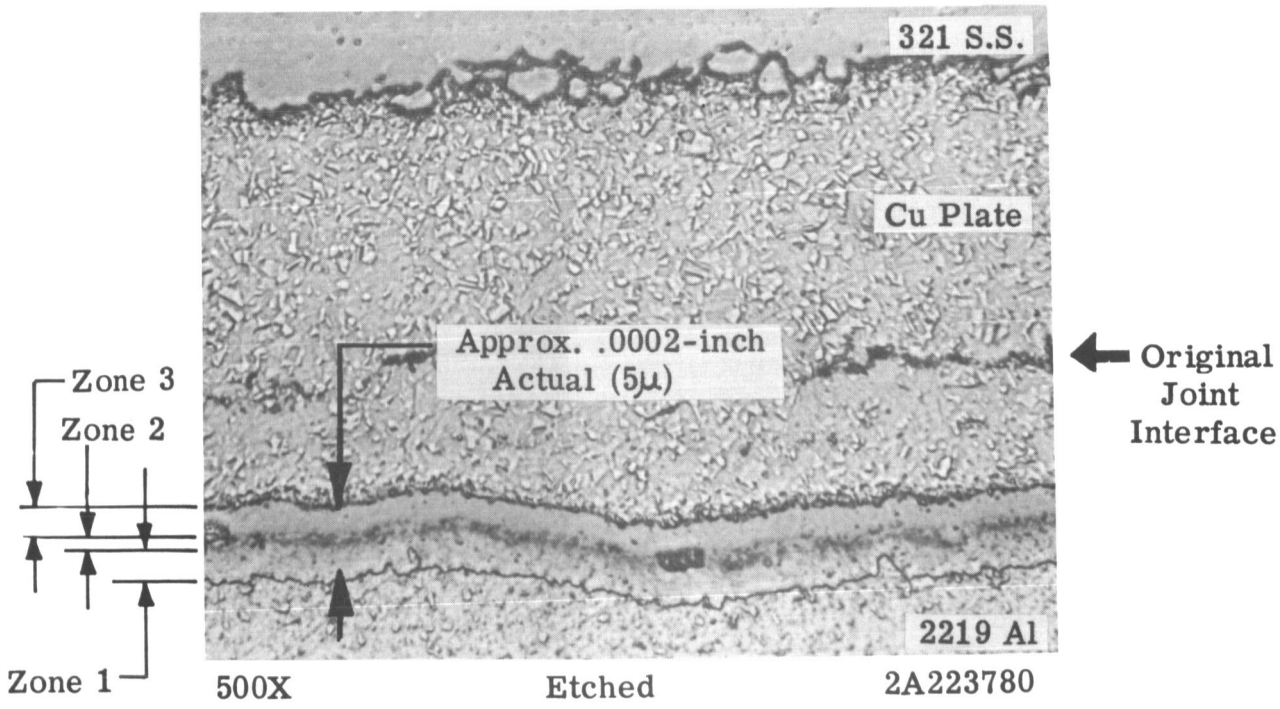


(b) #626 600°F/30KSI/2 Hours

FIGURE 65: MICROSTRUCTURE OF 2219-T6 ALUMINUM ALLOY TO 321 STAINLESS STEEL DIFFUSION WELDS - COPPER ELECTROPLATED 15° TAPER MICROSECTIONS

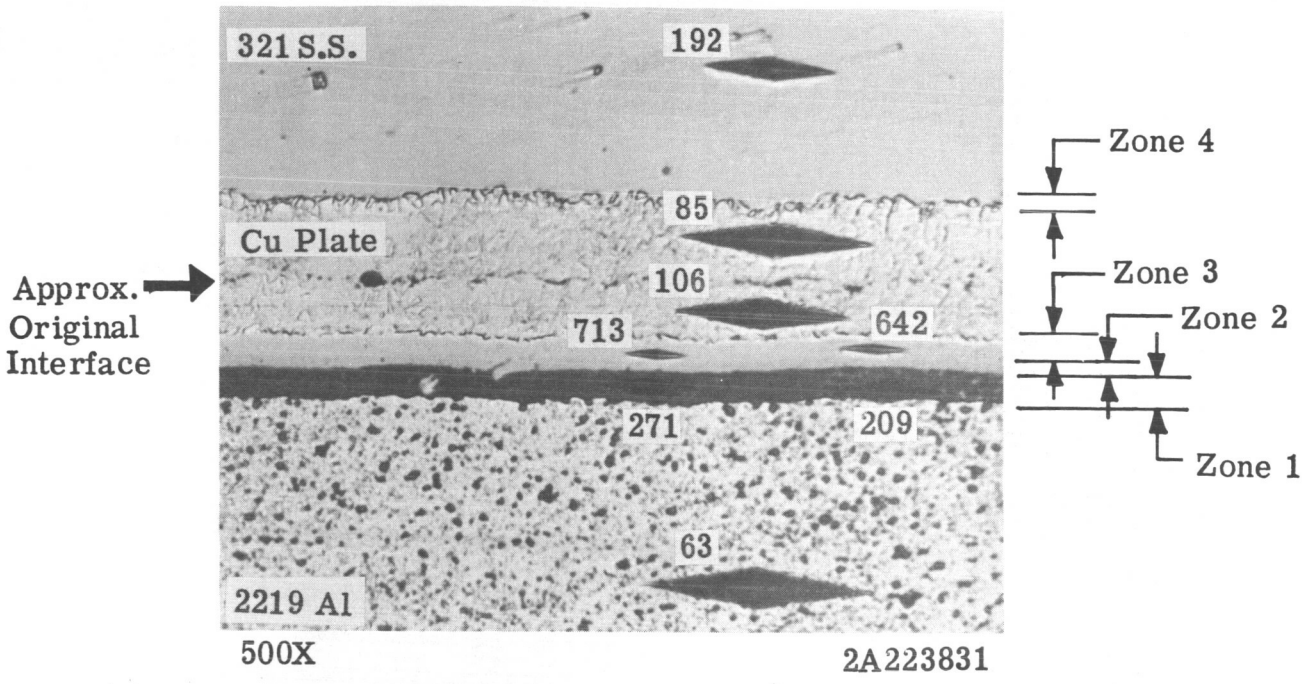


(a) #627 700°F/20 KSI/10 Min.

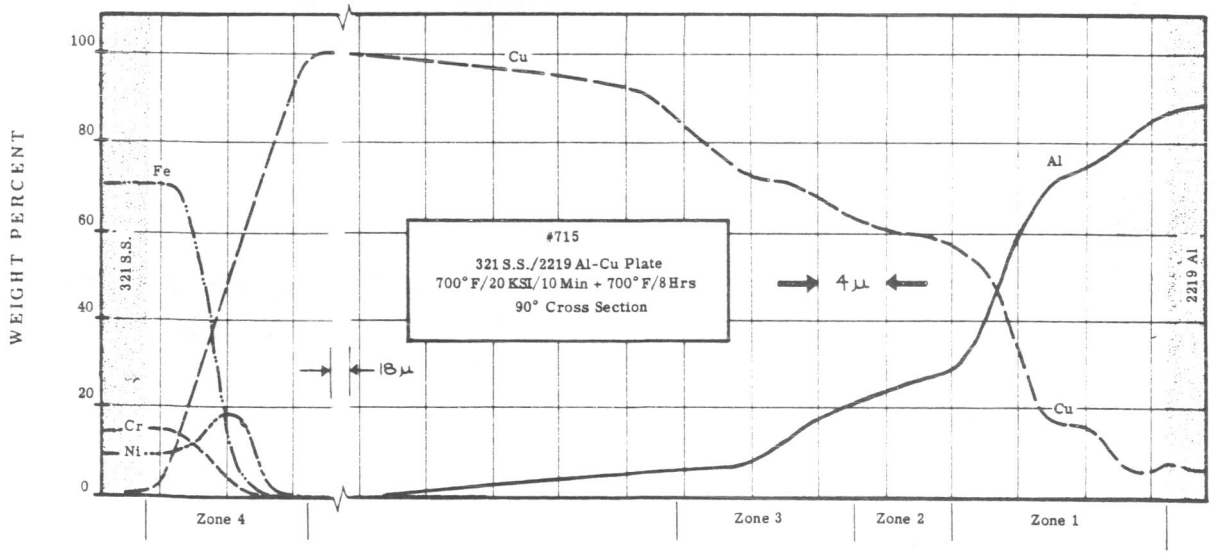


(b) #629 700°F/20 KSI/60 Min.

FIGURE 66: MICROSTRUCTURE OF 2219-T6 ALUMINUM ALLOY TO 321 STAINLESS STEEL DIFFUSION WELDS - COPPER ELECTROPLATED 15° TAPER MICROSECTIONS



(a) Reichert Microhardness Traverse (KHN) of 321 S.S. to 2219 Al Diffusion Weld - #715 90° Cross Section



(b) Microprobe Analysis of 321 S.S. to 2219 Al Diffusion Weld - #715

FIGURE 67: MICROHARDNESS TRAVERSE AND MICROPROBE ANALYSIS OF 321 STAINLESS STEEL TO 2219-T6 ALUMINUM ALLOY DIFFUSION WELDS - COPPER ELECTROPLATED

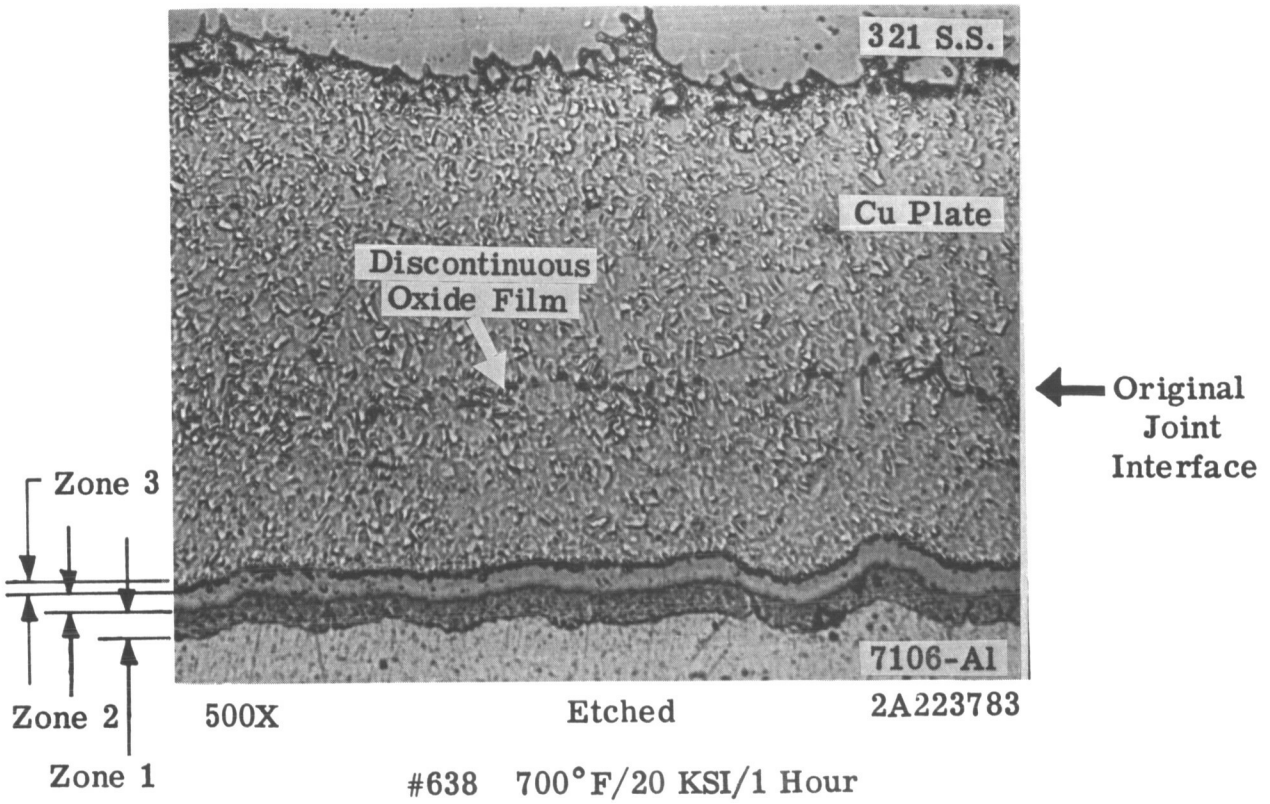
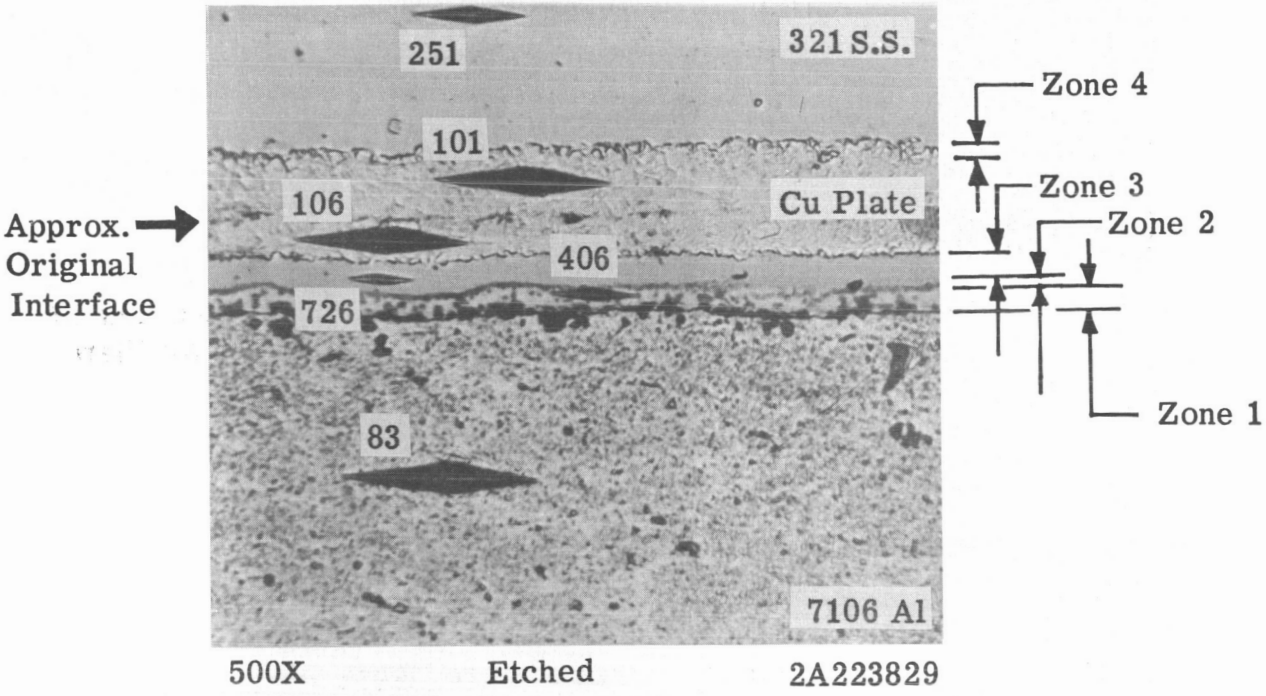
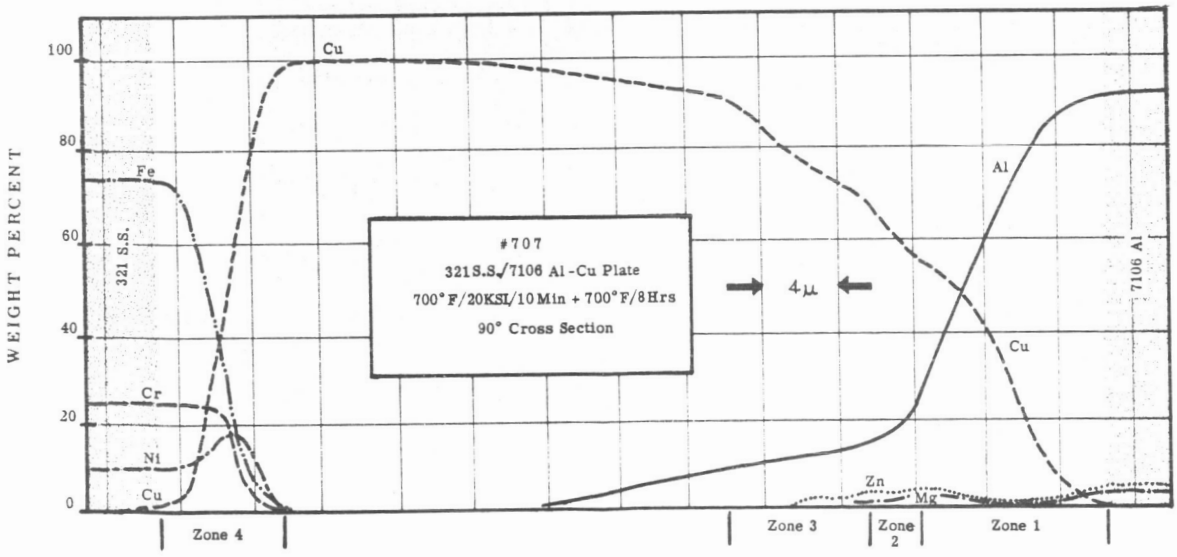


FIGURE 68: MICROSTRUCTURE OF 7106-T6 ALUMINUM ALLOY TO 321 STAINLESS STEEL DIFFUSION WELD - COPPER ELECTROPLATED

15° TAPER MICROSECTION

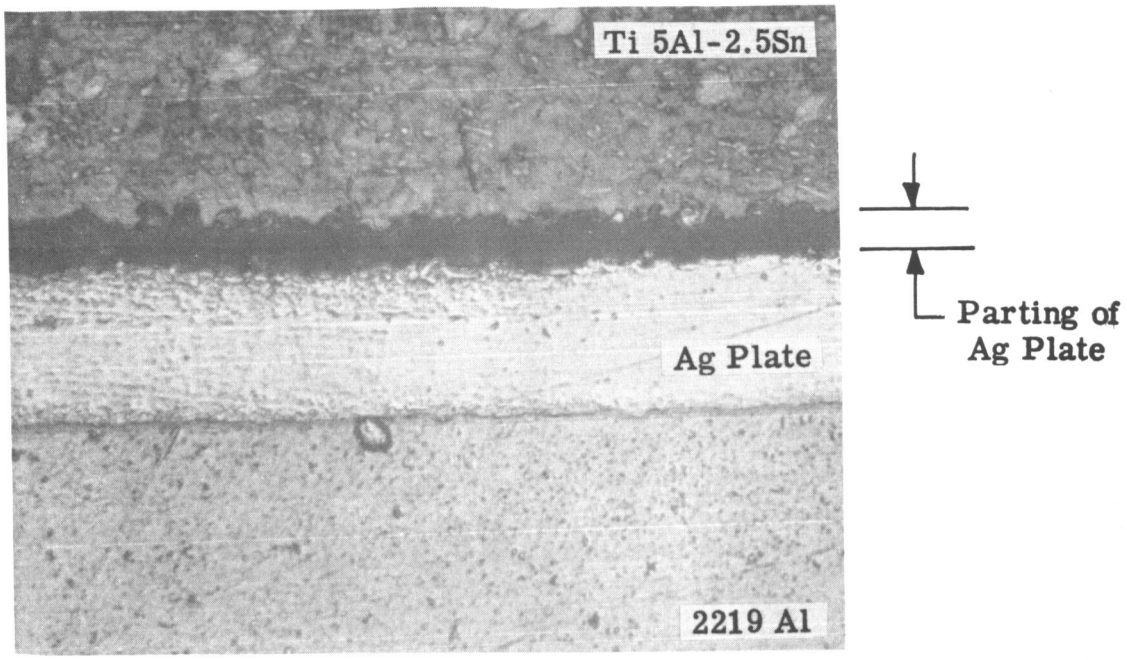


(a) Reichert Microhardness Traverse (KHN) of 321 S.S. to 7106 Al Diffusion Weld - #707 90° Cross Section



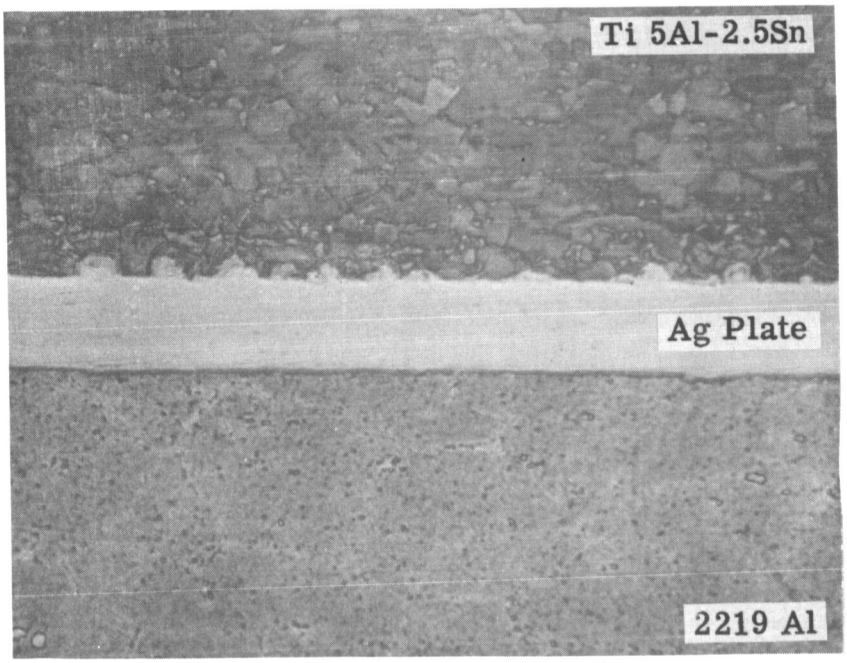
(b) Microprobe Analysis of 321 S.S. to 7106 AL Diffusion Weld - #707

FIGURE 69: MICROHARDNESS TRAVERSE AND MICROPROBE ANALYSIS OF 321 STAINLESS STEEL TO 7106-T6 ALUMINUM ALLOY DIFFUSION WELDS - COPPER ELECTROPLATED



500X Etched 2A223911

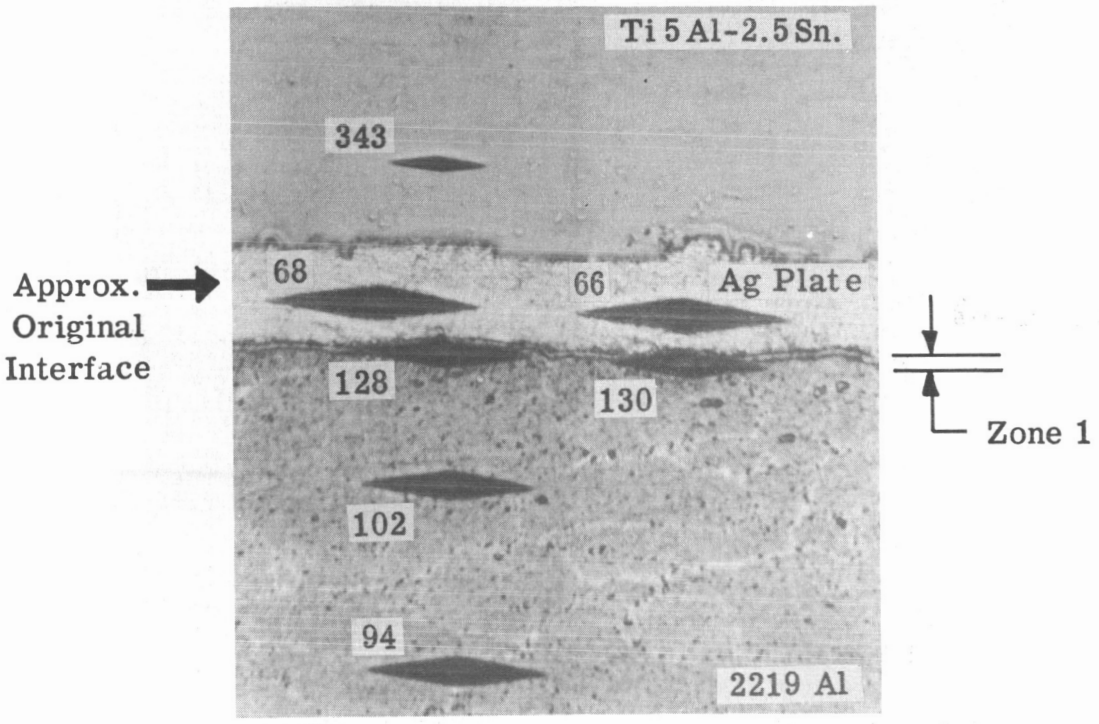
(a) #639 600°F/30 KSI/30 Min



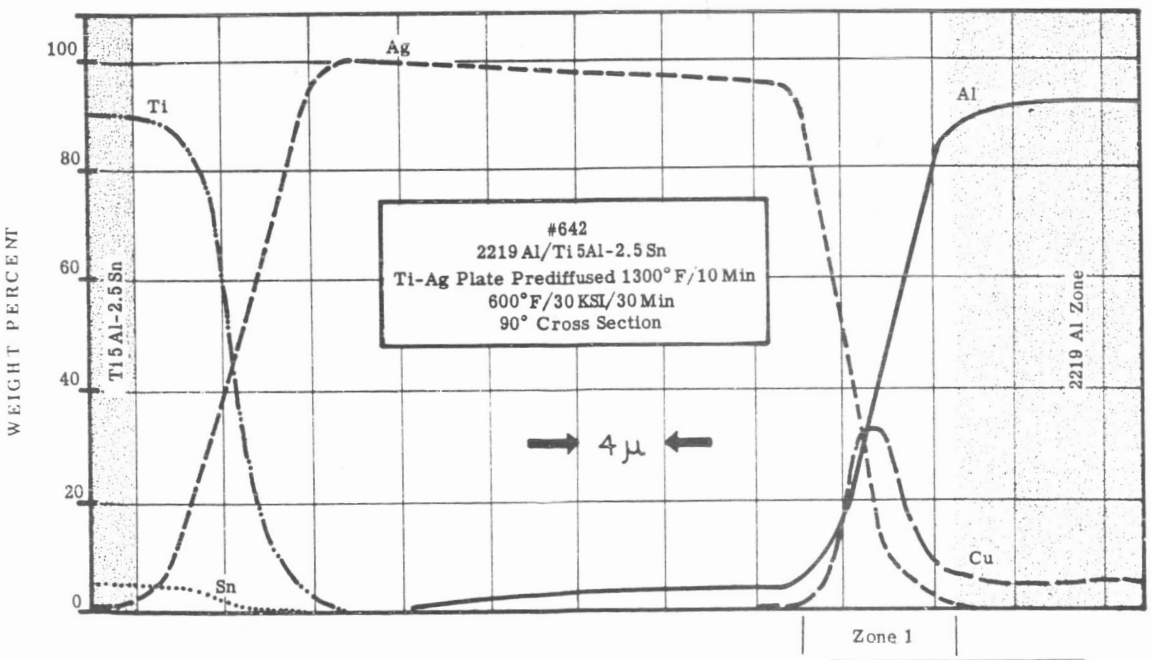
500X Etched 2A223834

(b) #642 Ti-Ag Plate Prediffused at 1300°F/10 Min.
600°F/30 KSI/30 Min.

FIGURE 70: MICROSTRUCTURE OF Ti 5Al-2.5Sn ALLOY TO 2219-T6 ALUMINUM ALLOY DIFFUSION WELDS - SILVER ELECTROPLATED

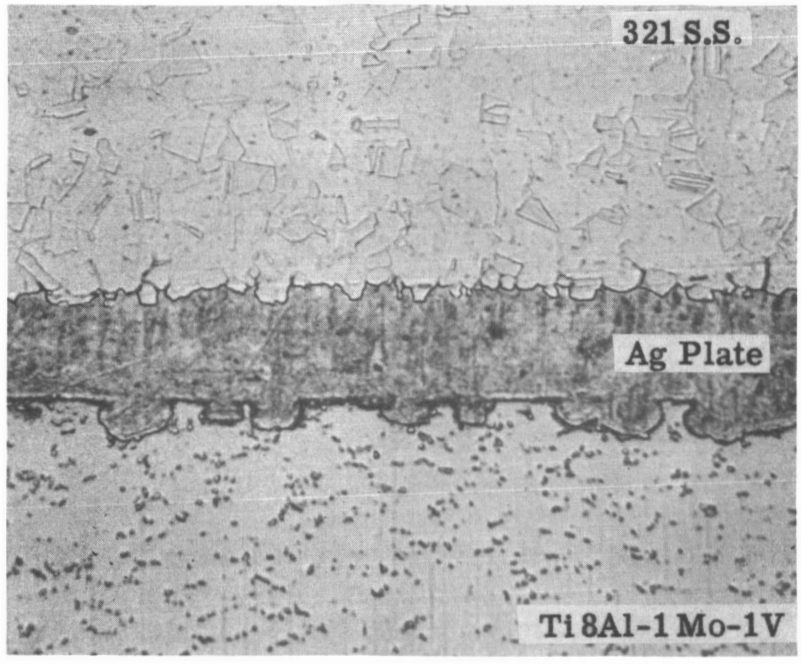


(a) Reichert Microhardness Traverse (KHN) of Ti 5Al -2.5Sn to 2219 Diffusion Weld - #642 90° Cross Section



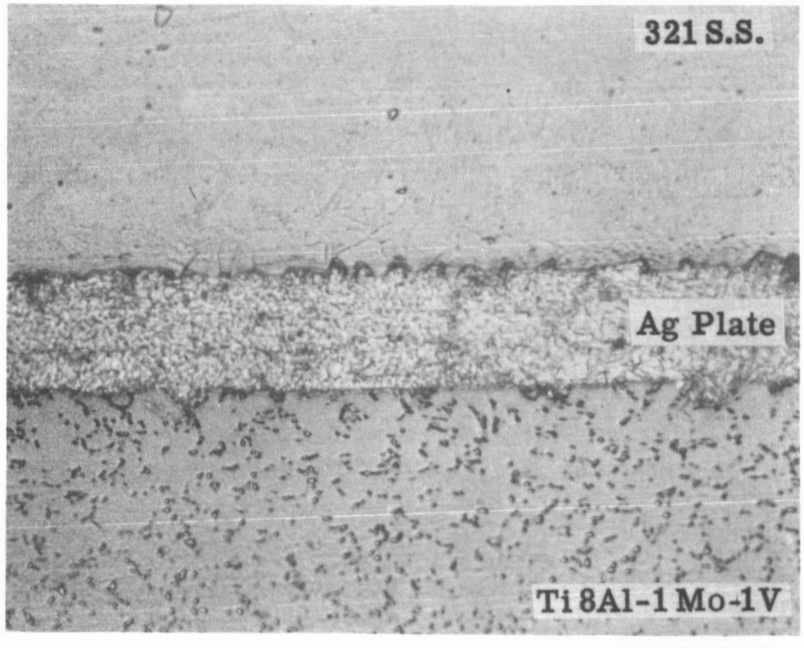
(b) Microprobe Analysis of Ti-5Al-2.5 Sn to 2219 Al Diffusion Weld - #642 90° Cross Section

FIGURE 71: MICROHARDNESS TRAVERSE AND MICROPROBE ANALYSIS OF Ti-5Al-2.5Sn ALLOY TO 2219-T6 ALUMINUM ALLOY DIFFUSION WELD - SILVER ELECTROPLATED



500X Etched 2A223842

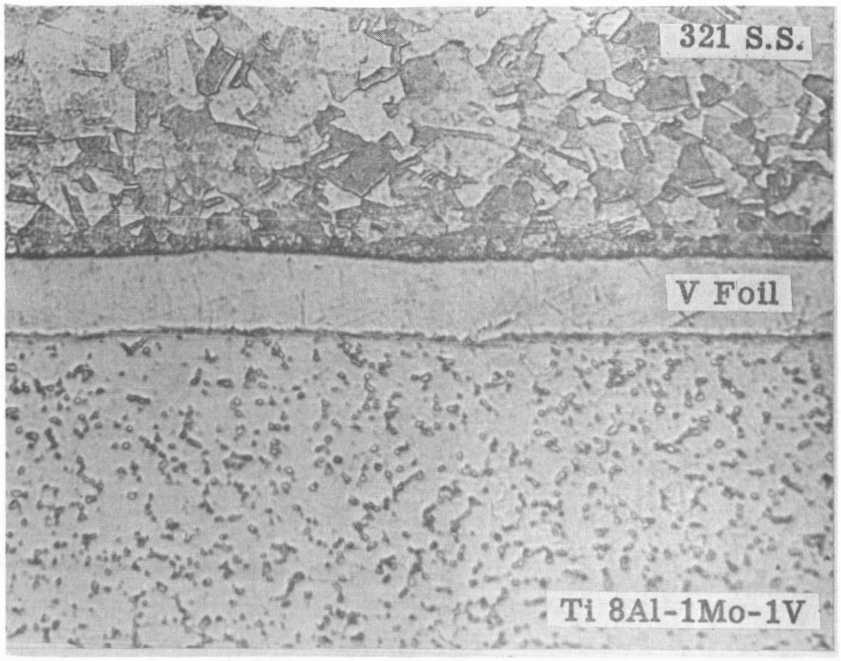
(a) #664 No Prediffusion 1300°F/30KSI/1 Hour



500X Etched 2A223967

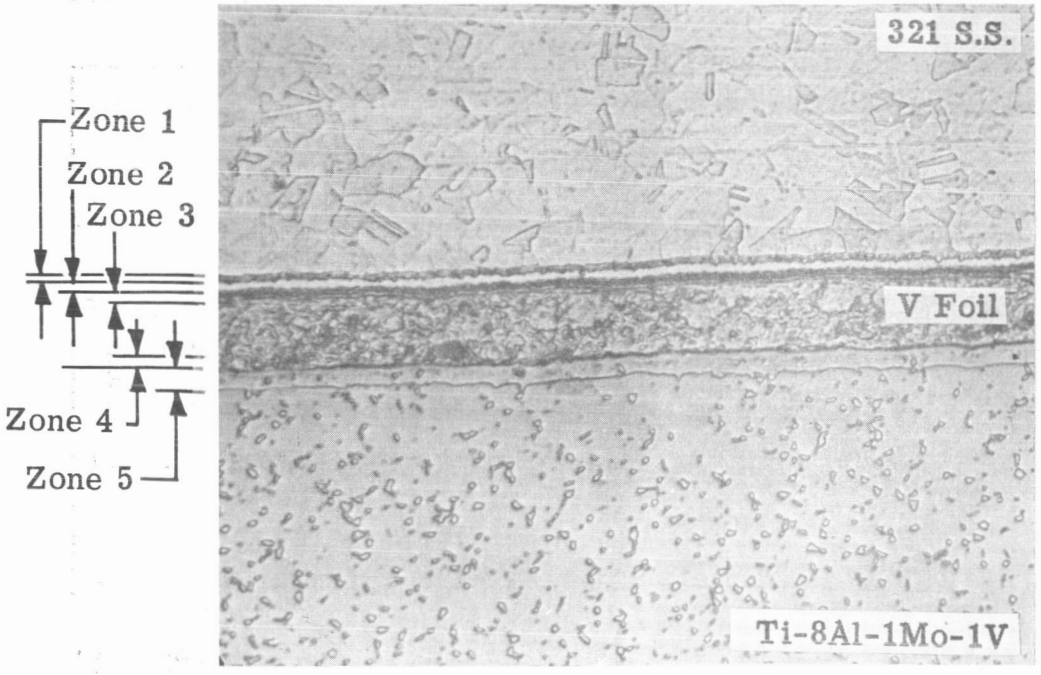
(b) #766 Prediffused 1300°F/10 Min, 600°F/20 KSI/30 Min.

FIGURE 72: MICROSTRUCTURE OF 321 STAINLESS STEEL TO Ti 8 Al-1 Mo-1V DIFFUSION WELDS- SILVER ELECTROPLATED



500X Etched for 321 SS and Ti 2A223768

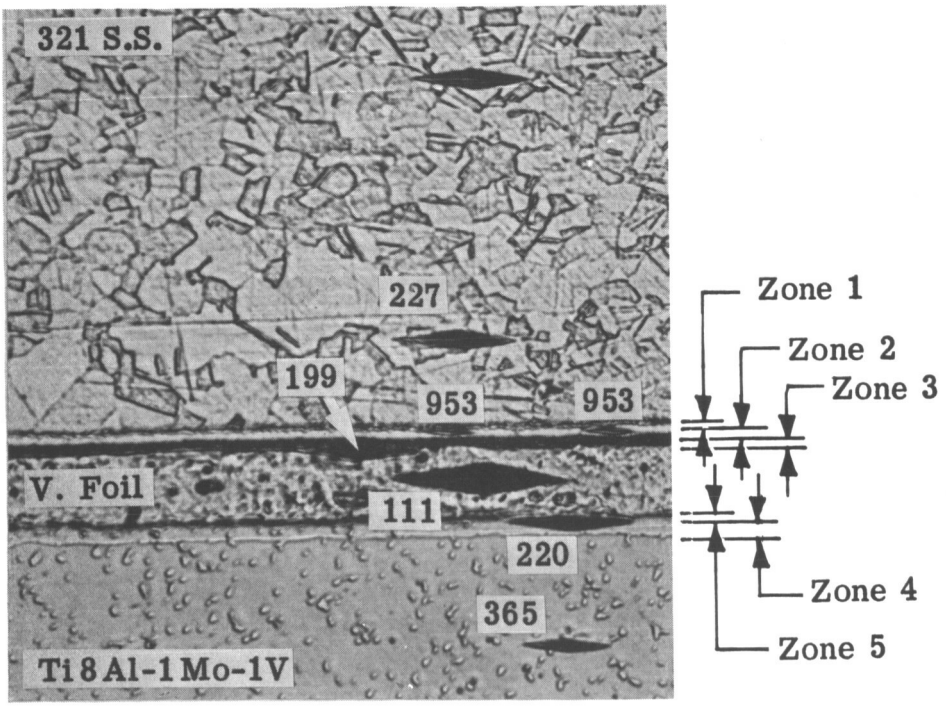
(a) #671 1400°F/30 KSI/30 Min.



500X Etched 2A223943

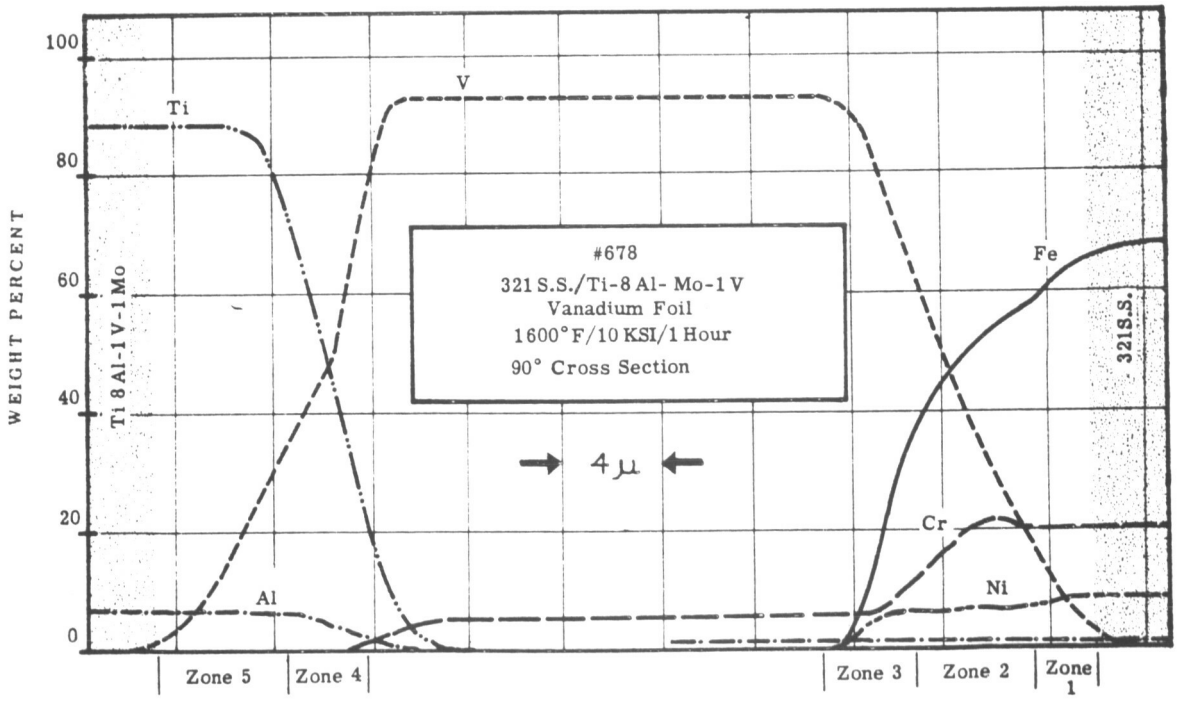
(b) #678 1500°F/30 KSI/1 Hour

FIGURE 73: MICROSTRUCTURE OF 321 STAINLESS STEEL TO Ti8Al-1Mo-1V DIFFUSION WELDS - VANADIUM FOIL



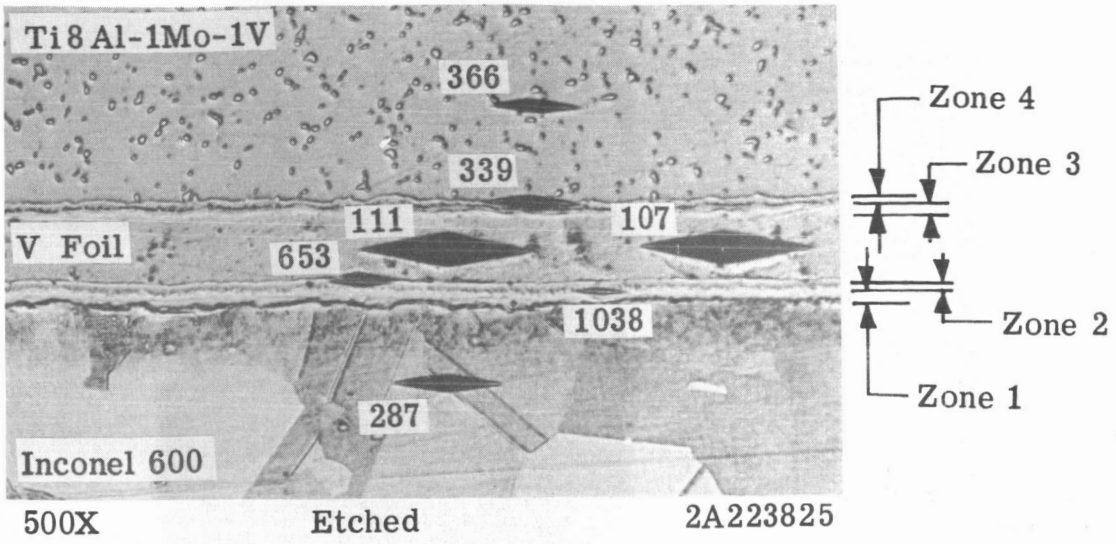
500X Etched 2A223826

(a) Reichert Microhardness Traverse (KHN) of 321 SS to Ti 8AL-1Mo-1V Diffusion Weld-#678 90° Cross Section

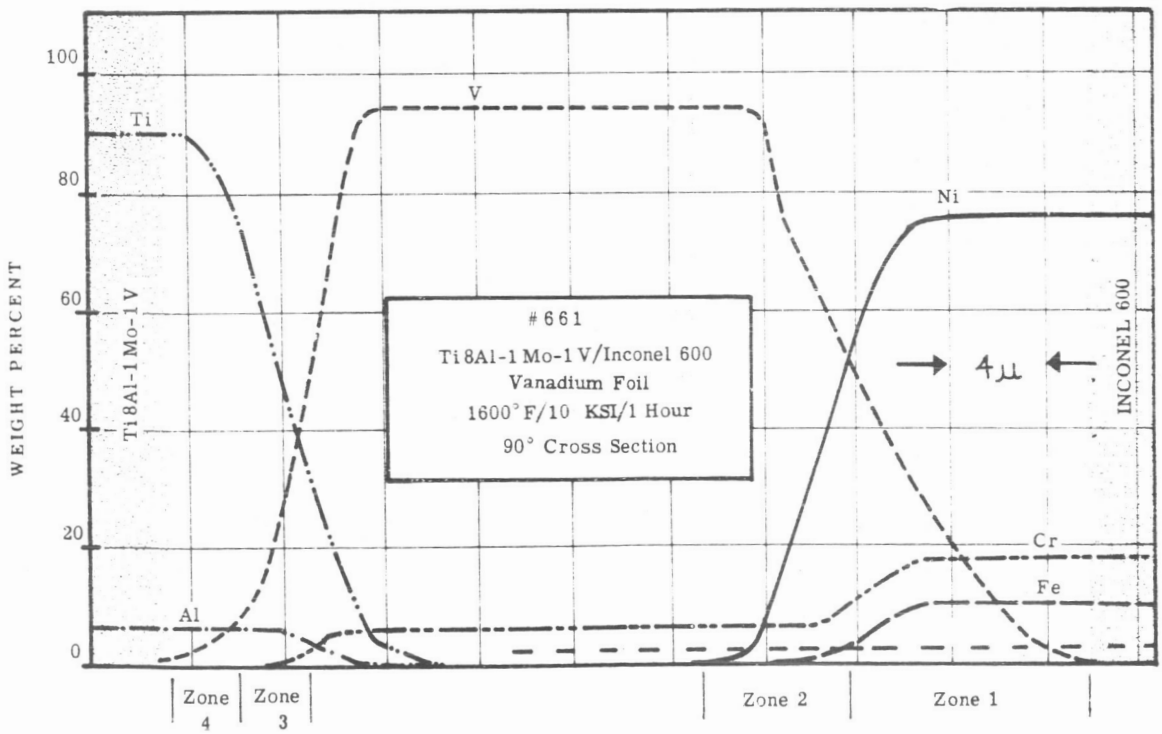


(b) Microprobe Analysis of 321 S.S. to Ti 8Al -1Mo-1V Diffusion Weld - #678

FIGURE 74: MICROHARDNESS TRAVERSE AND MICROPROBE ANALYSIS OF 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V ALLOY DIFFUSION WELD - VANADIUM FOIL

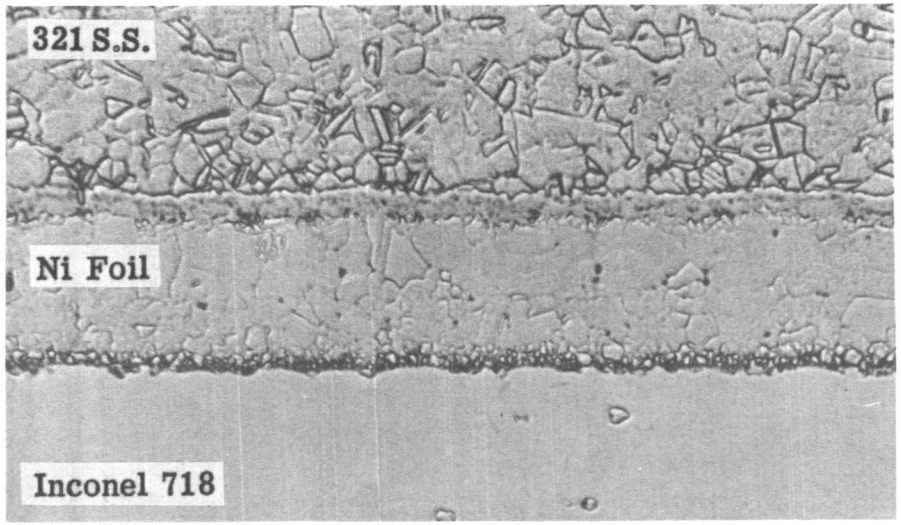


(a) Reichert Microhardness Traverse (KHN) of Ti 8Al-1Mo-1V to Inconel 600 Diffusion Weld - #661 90° Cross Section



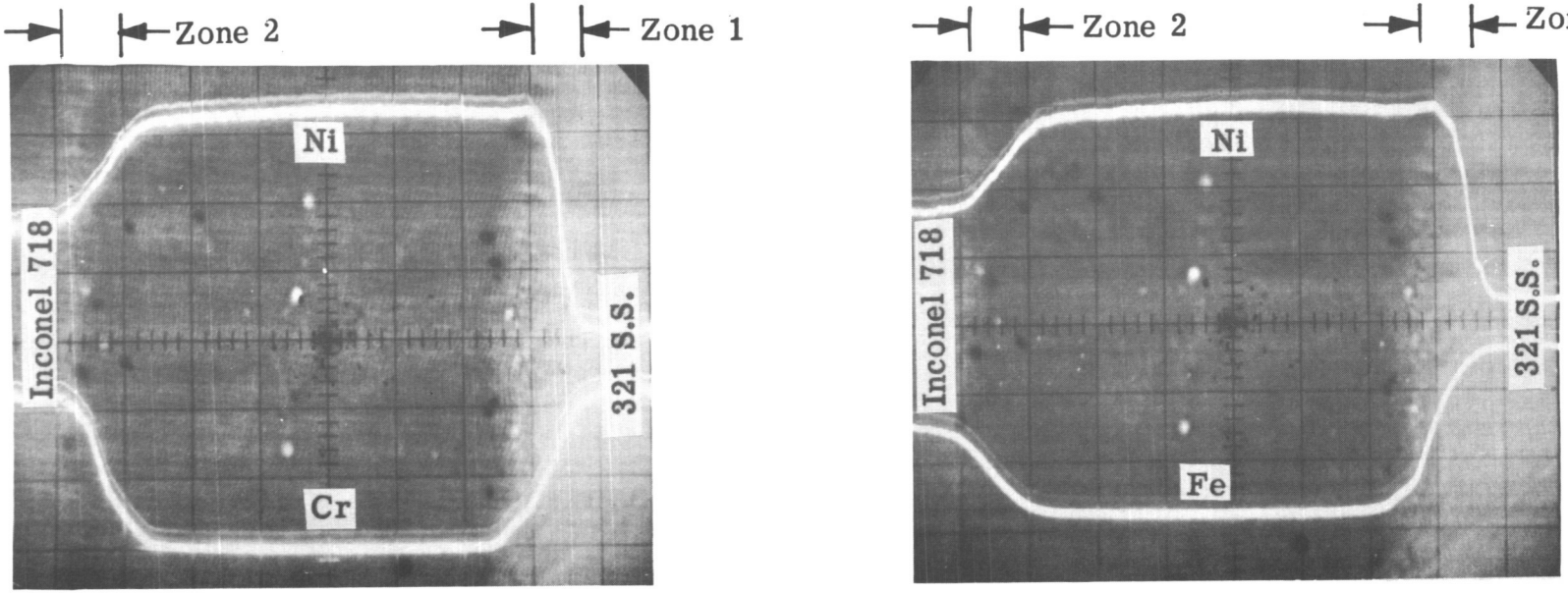
(b) Microprobe Analysis of Ti 8Al-1Mo-1V to Inconel 600 Diffusion Weld - #661

FIGURE 75: MICROHARDNESS TRAVERSE AND MICROPROBE ANALYSIS OF Ti-8Al-1Mo-1V ALLOY TO INCONEL 600 DIFFUSION WELD - VANADIUM FOIL



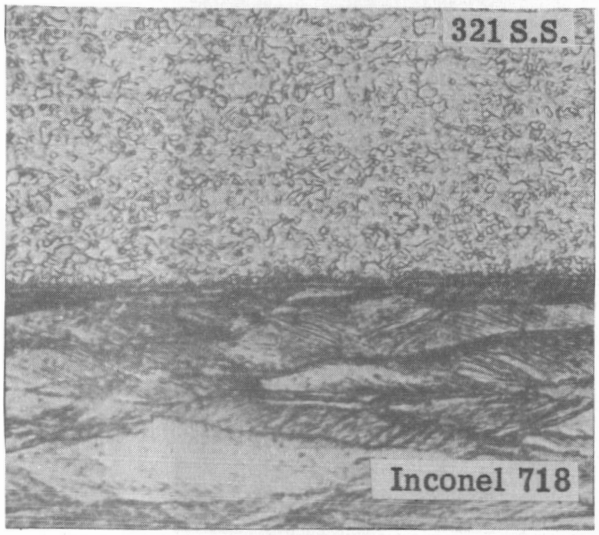
500X Etched 2A223937

(a) #692 1300°F/20 KSI/2 Hours



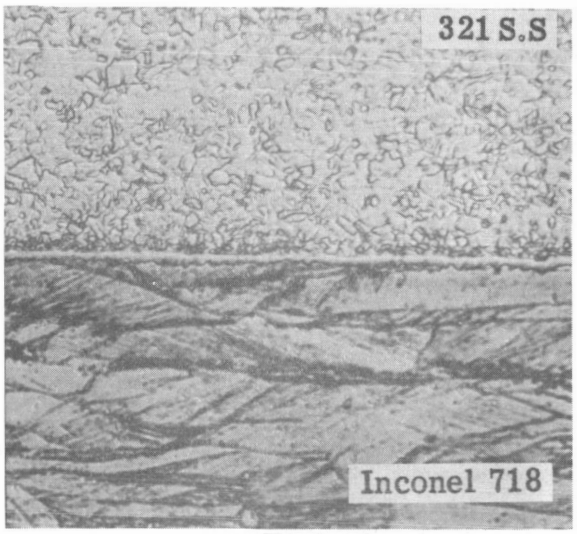
(b) Sample Current (Collected Electrons) Scans and Superinposed Concentration Profiles

FIGURE 76: MICROSTRUCTURE AND MICROPROBE PHOTOGRAPHS OF 321



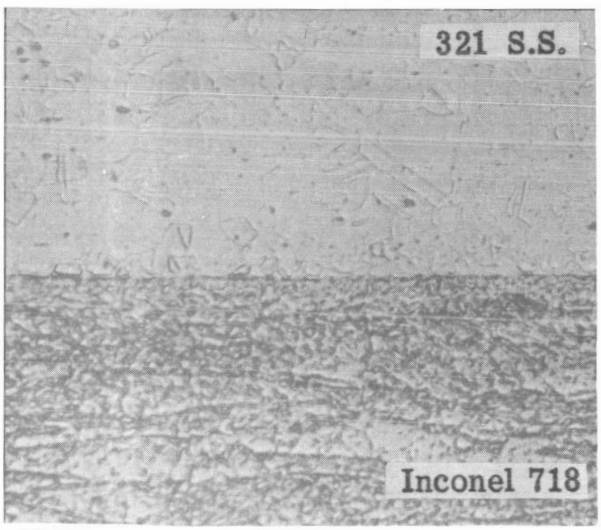
500X Etched 2A230074

(a) #725 1300°F/40 KSI/60 Min



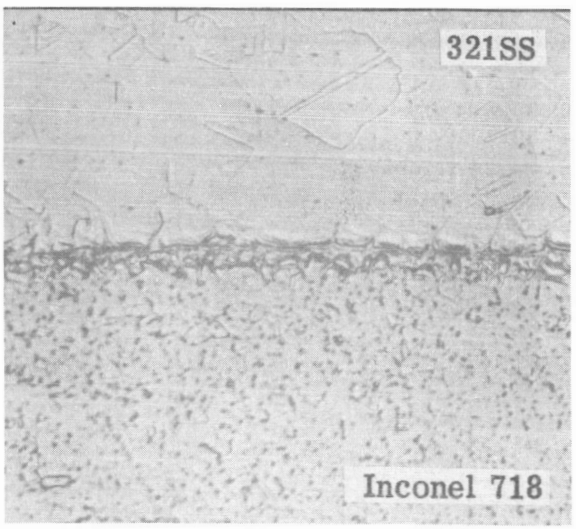
500X Etched 2A230077

(b) #738 1500°F/30 KSI/60 Min



500X Etched 2A230083

(c) #752 1700°F/12.5 KSI/60 Min

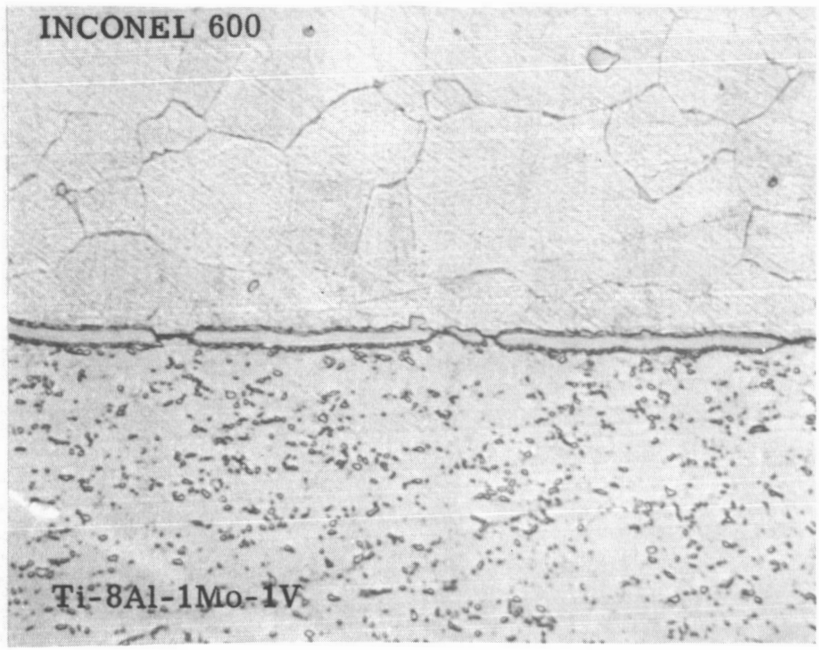


500X Etched 2A230086

(d) #758 1800°F/7.5 KSI/60 Min

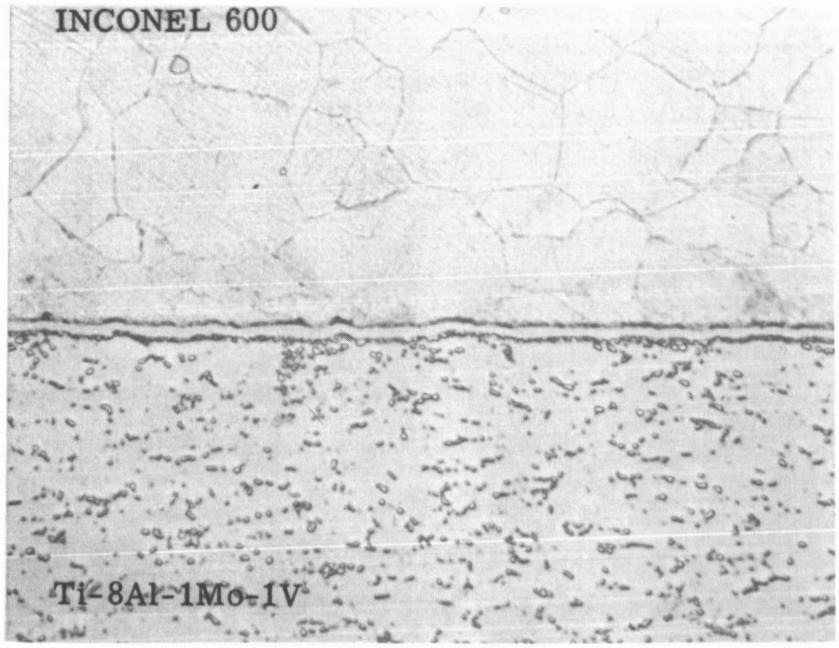
Inconel 718 Cold Reduced 60%
321 S.S. Cold Reduced 65%

FIGURE 77: MICROSTRUCTURES OF STRAIN HARDENED INCONEL 718 AND 321 STAINLESS STEEL AFTER DIFFUSION WELDING



500X 2A223316

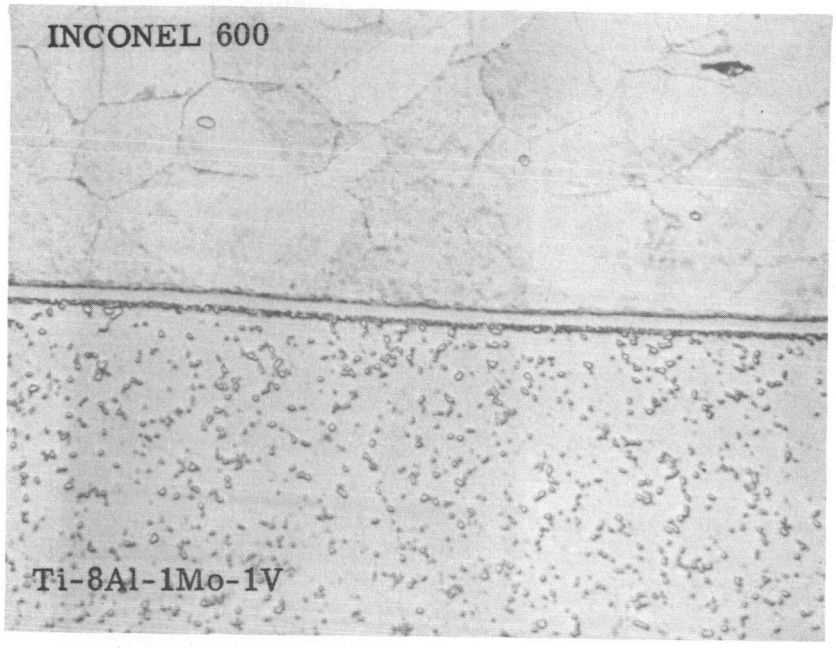
(a) #324 1350°F/20 ksi/60 min. Etched
ABRASIVE SANDED



500X 2A223317

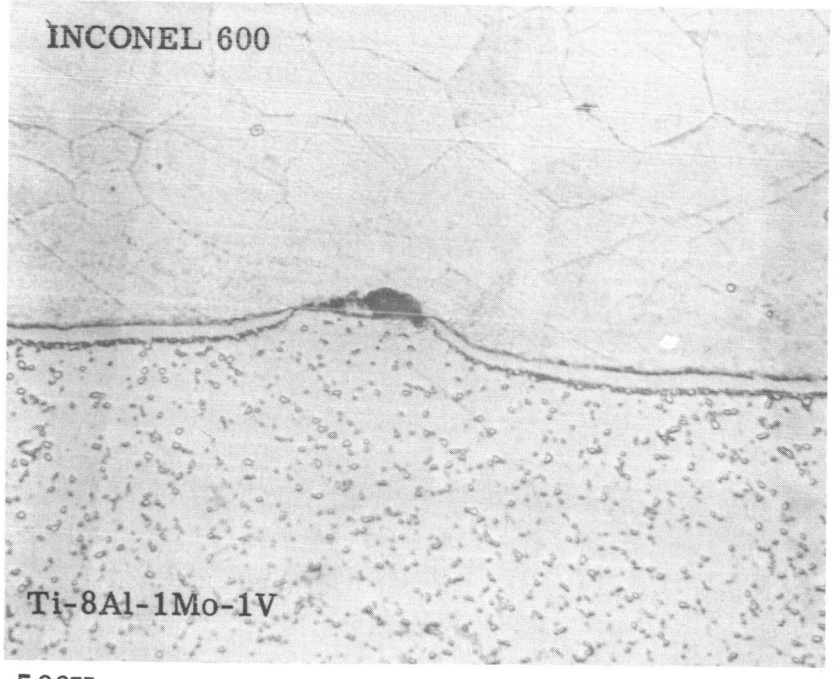
(b) #325 1350°F/20 ksi/60 min. Etched
CHEMICALLY CLEANED

FIGURE 78: PHOTOMICROGRAPHS SHOWING THE EFFECT OF SURFACE PREPARATION ON THE APPEARANCE OF THE DIFFUSION WELD BETWEEN INCONEL 600 AND Ti-8Al-1Mo-1V.



500X 2A223318

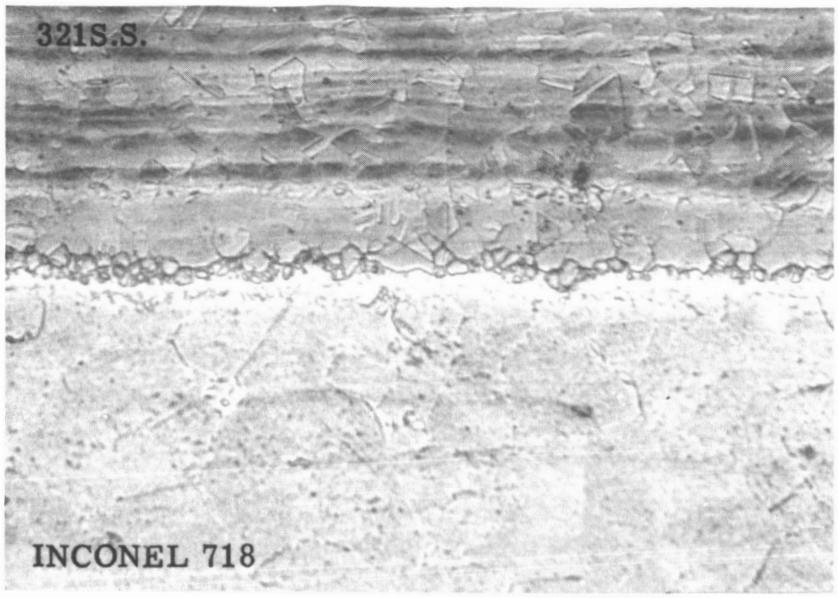
(a) #326 1350°F/20 ksi/60 min. Etched
POLISHED SURFACE



500X 2A223319

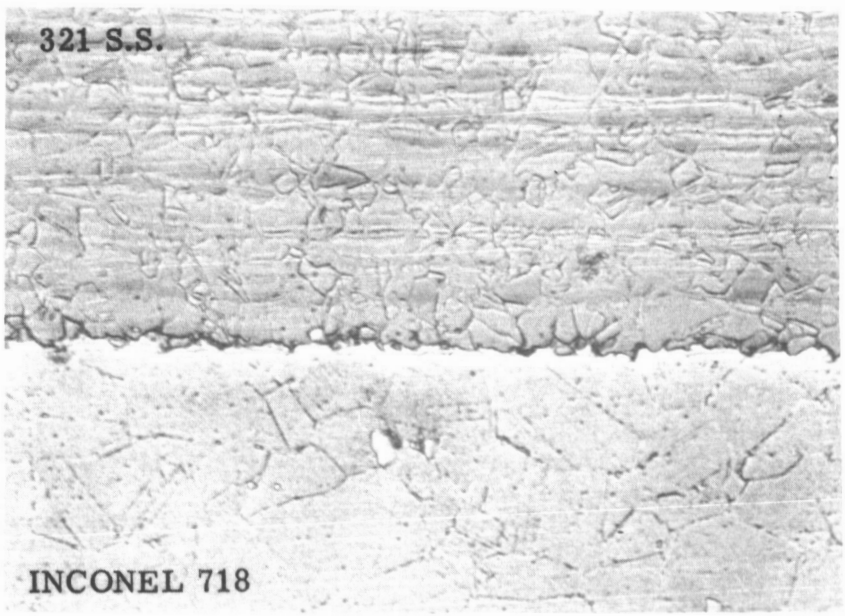
(b) #327 1350°F/20 ksi/60 min. Etched
MACHINED SURFACE

FIGURE 79: PHOTOMICROGRAPHS SHOWING THE EFFECT OF SURFACE PREPARATION ON THE APPEARANCE OF THE DIFFUSION WELD BETWEEN INCONEL 600 AND Ti-8Al-1Mo-1V.



500X 2A223309

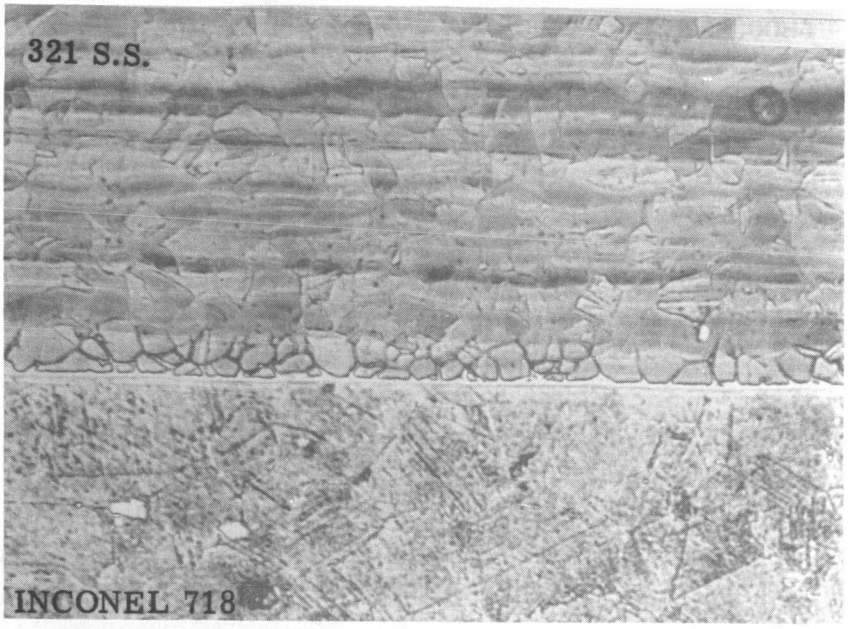
(a) #340 1600°F/12.5 ksi/60 min. Etched
ABRASIVE SANDED SURFACE



500X 2A223310

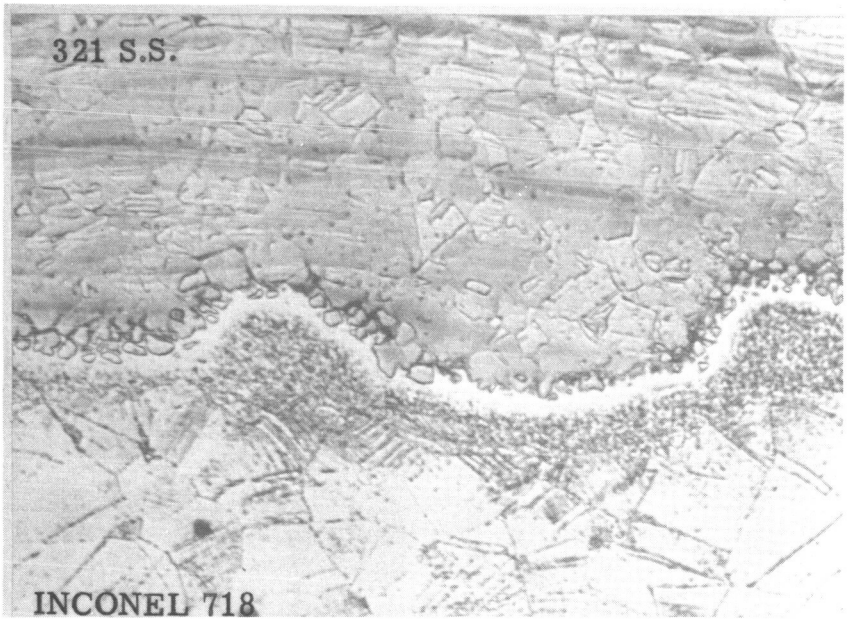
(b) #341 1600°F/12.5 ksi/60 min. Etched
CHEMICALLY CLEANED SURFACE

FIGURE 80: PHOTOMICROGRAPHS SHOWING THE EFFECT OF SURFACE PREPARATION ON THE APPEARANCE OF THE DIFFUSION WELD BETWEEN INCONEL 718 and 321 STAINLESS STEEL.



500X 2A223311

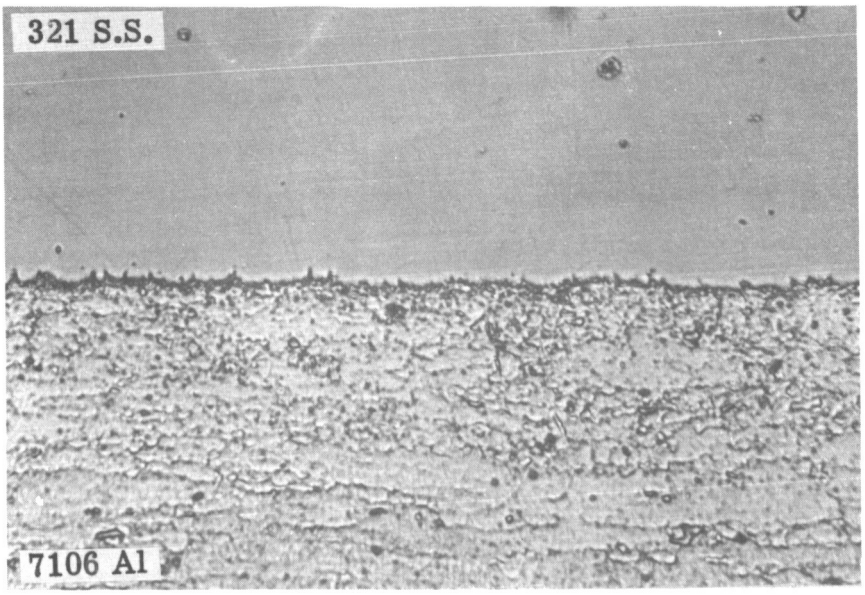
(a) #342 1600°F/12.5 ksi/60 min. Etched
POLISHED SURFACE



500X 2A223312

(b) #343 1600°F/12.5 ksi/60 min. Etched
MACHINED SURFACE

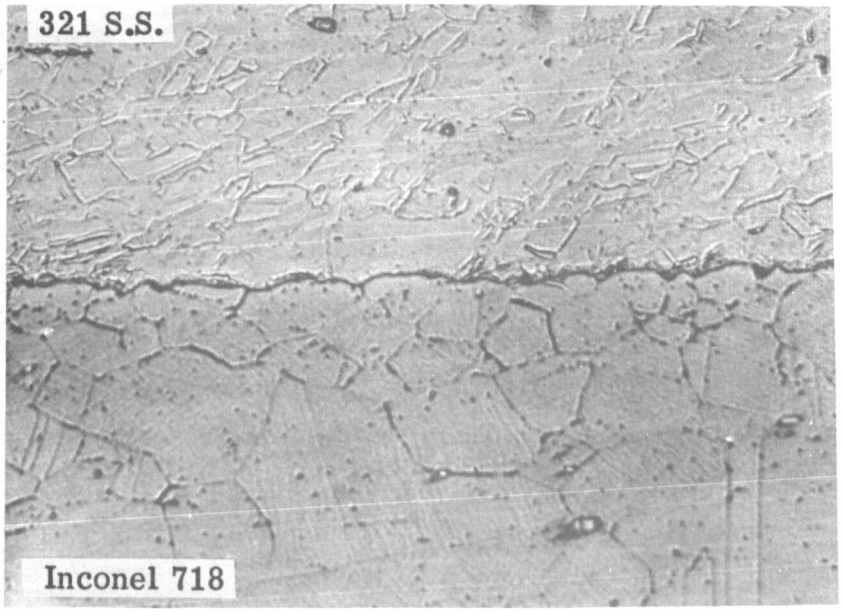
FIGURE 81: PHOTOMICROGRAPHS SHOWING THE EFFECT OF SURFACE PREPARATION ON THE APPEARANCE OF THE DIFFUSION WELD BETWEEN INCONEL 718 and 321 STAINLESS STEEL



500X Etched 2A223657

#584 Rolling Preheat Temperature - 850°F

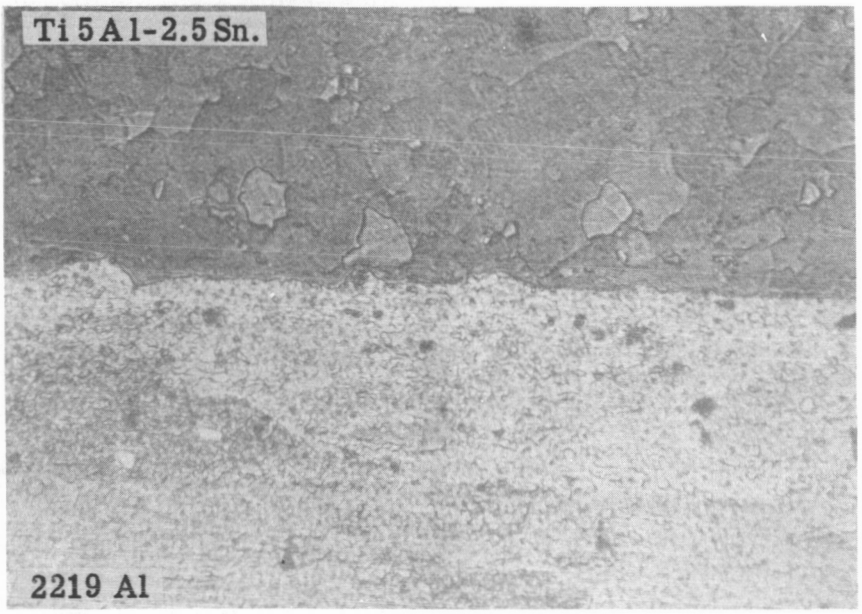
FIGURE 82: MICROSTRUCTURE OF 321 STAINLESS STEEL TO 7106 ALUMINUM ALLOY DIFFUSION ROLL WELD



500X Etched 2A223659

#596 Rolling Preheat Temperature - 1400°F

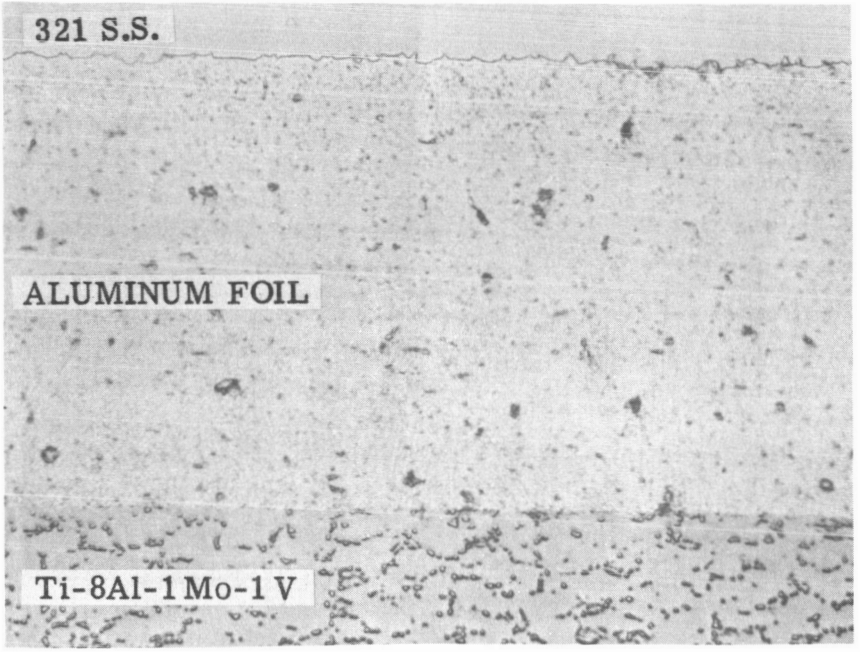
FIGURE 83: MICROSTRUCTURE OF 321 STAINLESS STEEL TO INCONEL 718 DIFFUSION ROLL WELD.



500X Etched 2A223660

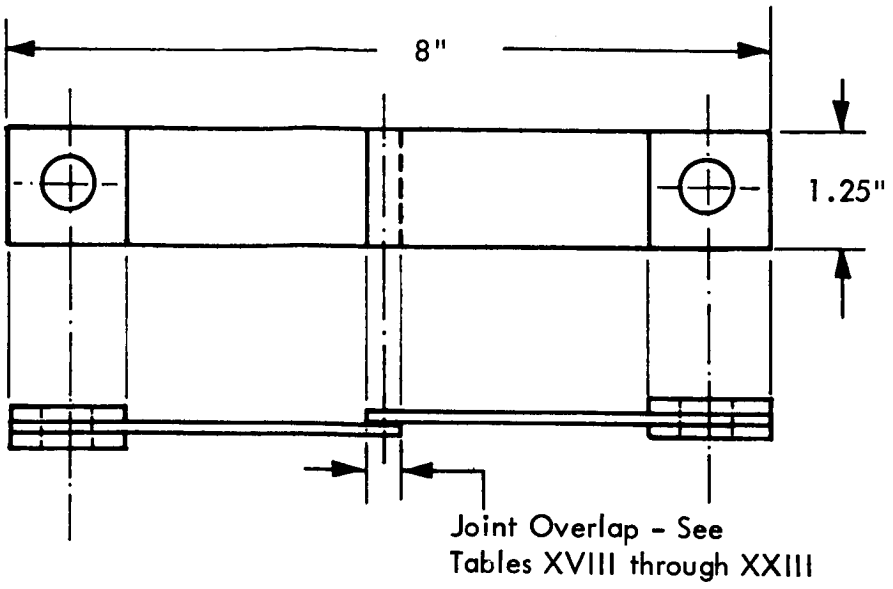
#589 Rolling Preheat Temperature - 950°F

FIGURE 84: MICROSTRUCTURE OF Ti-5 Al-2.5 Sn ALLOY TO 2219 ALUMINUM ALLOY DIFFUSION ROLL WELD

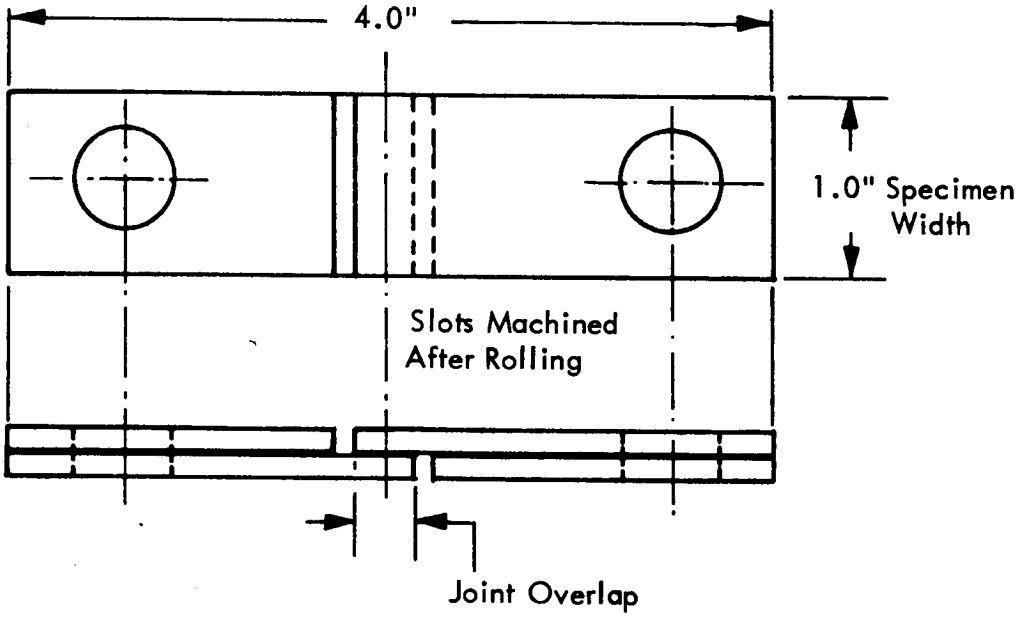


500X Etched 2A230775

FIGURE 85: MICROSTRUCTURE OF 321 STAINLESS STEEL TO Ti-8Al-1Mo-1V ROLL WELD - ALUMINUM FOIL INTERLEAF



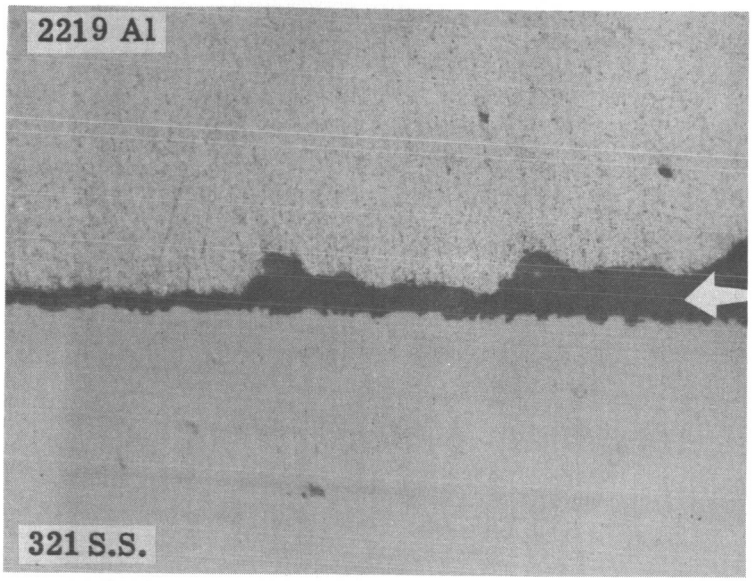
PRESS WELDED SPECIMEN



For specimen width and joint overlap see Table XXIV.

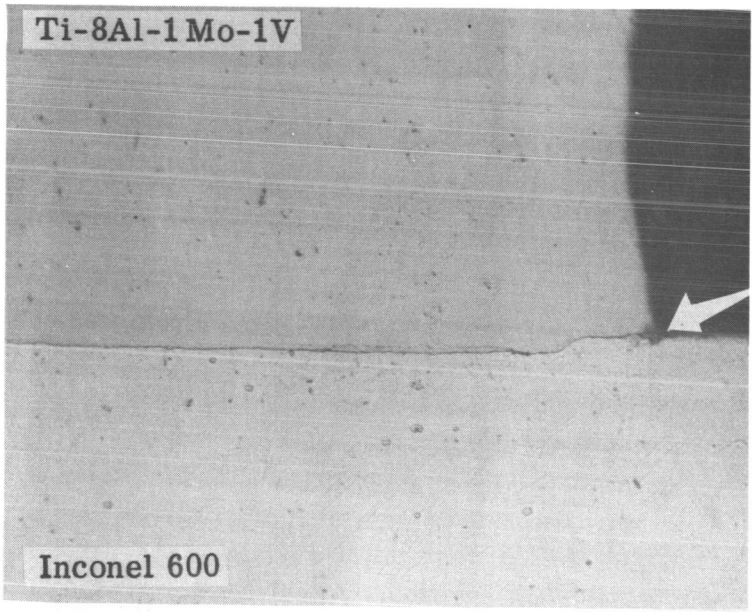
ROLL WELD SPECIMEN

FIGURE 86: SHEAR SPECIMEN CONFIGURATION



Etched 2A230971 500X

(a)



Etched 2A230970 500X

(b)

FIGURE 87: PHOTOMICROGRAPHS OF DIFFUSION WELDED JOINTS AFTER SIXTY DAY EXPOSURE TO CONDENSING HUMIDITY ENVIRONMENT.

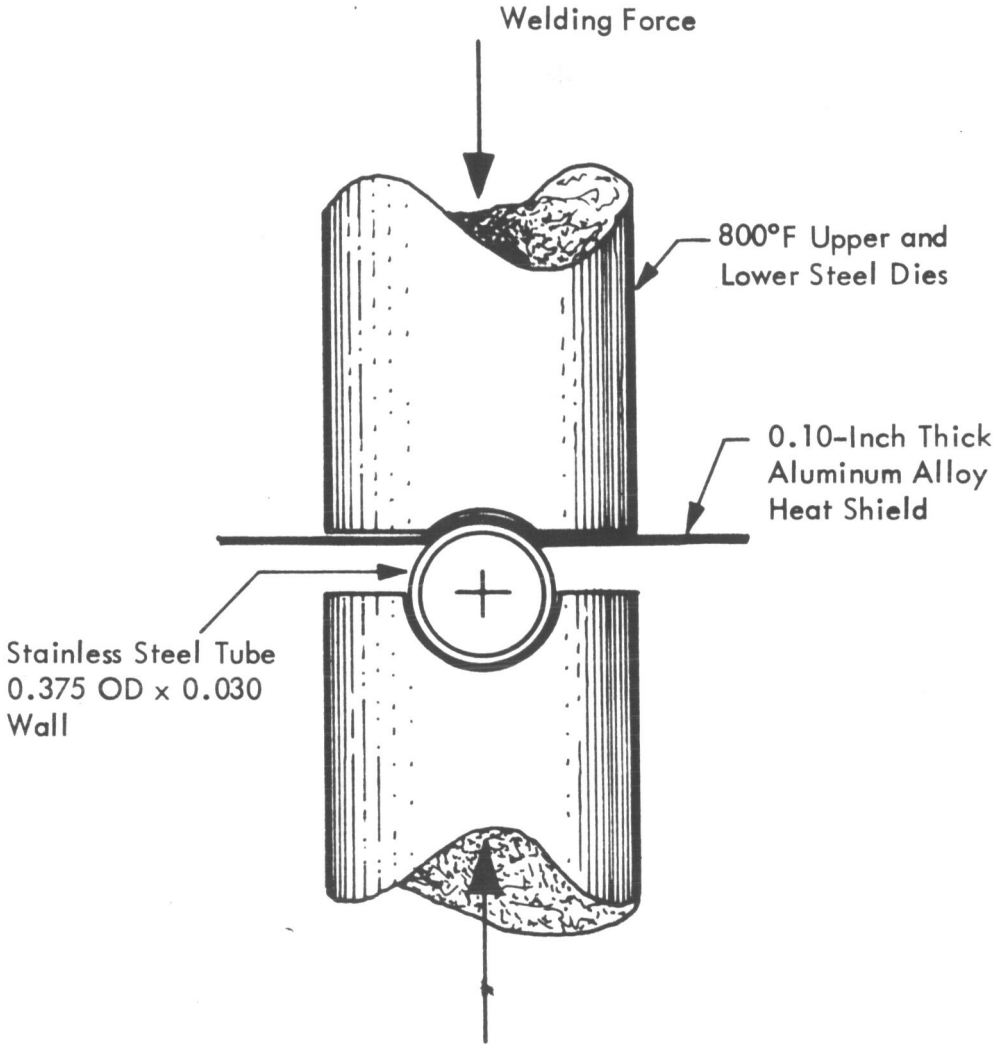


FIGURE 88: ARRANGEMENT FOR DIFFUSION WELDING OF CYROGENIC HEAT SHIELD ASSEMBLIES

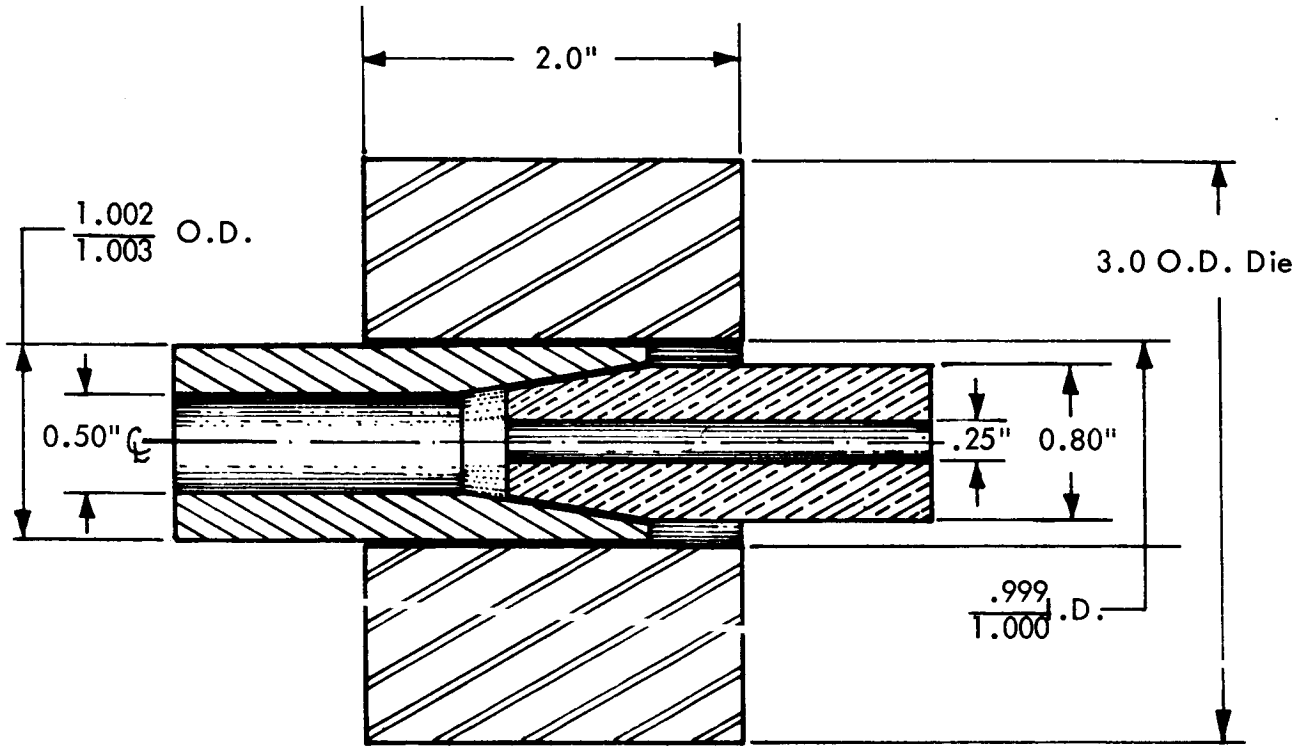


FIGURE 89: JOINT AND TOOLING ARRANGEMENT FOR DIFFUSION WELDING DISSIMILAR METAL TUBULAR ASSEMBLIES

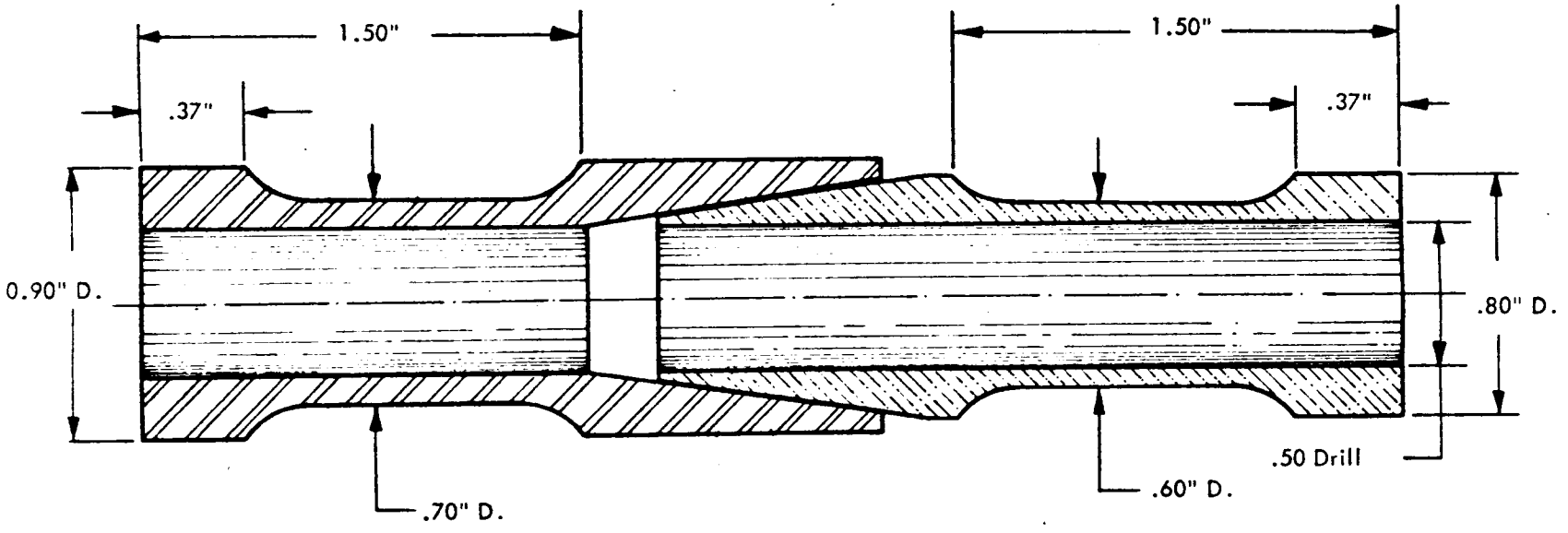


FIGURE 90: DISSIMILAR METAL JOINT

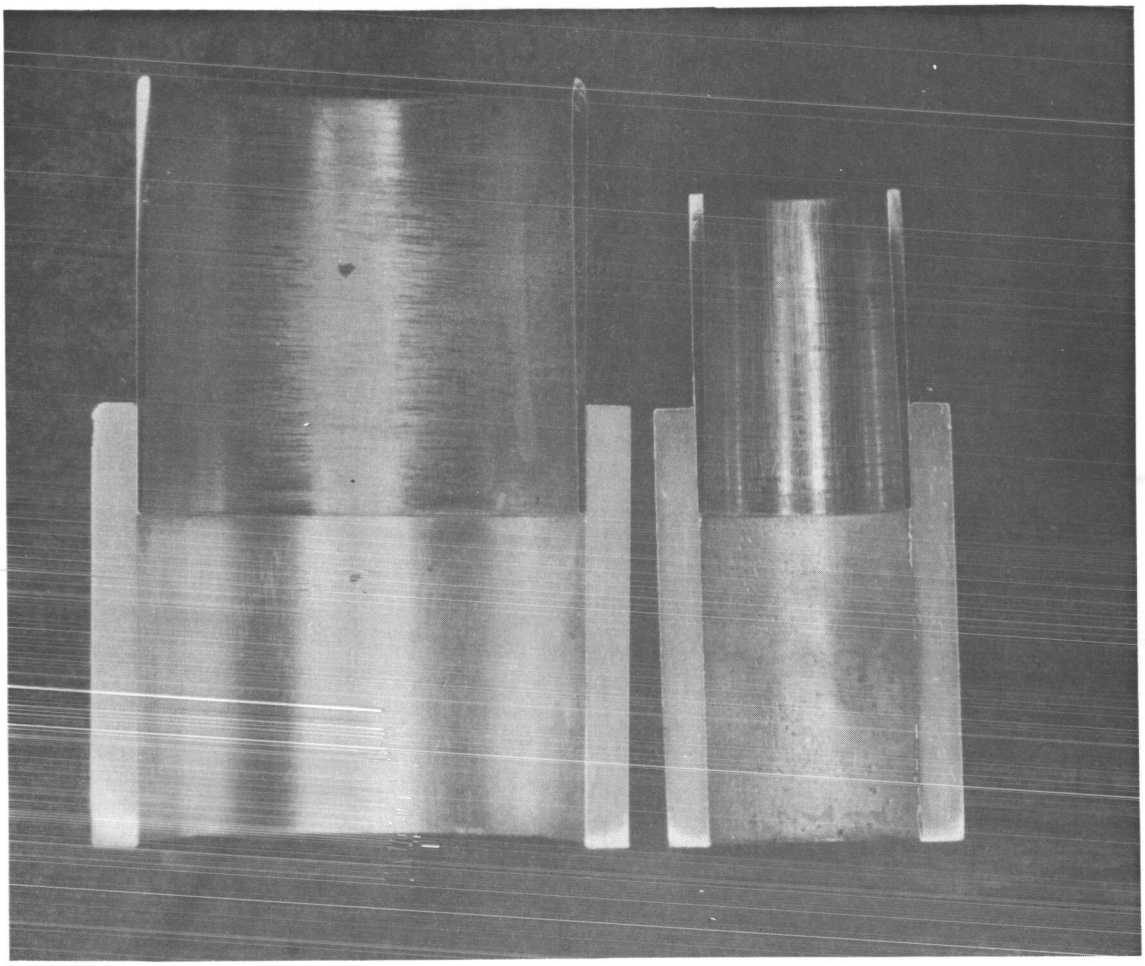


FIGURE 91: CROSS-SECTION OF DIFFUSION WELDED 2219 ALUMINUM ALLOY TO 321 STAINLESS STEEL TUBULAR ASSEMBLIES.

APPENDIX A

STATE-OF-THE-ART SURVEY OF DISSIMILAR METAL JOINING BY SOLID STATE WELDING

ABSTRACT

The state-of-the-art of joining dissimilar metals by solid state welding was determined by a literature survey and visits to five selected organizations. Useful data are available on solid state welding of aluminum alloys to stainless steel. Available information on joining of other dissimilar metal systems is limited. General information has been compiled on processing, metallurgical techniques, diffusion phenomena and solid state welding characteristics of similar and dissimilar metals. These data are reported in three parts: a review of pertinent information, a summary of the state-of-the-art visists and an annotated bibliography. This survey was completed in July 1965.

TABLE OF CONTENTS

	Page
INTRODUCTION	A4
FUNDAMENTALS OF DIFFUSION BONDING	A6
SOLID STATE WELDING PROCESSES	A8
Press Bonding	A8
Roll Bonding	A9
Gas-Pressure Bonding	A10
Explosive Bonding	A10
Resistance Diffusion Bonding	A10
SOLID STATE BONDING OF DISSIMILAR METALS	A11
Joining of Bare Metals	A11
Joining with Intermediate Materials	A14
STATE-OF-THE-ART TOUR	A18
CONCLUSIONS	A24
ANNOTATED BIBLIOGRAPHY	A25

INTRODUCTION

A comprehensive state-of-the-art survey has been conducted on joining of dissimilar metals by solid state welding. This work was performed as the first phase of Contract NAS 8-20156, "Study of Dissimilar Metal Joining by Solid State Welding". The objectives of this research and development program are: (1) to study the mechanisms by which dissimilar metal joining of various alloy combinations is accomplished by press bonding and roll bonding and means by which such solid state bonding can be facilitiated, and (2) to determine the characteristics of completed joints between the dissimilar metal combinations to be studied.

The survey consisted of a literature search for information related to solid state welding of dissimilar metals and a state-of-the-art tour to selected organizations believed to be most able to provide useful information. The prime objective of the survey was to compile data in order to facilitate planning and performance of the experimental phases of the program. The following types of dissimilar metal combinations have been designated for study on the experimental program:

Aluminum alloy to stainless steel
Titanium alloy to aluminum alloy
Titanium alloy to stainless steel
Titanium alloy to nickel-base alloy
Stainless steel to nickel-base alloy

The emphasis of the survey was on joining of these material combinations. Consideration was given to joining with and without the use of intermediate materials. Review was made of the various solid state welding methods, but emphasis was placed on press bonding and roll bonding since these techniques will be used in the experimental study.

It became apparent early in the literature search that limited useful data were available on solid state welding of the specified dissimilar metal combinations being considered in the experimental program. For this reason, selected information was included on diffusion phenomena and bonding characteristics of related materials or material combinations which would contribute to an improved overall knowledge of the subject.

This report on the state-of-the-art survey is composed of essentially three major parts:

Review of pertinent information

Summary of the state-of-the-art tour

Annotated bibliography

The initial portion of the report reviews pertinent information on solid state welding under the following technical categories:

Fundamentals of Diffusion Bonding

Solid State Welding Processes

Solid State Bonding of Dissimilar Metals

The summary of the state-of-the-art tour is a review of the visits made to five selected organizations and of the technical information obtained which is related to solid state welding of dissimilar metals.

The bibliography contains 71 selected references related to solid state welding. References are listed alphabetically by author. Each reference is accompanied by an abstract or summary, which in some cases was contained in the article but in other cases was prepared or edited to suit this bibliography.

No treatise on this subject would be complete without clarification of what is meant by the term "joining by solid state welding". Evans[31]*, in a review of the subject, defined diffusion bonding . . . "as a joining technique by which coalescence of clean, closely fitting parts is obtained by applying pressure with or without heating the assembly. No melting and no measurable deformation of the parts result from diffusion bonding". This definition appears to be somewhat too restrictive since in his summary of diffusion bonding techniques, he discusses forge welding and eutectic diffusion brazing. Forge welding involves extensive deformation and eutectic diffusion brazing involves melting in the form of a transient liquid phase.

A somewhat better definition has been provided by Albom[1]; "Solid state bonding is a joining technique in which time, temperature and pressure produces, through diffusion, coalescence of the base materials being bonded". For the purposes of this report the latter definition adequately describes solid state welding. To minimize confusion in this report, the terms - solid state welding, solid state bonding, solid state diffusion bonding and diffusion bonding - will be considered synonymous. Processes which involve a transient liquid phase variously called "diffusion brazing", "diffusion sink brazing" or "eutectic diffusion bonding" will be considered as related processes and will be covered also in this survey.

*Numbers denote references in the Bibliography

FUNDAMENTALS OF DIFFUSION BONDING

The technical literature contains numerous reports on fundamental studies of diffusion phenomena. Although many of these were concerned only with learning more about fundamental reactions, a number of reports were reviewed in which the studies were directed towards diffusion phenomena as applicable to development of dissimilar metal diffusion bonding processes.

Castleman[10-17] and his co-workers conducted extensive fundamental investigations from 1954 to 1962 on the diffusion bonding problem related to fabrication of components for nuclear reactors. Detailed studies[10] were conducted on formation of intermediate layers in the diffusion zone of Ni-Al diffusion couples. Only the Ni_2Al_3 and the $NiAl_3$ phases were observed to form layers in specimens press-bonded at temperatures of 750° to 1160°F. The other two possible intermetallic phases NiAl and Ni_3Al did not appear to form during diffusion bonding. A significant part of this work was devoted to determining the effect of pressure on phase formation.

Subsequent work[13,18,19] conducted with very long diffusion times, disclosed that the two missing stable intermetallic phases, NiAl and Ni_3Al were indeed present but in diffusion bonding the layers were too thin to be detectable.

Investigations[11,12] were conducted on interdiffusion and pressure effects on the somewhat less complicated U-Al system. Increased pressure was observed to increase the formation of the UAl_3 phase. Similar pressure effects were not obtained for the Ni-Al system.

Investigations[15,16] were conducted on the Cu-Zn system with particular emphasis on growth kinetics of beta-brass layers in the alpha-brass vs. gamma-brass diffusion couples. Studies were also initiated on diffusion phenomena of the more complex ternary Cu-Zn-Ni system.

The interdiffusional aspects of the diffusion bonding problem were viewed from an analytical approach by Castleman[9]. Three idealized types of dissimilar metal systems were discussed.

One Phase - Complete mutual solubility
Two Phase - Partial solid solubility
Three Phase - Growth of an intermediate phase

For the two-phase and three-phase systems, a detailed analytical evaluation was presented of the important roles played by the boundary and interface concentrations and the diffusion coefficients in controlling interface movements and interdiffusion.

McEwan and Milner[46] studied diffusion bonding phenomena of dissimilar metals using roll bonding techniques. The metal pairs studied were divided into four groups:

Immiscible Pairs	- Cd-Fe, Fe-Pb, Cu-Pb, Cu-Mo
Partially Miscible Pairs	- Cu-Fe, Cu-Ag, Al-Zn
Miscible Pairs	- Cu-Ni, Fe-Ni, Mg-Cd
Intermetallic Forming Pairs	- Cu-Al, Fe-Al, Ca-Pb, Mg-Al, Ag-Al, Fe-Mo

On roll bonding at high temperatures or on post-bonding heat treatment, the properties of the joints were found to be determined by the extent and effect of interdiffusion. Solid state bonded joints of immiscible and partially miscible systems were generally stable. Miscible systems could be readily bonded but sometimes the bond weakened upon heat treatment due to formation of diffusional porosity. Two types of behavior were observed for intermetallic forming pairs depending upon whether or not the interface layer possessed any ductility. In most cases a brittle intermetallic layer was formed and the bond was strong if the layer was maintained below a critical thickness, but weak if it grew above this thickness. In some cases a ductile intermediate phase was formed. These joints were usually strong, with failure generally occurring in the weaker metal.

LeClaire and Bear[44] investigated the interdiffusion of uranium and aluminum and related the diffusion zone width as a function of temperature, pressure and time. Their experiments showed an appreciable accelerating effect of pressure on the rate of interdiffusion. It was suggested that this phenomenon might result from one of the following pressure induced changes: (1) changes in the interface concentrations, (2) allotropic transformations in existing phase, or (3) nucleation of new stable phases. Castleman[12] confirmed the pressure induced acceleration of diffusion and attributed it to increased formation of UAl_3 phase possibly resulting from a decrease of voids in the diffusion zone.

Baird[3] studied formation of intermediate alloy layers in the interdiffusion of metals and observed that parabolic growth of phase layers takes place at relatively high temperatures where volume diffusion is the controlling factor. At low temperatures the growth takes place predominantly by grain boundary diffusion in accordance with the following growth equation:

$$x = Kt^{1/n}; \text{ where n may be between 2 and 4}$$

In this equation x is distance, t is time and K is a constant.

Eckel[29] studied diffusion across dissimilar metal joints using diffusion couples of ferritic steels to austenitic stainless steels or nickel-base alloys. Carbon was observed to migrate in the direction of higher alloy content and also in the direction of lower carbon content. Evidence indicated that Fe diffuses into an austenitic steel from a ferritic steel, that Ni diffuses into the ferritic steel and that Cr diffuses away from the interface in both directions.

SOLID STATE WELDING PROCESSES

In simple terms, the only requirement for solid state welding is to bring the mating clean surfaces close enough together to permit their interatomic attractive forces to become effective. The essential ingredients in solid state welding are time, temperature and pressure. These controlling factors are interdependent.

Solid state welding per se is not a new joining technique; in fact, forge welding is one of the oldest joining methods known. However, in recent years, solid state welding has received increased attention. Review of the literature reveals a variety of solid state welding processes and in addition a number of different terms are used to describe essentially the same process. For purposes of this survey, the various solid state welding processes will be placed in one of the following classifications:

Press Bonding
Roll Bonding
Gas-Pressure Bonding
Explosive Bonding
Resistance Diffusion Welding

Press bonding and roll bonding are of primary concern in this survey, and the other techniques will be reviewed briefly as related processes.

Press Bonding (Presssure Bonding)

Press bonding may be accomplished at room temperature, in which case it is sometimes referred to as cold pressure welding[4], or it may be performed at elevated temperatures, in which case it has been termed by various investigators as hot pressure bonding[59], recrystallization welding[55] or diffusion bonding[48,63].

Tylecote[61] conducted an investigation to establish certain of the principles involved in the process of pressure welding. The degree of deformation required to produce good welds at room temperature was determined for various metals and alloys in both similar and dissimilar pairs. Minimum deformation ranged from 10% to 90% for the various materials. Particular attention was given to determining the connection between weldability and properties of the surface oxide film.

Practical applications of pressure welding from 1946 to 1956 were summarized by Tylecote[62]. Techniques and advantages of the process were discussed. The main applications were given as: (1) lap joints in copper and aluminum alloy sheet and (2) butt joints in steel bar or sections.

Parks[55], as a result of investigating pressure welding at elevated temperatures, reached the conclusion that recrystallization is the basic mechanism of solid phase welding and stated that the process should be rightly called "recrystallization welding". Test data are presented to show relationship between recrystallization temperature, degree of deformation, weld temperature and weld strength of various common sheet metals. It is stated that welding below the recrystallization temperature can only be achieved if the surface layers are severely deformed during welding. Such welding is described as "deformation recrystallization welding".

Pressure diffusion bonding has been adapted to the fabrication of expandable honeycomb core in a process called Astroweld[67]. This process has been used to produce titanium, stainless steel, superalloy and refractory alloy honeycomb core with and without the use of intermediate alloys[63]. Titanium alloy honeycomb sandwich panels have been successfully fabricated by low pressure (creep controlled) bonding to avoid crushing of the core[47].

Although the more pertinent references have been reviewed, a number of other investigations of solid state welding by press bonding techniques involving both similar and dissimilar metals have been included in the bibliography.

Roll Bonding

Roll bonding has been extensively studied for joining of both similar and dissimilar metals and has led to the successful development of processes for cladding of sheet and plate and more recently for fabrication of structural shapes. Appreciable deformation, in the order of 25 to 90 percent in thickness, generally is required to achieve good metallurgical bonds during roll bonding.

Cladding of aluminum with stainless steel by roll bonding has been developed by Dulin[28,71]. Using this process, a stainless steel clad aluminum product has been marketed under the trade name "Duranel"[64].

Roll bonding has also been used to clad steel with titanium for applications in the chemical industry[40,51]. In the cladding process, the temperature during roll bonding is relatively low in order to minimize the interdiffusion of the bimetals and to avoid formation of brittle interface layers.

Recently roll bonding has been applied to fabrication of structural shapes for aerospace applications[70]. The process has been developed for fabrication of titanium alloy roll-bonded sandwich structures. Extensive deformation, in the order of 60% in thickness, is involved and steel inserts forming the internal voids are removed by acid leaching.

Gas-Pressure Bonding

The gas-pressure bonding process makes use of high isostatic pressures at high temperatures to produce solid state diffusion bonding[54]. No deformation results during gas-pressure bonding except that necessary to bring the mating surfaces into intimate contact. The components are assembled in an expendable container or are edge welded to provide a pressure tight evacuated envelope. The assembly is heated to an elevated temperature in an autoclave containing an inert gas at high pressure.

This process has been used to produce metallurgical bonds between a variety of similar and dissimilar metals with and without the use of intermediate materials. Gas pressures generally range up to 15,000 psi and bonding temperatures up to 3000°F are used[8].

Explosive Bonding

Explosive bonding is a relatively new concept in metal bonding and extensive development is still required before this method will be used for general application. Studies on explosive bonding of similar and dissimilar metals have been conducted by Pearson and Hayes[56]. Developments by several companies have been reviewed by Fairlie[32]. Potential applications include bimetal cladding of sheet and plate and bimetal lining of tubes. A fundamental study of explosive bonding by Cowan and Holtzman[23] indicated that three types of bonds can be achieved by high velocity impact of plates: (1) a direct bond, (2) a uniform layer of solidified melt and (3) a wavy interface of regions of direct bond and solidified melt. Bonding is related to jetting of the metal surfaces in the space ahead of the region of impact.

Resistance Diffusion Welding

The resistance diffusion welding process has been used to form solid-state metallurgical bonds in both similar and dissimilar metals using conventional resistance welding equipment. Applications for this process have included bonding of dissimilar metal combinations which form brittle compounds upon melting and to similar metal bonding where melting causes degradation of joint properties. Hess and Nippes[37] investigated resistance diffusion bonding of 3003 aluminum alloy to AISI 4140 steel. The best joint properties were developed using electroplated silver as an intermediate material.

SOLID STATE WELDING OF DISSIMILAR METALS

Review of the state-of-the-art of solid state bonding of dissimilar metals can be presented most effectively by dividing the subject on the basis of two joining systems: joining of bare metals and joining using intermediate materials.

It is apparent from a survey of the literature that joining of dissimilar metals with intermediate materials has achieved far greater success than using bare metals in both the application of diffusion bonding to production assemblies and to the development of optimized bonding parameters in research investigations. The following reasons have been indicated for the greater attention given to use of intermediate materials[31]: (1) the proper choice of intermediate materials permits bonding at temperatures below where any important metallurgical changes in the base metals take place, (2) another metal in the joint area may permit bonding to occur without the formation of detrimental intermetallics between the base metals, (3) the use of plated intermediate layers overcomes the problem resulting from the formation of tenacious oxides on the surfaces, and (4) it is possible to "diffusion braze", a process whereby a transient liquid phase forms at the interface and is then completely diffused away into the base metal.

In the following review of solid state welding of dissimilar metals, primary emphasis is placed on press bonding and roll bonding. Particular consideration is given to the following factors:

Dissimilar metal combinations

Time, temperature, pressure parameters

Intermediate materials

Atmosphere

Surface condition and preparation

Joining of Bare Metals

Storcheim[59] reported on a pressure bonding investigation with Al-Ni, Al-Cu, Al-Fe and Al-Zr diffusion couples. Variables of time, temperature and bonding pressure were studied with regard to joint strength and metallographic structure. In general, as the temperature increased, joint strength increased, reached a maximum and then decreased when brittle intermetallics were formed. Time at bonding temperature had the same effect. At properly chosen temperatures and pressures, depending upon the diffusion couple, the strength increased with increasing bond pressure. Metallographic studies indicated that detrimental diffusion-zone thicknesses can be controlled by proper application of pressure. Increasing pressure decreases the intermetallic zone thickness for the Al-Ni and Al-Cu systems, while the reverse is true for the Al-Fe system.

Specimens were bonded in a vacuum of less than 5 microns. Mechanical abrading of specimens immediately prior to bonding gave the most expedient and reproducible results. Data presented for Al-Ni couples showed bonding pressures to 40,000 psi, bonding temperatures from 750°F to 1110°F and times from 1 to 10 minutes. Maximum ultimate tensile strength (20,000 psi) was obtained using 40,000 psi pressure, 930°F temperature and 4 minutes bonding time.

Cooke and Levy[22] investigated the diffusion bonding of various aluminum alloys to 18-8 stainless steel. Diffusion bonding was accomplished by the following three methods:

1. By pressing a bar of aluminum to a bar of stainless steel (butt joint). At the desired pressure and temperature the bars were twisted in relation to each other to produce the bonded joint.

2. By inserting a tapered stainless steel rod into a tapered hole of an aluminum block and heating to the desired temperature followed by pressure to force the steel rod into the tapered hole to produce the bonded joint.

3. By pressing an aluminum alloy block against a stainless steel block (butt joint) at the desired temperature. Pressures approximating four times the yield strength were used. Both parts were enclosed in a die to prevent the aluminum from flowing.

Pressure bonding was conducted in air at temperatures from 400° to 850°F. Parts were cleaned by mechanical methods prior to bonding. Tensile strengths of the bonded joints varied from 10,000 to 30,000 psi.

Strengths of bonded assemblies were found to be increased by as much as 100 percent by subsequent annealing. It was suggested that this increased strength was due to formation by diffusion of a very thin (submicroscopic) film of an intermediate phase, probably an intermetallic compound. When this phase is thick enough to be observed microscopically, then the bond strength is greatly reduced.

Both 32S and B18S aluminum alloys bonded to 18-8 stainless steel (AISI 303, 310, 321) frequently could be strengthened by solution heat treatment and aging, without lowering the bond strength.

U.S. Patent 2,908,073[71] issued to Dulin and assigned to Alcoa, relates to methods for bonding aluminum alloys to steel and copper alloys. The methods outlined are adaptable for joining flat plates of aluminum to steel for use in the manufacture of electric flat irons and cooking utensils. Prior to joining, both the aluminum and the dissimilar alloy are cleaned by mechanical or chemical means. The parts being joined are pressed together to exclude air from the joint and are heated to a temperature range of 700 to 950°F. Pressure is increased to cause the aluminum to flow laterally. The pressure required varies from 15,000 to 50,000 psi depending on the temperature used. The aluminum thickness is reduced from 10 to 50% during bonding. The patent claims bonded joints can be obtained which have high peel strength and without the formation of intermediate phases.

Dulin[28] discusses various applications for the pressure bonding of aluminum to steel and copper alloys using the process described in the above patent. A number of examples are described of aluminum alloys bonded to stainless steel for fabrication of flat irons, cooking utensils and transition tubes.

Wood[64] discusses a stainless steel clad aluminum sheet product fabricated by the above process which is being marketed under the trade name "Duranel". The laminated sheet is composed of AISI 304 stainless steel roll bonded to 3004 aluminum alloy. The metallurgical bond can withstand forming into various shapes without detrimental effects.

Tylecote[61] pressure bonded Al to Fe and Al to Ni at room temperature with 50% and 60% deformation, respectively, required to achieve good bonds. Heat treatments of joints at 750°F caused no change in joint strength while heat treatment at 930°F caused severe loss in joint strength. Attempts to bond Ni to Fe at room temperature were unsuccessful even with deformations as high as 72%.

Hughson[40] described a process developed by Lukens Steel Company for producing titanium clad steel plate. An enclosed sandwich of titanium sheet and A-204 low-carbon manganese steel plate was flushed continuously with argon while being heated before rolling, to eliminate impurities that interfere with the bond. Window frame type spacers were used to separate the titanium sheet and steel plate during heating in order to permit argon flushing and to prevent diffusion. Two clad plates, with the titanium sheets back to back, were roll bonded in one sandwich. Preheat temperature limit before rolling was 1700° to 1750°F. A reduction of at least three to one was required for good bonding. No intermediate material was used. Formation of brittle compounds was prevented by limiting the time at elevated temperature in which diffusion could take place.

Moore[51] described the use of titanium-clad steel for process equipment. The methods of producing titanium clad steel are briefly described. The first method is the Lukens Steel process whereby the composite is produced by simple roll bonding at a temperature below that at which brittle compounds can form. Explosive cladding and brazing are described as additional methods for producing titanium-clad steel plate. Limited information is presented on fabrication details.

Diffusion phenomena were reviewed extensively in a previous section, "Fundamentals of Diffusional Bonding" and these references will not be repeated. However, it should be emphasized that formation of brittle phases at the interface of Al-Fe, Al-Ti, Ti-Fe and Ti-Ni couples is one of the key factors which is responsible for the lack of progress in development of processes for bare metal joining of these metals and their alloys.

Joining With Intermediate Materials

The literature contains only limited information on solid state bonding of dissimilar metals using intermediate materials. Most of these references involve joining of aluminum alloys to steel. However, the very use of an intermediate metal provides a dissimilar metal interface. For this reason pertinent information can also be obtained by review of similar metal joining using intermediate material and several of these references are included in this section.

Crane, et al[24], developed a diffusion bonding technique for joining of 2219 aluminum alloy to 321 stainless steel using electroplated silver as an intermediate material. Successful diffusion bonding was accomplished at temperatures of 500° to 600°F, pressures of 20 to 25 KSI and times of 2 to 4 hours. The joint faying surfaces were electroplated with silver prior to bonding. The silver prevented the formation of oxide-film barriers and controlled formation of embrittling phases.

Processing techniques for diffusion bonding of large diameter assemblies were successfully developed and demonstrated by fabrication and testing of four 20-inch diameter joints. A unique diffusion bonding method was developed utilizing simple differential thermal expansion tooling. The method can be economically adapted to production requirements.

It was concluded that diffusion bonding is the most satisfactory method for joining large diameter stainless steel to aluminum alloy cylinders and is superior in strength and reliability to welding or brazing.

Orysh, Betz and Hussey[53] investigated procedures for diffusion bonding 3003 aluminum alloy to 304 stainless steel and 2024 aluminum alloy to 1020 steel. In all cases the steel was precoated with a silver brazing alloy (BAg-10) using an oxyacetylene torch. The silver layer was then ground flat to a thickness of 0.005 inch.

Prior to bonding, the silver layer was cleaned with alcohol and the aluminum was chemically cleaned using an alkaline etch followed by dilute nitric acid and water rinse. Bonding was attempted at temperatures varying from 200°F to 800°F, varying pressure and time. From this screening test the authors selected a bonding temperature of 800°F and a pressure of 2400 psi (2.3% joint deformation) as being optimum.

The following data show the shear test results as a function of bonding time for silver coated 1020 steel bonded to 2024 aluminum alloy using a bonding pressure of 2400 psi and a bonding temperature of 800°F.

Time, min.	Shear Strength,* psi
10	2070
30	1900
60	2730
120	3330
180	3110
240	2300

*Average of three specimens.

Gatsek[36] reported that preliminary studies have shown feasibility of a process for diffusion bonding 2219 aluminum alloy to 321 stainless steel. The process involves applying and bonding an intermediate alloy to the surface of the stainless steel and plating the aluminum alloy with the same intermediate material. The interface material serves two purposes; it is used as a bonding agent and as a barrier material between the aluminum and the steel. Tin and silver are mentioned as interface materials but comparative results are not indicated.

Ness and Nippes[37] investigated joining of 3003 aluminum alloy to SAE 4140 steel using resistance welding techniques. It was found necessary to use an intermediate material to avoid overheating the steel. The intermediate material was applied by electroplating the steel. The metals used for plating were tin, zinc, silver, copper, nickel, chromium and cadmium. Aluminum was resistance bonded to electroplated steel using an 800 pound electrode force and 10 cycles

welding time. Current was varied to produce the desired penetration into the aluminum side of the joint. Silver was selected as the most desirable intermediate metal for bonding the 3003 aluminum alloy to 4140 steel. Copper was considered satisfactory but required more rigid welding controls to prevent brittle joints. It was observed that plating procedures must be rigidly controlled because much of the bond strength of the joint depends upon the adherence of the plating to the steel.

Barta[5] investigated low temperature (300°-450°F) similar metal diffusion bonding of 7075, 6061 and 2219 aluminum alloys using diffusion aids in various forms including electroplated, vacuum deposited, plasma sprayed, loose shim material and clad aluminum. The best intermediate material was clad aluminum. Shear strengths of 9000 to 10,000 psi were obtained on 7075 aluminum alloy clad with 7072 aluminum alloy which was bonded at 325°F for 1 hour at 24,000 psi pressure.

Electroplated Cu, Sn and Zn did not prove satisfactory as diffusion aids when bonded at low temperatures. Electroplated Ag gave good shear strengths (6700 psi) when bonded at 450°F for 4 hours at 16,000 psi pressure. Silver was not considered as a good intermediate material because it would create a galvanic reaction with aluminum under certain atmospheric conditions.

Search of the literature disclosed no references to diffusion bonding of titanium alloy to aluminum alloy, titanium alloy to stainless steel or titanium alloy to nickel-base alloy.

Several references were found on diffusion bonding of titanium to titanium using intermediate materials, but in most cases these involved a transient liquid phase. For example, DeCecco and Parks[26] investigated bonding titanium using silver as an intermediate material. The silver melted and was squeezed out of the joint and served primarily as a cleaning and flushing agent, while the clean titanium surfaces were forced into intimate contact and bonded by recrystallization welding.

Clark[20] investigated silver brazing of titanium to titanium in which the silver diffused away from the joint area by holding for 1 hour at 1850°F in a vacuum. Tensile strengths up to 67,000 psi at room temperature were obtained in Ti-5Al-2.5Sn alloy. Diffusing of the silver away apparently resulted in a ductile joint by dispersing of the detrimental silver-titanium intermediate phase.

No references were found on diffusion bonding of stainless steel to nickel-base alloy using intermediate materials. Davies and Stephenson[25] developed similar metal joining procedures to diffusion bond a nickel-base alloy utilizing nickel foil or electroplate. The process included final diffusion and aging treatments.

Several other interlayer materials were investigated and found to be unsatisfactory. Titanium and aluminum interlayers resulted in formation of brittle intermetallic compounds, and cracks were observed after the final diffusion treatment. Successful joints were obtained with copper interlayer, but shear strengths were lower than for nickel, and high bonding temperatures were needed.

Eckel[29] used nickel foil as a diffusion barrier in studying diffusion across dissimilar metal joints of ferritic steel to austenitic steel. The nickel barrier reduces but does not completely prevent carbon migration. The formation of voids in the barrier layer was attributed to nickel diffusion. The diffusion joints were bonded at 1300°F and then given diffusion treatments at 1300°F for times up to 8000 hours in vacuum.

Niemann, et al,[52] investigated techniques to diffusion bond beryllium copper to Monel at the aging temperature (650°F) of the beryllium copper. In all tests, two electroplated material combinations were used, one on the beryllium copper and a different metal on the Monel. A bonding pressure of 6700 psi and 3 hours bonding time (aging time of Be-2Cu) were found to be adequate. Diffusion bonding was conducted in an inert gas atmosphere. Ductile, high strength joints were obtained with Au-Cu and Au-Ag plating combinations. Joints bonded with Au-Pb and Au-Al plating combinations were found to be quite brittle. The average shear strengths obtained for Au-Cu (10,150 psi) and Au-Ag (10,550 psi) systems were assumed to provide a tensile strength of at least 20,000 psi for these joints. The tensile strengths of gold and silver are about 20,000 psi and for copper about 32,000 psi. It was indicated that joints made with these metals could be as strong or stronger than the metals themselves because of alloying that takes place and the state of stress that exists because of joint dimensions.

STATE-OF-THE-ART TOUR

State-of-the-art visits were conducted to five selected organizations believed to be most able to provide information directly related to solid state welding of dissimilar metals. The tour was taken to supplement the literature survey in determining the work on solid state bonding which has been completed or is in progress by industry, government agencies or research institutions.

Organizations to be visited were selected on the basis of information gathered by the literature search followed by direct confirmation with the organization. Visits were made to:

Alcoa Research Laboratories
Battelle Memorial Institute
North American Aviation
Northrup-Norair
Westinghouse Astronuclear Laboratories

The two current Boeing-NASA contracts on joining dissimilar metals were reviewed with each organization in order to promote a better discussion of diffusion bonding techniques.

The general conclusions drawn from these visits are as follows:

1. Extensive R&D work is being conducted on diffusion bonding, but only a very limited amount of this effort is devoted to joining of dissimilar metals.

2. Organizations engaged in diffusion bonding development consider their work very proprietary and extremely competitive, and for these reasons are reluctant to discuss details of bonding procedures or to show their laboratory facilities.

3. The primary benefit resulting from this state-of-the-art tour was the personal cognizance of the work being conducted under active and completed R&D contract effort on diffusion bonding and the sources for obtaining the reports prepared under these programs.

Following is a summary of pertinent technical information obtained:

ALCOA RESEARCH LABORATORIES, ALUMINUM CO. OF AMERICA - New Kensington, Pa.

Principal Contact: Dr. P. T. Stroup
Assistant Director of Research

Alcoa has been active in development of solid-state diffusion bonding and transient liquid phase bonding methods for joining of aluminum alloys and joining of aluminum alloys to dissimilar metals, particularly stainless steel and copper. Solid-state diffusion bonding processes have been developed which include a process for roll bonding of stainless steel clad aluminum and a process for pressure bonding of aluminum to stainless, carbon and alloy steels, and to copper.

Roll-bonded stainless steel clad aluminum sheet is marketed under the trade name "Duranel" and consists of a thin sheet of 304 stainless steel bonded to 3004 aluminum alloy. This material is currently in production for cooking utensils. Alcoa is promoting stainless steel clad aluminum for other applications and The Boeing Company, Commercial Airplane Division, has shown interest in this material for engine fire walls and for water storage tanks.

Dr. Stroup indicated that they have no currently active R&D programs for solid-state diffusion bonding of either aluminum alloys or dissimilar metals. Although Alcoa has conducted diffusion bonding work with electroplated silver, they felt that the problem of galvanic corrosion between silver and aluminum limited the potential applications for this process.

Recent R&D efforts have been directed at liquid-phase diffusion-controlled eutectic bonding techniques. The R-260 bonding process has been developed for joining aluminum and the R-318 bonding process for joining copper to aluminum. Both of these techniques utilize a carbon block brazing press with electrical contact resistance heating. Copies of reports on the eutectic bonding techniques and several other useful reports were obtained.

BATTELLE MEMORIAL INSTITUTE - Columbus, Ohio

Principal Contact: Donald C. Carmichael
Assistant Chief, Materials Development Division

Battelle has been very active in development of solid state diffusion bonding techniques with primary emphasis on similar metals although some effort has been devoted to dissimilar metal joining. Major developments have been accomplished in gas-pressure bonding, diffusion bonding of refractory metals and roll bonding of sandwich structure.

R&D programs on solid-state bonding have been conducted by the Materials Joining, Materials Development and Non-Ferrous Metallurgy Divisions. The Materials Development Division which is responsible for gas-pressure bonding has performed the major part of past R&D contracts on diffusion bonding. The Non-Ferrous Metallurgy Division is responsible for development of roll bonding of sandwich structure. The Joining Division is responsible in general for solid-state bonding development with the exception of gas-pressure bonding and roll bonded sandwich structure.

A list was obtained of fifteen diffusion bonding programs completed or in progress at Battelle. Four of these may provide useful information for the current Boeing-NASA contract.

	Title	Agency	Contract No.
1.	Preliminary Study of Diffusion Bonding Techniques for Use in Making Tubing Connections in Stainless Steel	NASA-GE	Sub-contract from General Electric
2.	Fundamentals of Solid-State Welding and Their Application To Beryllium, Aluminum and Stainless Steel	Army Missile Command, Redstone Arsenal	DA-01-021-AMC-11706 (Z)
3.	Effects of Surface Preparation on Solid State Bonding	AEC	W-7405-eng-92
4.	Development of Techniques for Making Throat Blocks for Gas Dynamics Facilities by Diffusion Bonding	USAF	AF 40(600)-706

The following reports in connection with these programs were recommended:

"Preliminary Study of Diffusion Bonding Techniques for Use in Making Tubing Connections in Stainless Steel" by P. A. Kammer, R. E. Monroe, and D.C. Martin, dated July 29, 1964.

Obtain from:
Mr. Forrest O. Rathbun
Advanced Technology Laboratories
General Electric Company
Schenectady 5, New York

"Fundamentals of Solid State Welding and Their Application to Beryllium, Aluminum and Stainless Steel" by D. Hauser, P.A. Kammer, and D.C. Martin, dated July 15, 1965.

Obtain from:
Army Missile Command
Redstone Arsenal
Huntsville, Alabama

"Effects of Surface Preparation on Solid State Bonding" by D.J. Diersing and D. C. Carmichael.

Obtain from:
AEC (Expected to be released by October 1965)

A number of abstracts of pertinent literature were obtained during a visist to the DMIC library.

NORTH AMERICAN AVIATION INC./LOS ANGELES DIVISION, Los Angeles, Calif.

Principal Contact: Julian King, Jr.
Supervisor, Metallurgy, Research and Engineering

North American has been very active in diffusion bonding and has developed processes for electric blanket bonding, resistance spot diffusion welding, roll bonding and press bonding. Mr. King indicated that NAA has been supporting diffusion bonding development on company research funds for the past six years. In view of the proprietary and competitive nature of solid state bonding research, discussion was restricted to government sponsored programs and no tour was made of the laboratories.

The following programs were mentioned as being currently active:

NASA: Development of High-Strength Low-Density Composite Materials for Saturn Applications

Roll Bonded Titanium Alloy "Y" Ring

Roll Bonded Tank Wall Shape

Research and Development for Fabricating a Simulated Titanium Alloy Segment for S-1C

Titanium S-1C Skin Sections (Steel Tank Wall)

USAF: Roll Bonded Conjugate Tank Development

Diffusion Bonded Honeycomb Sandwich Panels

Spot Diffusion Bonding of Beryllium and Titanium

Mr. King was up-to-date on the Boeing-NASA contract for joining of stainless steel to aluminum alloy tubes. He indicated that in view of the success achieved by Boeing on diffusion bonding of dissimilar metal tubing he was considering this technique in connection with some of the NAA programs.

NORTHRUP-NORAIR, Hawthorne, California

Principal Contact: Dr. E. B. Mikus
Chief, Materials Research

Northrup is actively engated in development of diffusion bonding techniques with particular emphasis on diffusion bonded sandwich structure. Dr. Mikus was most cooperative in discussing their research programs and showing their laboratory facilities. However, he emphasized that information on diffusion bonding of titanium alloy sandwich structure is highly proprietary and competitive and should only be considered as being given on a confidential basis. In any event the Northrup titanium diffusion bonding process is not applicable to the Boeing-NASA dissimilar metals program and specific processing details will not be discussed in this report.

Northrup has not been working on diffusion bonding of dissimilar metals. Current and past diffusion bonding research has emphasized titanium alloys and refractory metals with the greatest davances made in liquid-phase diffusion bonding techniques. They feel this is the most feasible approach for honeycomb sandwich structures because of the light pressures which can be tolerated during bonding. The most significant problems encountered have been core crush and procedures for scale-up evaluation. Solid-phase diffusion bonding is being developed for refractory alloys in addition to the diffusion sink brazing approach. This work is being conducted on several in-house diffusion bonding research programs and several USAF R&D contracts.

Several unique items of research equipment were observed during the tour of the laboratories. One of these was a welding research instrument, called a "Gleeble" Model 510, manufactured by Duffers Associates, Inc. This instrument can duplicate time-temperature or time-temperature-pressure parameters to simulate conditions in welds and heat affected zones on an expanded scale. The instrument contains a dilatometer which is particularly useful for study of phase transformations.

WESTINGHOUSE ASTRONUCLEAR LABORATORIES, Large, Pa.

Principal Contact: David C. Goldberg
Director, Materials Development

Westinghouse Astronuclear Laboratories are currently active in diffusion bonding on classified AEC programs. Mr. Goldberg indicated that this work involves bonding to graphite, and the information would not be applicable to the Boeing-NASA program in any event. In addition to the classified work, the Laboratories recently received two NASA R&D programs on austenitic/refractory bimetallic materials. These are:

Joining of Austenitic/Refractory Bimetal Tubing

Evaluation of Austenitic/Refractory Bimetals

The project engineer for these programs is:

Phil Stone
NASA Lewis Research Center
Cleveland, Ohio

The joining program involves development of gas tungsten-arc and electron beam welding techniques for joining of the dissimilar metal tubing. Tubing will be supplied from another NASA program and will include stainless steel clad and Inconel clad columbium and tantalum alloys.

The bimetal evaluation program involves investigation of thermal exposure and thermal cycling, under simulated space power system environmental conditions, on properties of dissimilar metal sheet. Diffusion and thermal stresses between the dissimilar metals under ultrahigh vacuum and temperatures up to 1550°F for thousands of hours of service are the problem areas. The materials are explosive bonded bimetal sheet consisting of 316 stainless steel and Inconel 600 bonded to Cb-1Zr, FS-85 columbium alloy and T-222 tantalum alloy.

CONCLUSIONS

The state-of-the-art of joining dissimilar metals by solid state welding has been determined. The conclusions reached as a result of this survey are:

1. Extensive development work has been conducted on solid state welding, but only a very limited amount of this effort has been devoted to joining of dissimilar metals. Basic research and development work to delineate the problems and their solution is now needed as the first step toward development of practical processes for solid state welding of dissimilar metals.

2. A considerable amount of useful information is available on solid state welding of aluminum alloys to steels. Available information on joining of other dissimilar metal systems which can be directly applied to Contract NAS 8-20156 is limited.

3. Solid state welding of dissimilar metals has been more successful when intermediate materials are used than when only the bare metals are joined. The principal reasons for this greater success are that intermediate materials have enabled use of lower bonding temperatures, control of detrimental intermetallic formation, control of oxide formation and development of a transient liquid phase bonding process.

4. Interdiffusion of Al-Fe, Al-Ti, Ti-Fe and Ti-Ni results in formation of brittle phases at the interface. Control of this interdiffusion is a key factor in the development of solid state welding processes for dissimilar metals. Control of detrimental interdiffusion is greatly simplified by use of intermediate materials.

5. Accelerated rate of corrosion is a potential problem in joining of any dissimilar metal combination. The probability of encountering this problem is significantly increased by use of intermediate materials. Careful consideration should be given to corrosion effects in study of solid state welding of dissimilar metals.

ANNOTATED BIBLIOGRAPHY

1. Albom, M.J., "Solid State Bonding", Welding Journal, June 1964, pp 491-504.

   A review of the fundamentals of solid state bonding is presented with a limited discussion on actual bonded samples. Beryllium, Ti-75A titanium, Cb-752 columbium, Mo-0.5Ti, and Ta-10W tantalum alloys were pressure bonded. Beryllium was bonded at a temperature range from 1500° to 2800°F for 1 hour in a vacuum of 5×10^{-5} torr. Molybdenum clamps were used as fixtures with differential thermal expansion between the molybdenum and beryllium providing the pressure needed. The resultant joint showed no evidence of grain coarsening, and pull tests produced 100% joint efficiencies in butt joint round test specimens. For Ti-75A, temperatures less than 1700°F at pressures ranging from 200-600 psi at times up to 15 minutes in a protective atmosphere were used. Satisfactory solid state bonds in Cb-752 were obtained at pressures less than 1000 psi at 2000° to 2200°F in a protective atmosphere. The Mo-0.5Ti alloy was bonded at 2100°F for 15 minutes at 500 psi in a protective atmosphere.

   Examples of dissimilar metal combinations of Mo-0.5 Ti to Cb-752, Mo-0.5Ti to Ta-10W, and stainless steel to titanium were also mentioned.. Diffusion of titanium and stainless steel was observed to cause formation of brittle interface layers.

2. Anderson, O.L., "Adhesion of Solids: Principles and Applications", Bell Laboratories Record, November 1957.

   The principles of adhesion of solids are discussed with emphasis on the effect of localized plastic deformation and piercing of oxide film in facilitating adhesion. Investigation led to development of a technique called thermo-compression bonding for connecting electrical leads to germanium and silicon semiconductors. Features of process are bonding in air without fluxes, low pressures ensure no mechanical or crystal structure changes in semiconductor, low temperatures ensure no diffusion of metal into semiconductor. Most success is achieved when metallic filament is very soft.

3. Baird, J.D., "The Formation of Intermediate Alloy Layers in the Inter-Diffusion of Metals", Journal of Nuclear Energy, Part A: Reactor Science, Vol. 11, 1960, pp 81-88.

   An analytical discussion is given of conditions where the equilibrium phases are not formed in a diffusion couple of two metals. The absence of a phase predicted by the equilibrium diagram could be due either to difficulty of

nucleation or to a very low growth rate. The latter is probably the reason for many of the reported cases, especially where missing phases have higher melting points (and therefore probably lower diffusivities) than the other intermediate phases in the system. It is postulated that once nucleated, a phase layer should grow parabolically if growth is controlled by volume diffusion through the layer. However, if grain boundary diffusion predominates, it is stated that non-parabolic growth of a phase layer occurs. In addition, grain boundaries must be considered as a channel which feeds diffusing material into the grains on either side. Grain boundary diffusion is predicted to predominate at low temperatures and volume diffusion at high temperatures. Oxide layers are expected to be important mainly in the earlier stages of interdiffusion and will limit initial phase growth intermediate between linear and parabolic.

The most striking and unexpected feature of experimental work on layer growth is the large effect of pressure. One explanation of the effect is that the stabilities of the intermediate phases are altered by pressure.

According to the conclusions reached, parabolic growth rates of layers are to be expected at relatively high temperatures where good contact is maintained between the metals by the application of pressure, and where precautions are taken to prevent interference from oxide films.

4. Barnes, W.A., "Cold Pressure Welding," Tool Engineer, Vol. 32(5), May 1954, pp 75-78.

   A general summary of cold pressure welding is discussed without getting into any of the technicalities involved. This method is effective only in joining relatively soft materials such as aluminum, copper, lead, tin, nickel, silver, and platinum to themselves or each other.

   When joining foils of 0.005 inch or less, a clean oxidized surface is required; materials over 0.006 inch are required to have an abraded or galled surface. Lap or butt welds are feasible. Wires can even be joined by butting them and progressively cold flowing them together. Wire diameters successfully cold welded range from 0.032 inch to 0.375 inch.

   Impact tools can be used for some applications of cold welding; however, generally uniformly applied pressures are more satisfactory. Tensile and torsion tests on regular butt and lap welds have indicated strengths above 95% of that of the base metal.

5. Barta, I.M., "Low Temperature Diffusion Bonding of Aluminum Alloys", Welding Journal, Vol. 43, June 1964, pp 241s-257s

   The diffusion bonding of aluminum alloys can be achieved at 300° to 450°F with clad aluminum sheet providing the best diffusion aid or intermediate

material. Plasma spraying showed promise as a technique for applying diffusion aids. Electroplated Cu, Sn and Zn did not prove satisfactory as diffusion aids when bonding at low temperatures. Bare metal bonding proved unsatisfactory at low temperatures for the alloys tested: 7075, 6061, 2219. Surface preparation and cleaning are important for successful diffusion bonding. Machined serrations on interface surfaces give higher strength bonds with low temperature bonding.

6. Buginas, S.J., "Diffusion Bonding: An Annotated Bibliography", Lockheed Missiles and Space Co., Sunnyvale, California, Special Bibliography SB-63-5, March 1963.

   This bibliography contains selected references on diffusion bonding and hot pressure welding from the years 1940-1962.

7. Butts, A., and Van Duzee, G.R., "Cold Welding of Silver", Trans. of the Electro Chemical Society, Vol. 74, 1938, pp 327-339.

   Time-temperature-pressure relationship in pressure welding of silver was studied at temperatures from 390°F to 750°F and pressures up to 45,000 psi. A curve was obtained showing the minimum time necessary to obtain adherent welds at various temperatures under a pressure of 45,000 psi and under varying pressures at a temperature of 750°F. It was found that 390°F, the recrystallization temperature of the silver, is the lowest temperature at which adherent welds could be obtained, except possibly with greatly prolonged application of pressure. Above 390°F, the time necessary to produce an adherent weld decreases rapidly.

   Welds obtained by rolling had greater bond strength than welds obtained by constant pressure in a fixed position. Very thin films of foreign matter between the silver surfaces under pressure caused little interference with welding.

8. Carmichael, D.C., "Diffusion Bonding Sets Sights on the Near Perfect Joint", Iron Age, July 18, 1963, pp 81-83.

   Discussion of solid-state diffusion bonding, including the technique of gas-pressure bonding (isostatic bonding), vacuum-diffusion bonding and eutectic-diffusion bonding, of dissimilar metals and ceramics of complex shapes. High joint strengths are obtained, usually equal to that of the base metal. Emphasis on gas-pressure bonding using a high pressure autoclave with gas pressure up to 15,000 psi at up to 3000°F. Atomic diffusion bridges the differences between many dissimilar metals. Advantages are high strength bonds produced with comparatively low temperatures and with minimum of distortion.

9. Castleman, L.S., "An Analytical Approach to the Diffusion Bonding Problem", Nuclear Science and Engineering, Vol. 4, 1958, pp 209-226.

Attention is focused on the interdiffusional aspects of the diffusional bonding problem as it related to the fabrication of clad fuel elements and their operation at elevated temperatures. Certain idealized cases of core-cladding interdiffusion occurring in single phase, two-phase, and three-phase systems are examined analytically. In the two-phase and three-phase systems, the importance of the roles played by the boundary and interface concentrations and the diffusion coefficients in controlling interface movement and interdiffusion is evaluated in detail.

10. Castleman, L.S., and Seigle, L., "Fundamentals of Diffusional Bonding I", Report No. SEP-227, General Telephone and Electronics Laboratories, Bayside, New York, August 13, 1956.

A detailed study has been initiated of the formation of intermediate layers in the diffusion zone of Al-Ni diffusion couples. This system was chosen because of its significance in fuel element technology. It has been confirmed that only two out of four possible layers form observably during diffusion - the Ni_2Al_3 and $NiAl_3$ phases. The growth of the intermediate layers occurs initially at a rate different from that predicted by the ideal diffusion equations; however, once a minimum thickness is reached, behavior becomes more normal.

11. Castleman, L.S. and Seigle, L., "Fundamentals of Diffusional Bonding II", Report No. SEP-245, General Telephone and Electronics Laboratories, New York, Feb. 15, 1958.

The study of the kinetics of layer growth in the aluminum-nickel system and the effect thereon of applied pressure has been continued. Additional information has been obtained about the growth of beta phase, and a method was developed whereby the kinetics of growth of the beta phase could be investigated. The implications of Vasileff's equations which provide the solution for interdiffusion in a three-phase two-component system have been examined semi-analytically, and quantitative insight has been gained into the kinetics of interface movement. Finally, an investigation of the kinetics of interface movement and layer growth has been begun on systems which have less complicated phase equilibrium relationships than those existing in the aluminum-nickel system.

12. Castleman, L.S., and Seigle, L., "Fundamentals of Diffusional Bonding III", Report No. SEP-251, General Telephone and Electronics Laboratories, Bayside, N.Y., June 30, 1958.

An investigation has been begun of interdiffusion in the aluminum-uranium system and of the effects thereon of applied pressure. In confirmation of the

results of other investigations, it has been found that UAl_3 layer growth is accelerated by increasing applied pressure. The growth kinetics are characterized by a "transient" period, during which growth occurs non-parabolically, which is followed by a "steady state" period of parabolic growth. Interesting correlations are shown to exist between annealing time, annealing temperature, and applied pressure on the one hand, and the nature and distribution of structural defects in the UAl_3 diffusion zone.

13. Castleman, L.S. and Seigle, L., "Fundamentals of Diffusion Bonding IV", Report No. SEP-253, General Telephone and Electronics Laboratories, Bayside, N.Y., June 30, 1959.

    The investigation of interdiffusion in the aluminum-uranium system and of the effects of applied pressure thereon have been substantially completed. The kinetics of growth of the UAl_3 phase have been determined in the temperature range 750° to 1110°F and at pressures of 3500, 10,000 and 20,000 psi. The origin of the macroscopic defects occurring in the UAl_3 layer during interdiffusion has been clarified. The solubility range of UAl_3 has been determined by a nuclear track emulsion technique to be about 2.6 a/o uranium. Exploratory runs have been made with incremental diffusion couples of aluminum vs. UAl_3 and UAl_3 vs. uranium discs to determine the growth rates of the UAl_4 and UAl_2 phases. A theoretical estimate has been made of the extent to which pressure-induced shifts in equilibrium concentrations are important in influencing intermetallic layer growth in the aluminum-uranium and aluminum-nickel systems.

14. Castleman, L.S., Froot, H.A., and Seigle, L., "Fundamentals of Diffusional Bonding V", Report No. SEP-256, General Telephone and Electronics Laboratories, Bayside, N.Y., June 30, 1960.

    An exploratory investigation has been completed of the effects of applied pressure on the kinetics of growth of intermetallic layers in the aluminum-thorium system. Contrary to an earlier published report, no appreciable effect of pressure is found, and the growth kinetics appear to be conventional. Also, preliminary data have been obtained on the effects of pressure on the kinetics of growth of the beta brass intermetallic layer in saturated alpha brass vs. saturated gamma brass couples.

15. Castleman, L.S., Froot, H.A., Seigle, L., "Fundamentals of Diffusional Bonding VI", Report No. SEP-258, General Telephone and Electronics Laboratories, Bayside, N.Y., June 30, 1961.

    The study of the effects of pressure on the kinetics of growth of intermetallic layers in binary diffusion couples was continued. It was found that pressure diminishes beta-brass layer growth in saturated alpha-brass vs. saturated

gamma-brass diffusion couples both above the below the critical transition temperature range for ordering. The effect of pressure appears to be less in the ordered temperature range. In the aluminum-uranium system, the growth of the UAl_3 intermetallic layer contrary to expectations, is not diminished in the pressure range 20,000 to 200,000 psi. An argument is advanced, based on the activation volume concept, that the aluminum ions diffuse in UAl_3 by an interstitial mechanism.

16. Castleman, L.S., Froot, H.A., and Seigle, L., "Fundamentals of Diffusional Bonding VII", Report No. SEP-260, General Telephone and Electronics Laboratories, Bayside, N.Y., June 30, 1962.

    An investigation has been completed of the growth kinetics of beta-brass layers in alpha-brass vs. gamma-brass diffusion couples. It was found that useful estimates of the diffusion coefficients at the interfaces can be made from interface displacement data, and a useful estimate of the mean heat of activation for diffusion can be made from layer growth data. The effects of pressure on layer growth kinetics were explored and found to be consistent with a vacancy model for diffusion in beta-brass in both the disordered and ordered temperature ranges. Preliminary work has been started on investigation of multi-phase diffusion in ternary systems.

17. Castleman, L.S. and Seigles, L., "Fundamentals of Diffusional Bonding VIII Final Report:" Report No. GTR-21, General Telephone and Electronics Laboratories, Bayside, N.Y., Dec. 15, 1963.

    A study was undertaken of interdiffusion in the copper-zinc-nickel system. The identity and sequence of appearance of the intermediate phases found in the diffusion zone were determined by correlation of metallographic observations of microstructure with details of the equilibrium phase diagram and with electron-beam-probe microanalysis. It was found that all except possibly one of the intermediate layers growing in the diffusion zones of the diffusion couples investigated consisted of single phases. In some of the couples the concentration consisted of single phases. In some of the couples the concentration of zinc did not vary monotonically with distance. The sequence of phases in the diffusion couples was independent of time at each temperature. The diffusion paths for couples having the same component as one terminus and a binary alloy of the remaining two components as the other terminus did not appear to cross. The tangent to the diffusion path in the vicinity of the terminal compositions tended to orient itself so that the angle between it and the lines radiating from the apex of the fastest diffusing component was small. In general, the results corroborated many of the observations and conclusions of Clark and Rhines for the aluminum-magnesium-zinc system.

18. Castleman, L.S., and Seigles, L.L., "Formation of Intermetallic Layers in Diffusion Couples", Trans. AIME, Vol. 209, 1957, pp 1173-1174; Journal of Metals, October 1957.

Diffusion bonding studies of the aluminum-nickel system were used to demonstrate that the diffusion couple technique must be used with caution when attempting to identify phases present in an equilibrium diagram.

It was shown that the beta ($NiAl_3$) and gamma (Ni_2Al_3) phases occur at 600°C (1110°F) within minutes. Times in excess of 340 hours at 1110°F were required to produce identifiable delta (NiAl) and epsilon (Ni_3Al) phases. This indicated that high melting intermediate phases grow very slowly in diffusion couples. The delta and epsilon phases were observed to grow very rapidly at temperatures above the eutectic, which occurs at 640°C(1180°F).

19. Castleman, L.S., and Seigles, L.L., "Layer Growth During Interdiffusion in the Aluminum-Nickel Alloy System", Trans. AIME, Vol. 212, 1958, pp 589-596.

The kinetics of growth of intermediate phase layers in the aluminum-nickel system has been explored in diffusion couples annealed in the temperature range 750° to 1160°F for times up to 340 hr. and under pressures up to 10,000 psi. It has been found that all phases appear in the interdiffusion zone at 1160°F that are thermodynamically stable at the diffusion temperature; these phases are the $NiAl_3$(beta), Ni_2Al_3 (gamma), NiAl(delta), and Ni_3Al (epsilon) intermetallic compounds. The rate controlling factor affecting the kinetics of growth of the gamma phase in the early stages is not yet clear; after a minimum thickness of 0.025 to 0.030 mm is reached, however, volume diffusion controls layer growth. It is estimated that the chemical diffusion coefficient is 9.1×10^{-10} sq cm per sec and that the heat of activation for diffusion is 31,000 cal per mol. An applied pressure of 10,000 psi reduces the diffusion rate by about 27 pct. Volume diffusion controls the growth kinetics of the beta phase after a minimum thickness of 0.040 mm is reached; it is estimated that the 1160°F diffusion coefficient is about 1.8×10^{-11} sq cm per sec and the heat of activation is approximately 27,000 cal per mol. Tentatively, it appears that pressure affects the growth of the beta phase much less than the gamma phase. The growth kinetics of the delta and epsilon phases also appear to be volume diffusion controlled.

20. Clark, E.J., "Vacuum Diffusion Joining of Titanium", Welding Journal, Vol. 38(6), June 1959, pp 251s-259s.

Titanium alloy Ti-5Al-2.5Sn components can be vacuum brazed with fine silver filler and diffused in one operation to give joints with tensile and shear properties equal to that of base metal.

Where a metal-to-metal fit of parts exists, titanium-alloy joints can be vacuum diffusion bonded in the 1800 to 1900°F temperature range, without filler, to give metallographic homogeneity and strengths equal to base metal.

The procedures described in this article offer the basic advantages normally associated with a brazing process together with exceptionally high joint properties which are usually achieved only by welding.

21. Colton, R.M., Fitzpatrick, R., and Rizzitano, F.J., "Solid State Bonding of Prototype Titanium Rocket Motor Casings", U.S. Army Materials Research Agency, Watertown, Mass., ARMA MS64-04, March 1964.

Solid state bonding techniques were successfully used to fabricate large diameter thin wall titanium motor casings. The material used for the investigation was Ti-6Al-6V-2Sn titanium alloy rings having a diameter of 22 inches. The rings were joined by bonding using a butt joint. Axial pressure was applied using hydraulic pistons. Heat was applied externally using an oxy-acetylene flame ring. The inside surfaces of the ring were protected by argon gas during bonding. An initial pressure of 8000 psi was applied to the joint. The part was then heated to 1650°F and at the start of plastic flow (upsetting) the pressure was reduced to 4000 psi. The entire bonding cycle required 2 minutes - 13 seconds.

Prior to bonding, the material had been solution heat treated at 1580°F for 1 hour and water quenched. After bonding, the parts were aged at 1100°F for 1 hour. Tensile specimens taken perpendicular to the bonded interface gave a joint efficiency of 90%. Metallographic examination showed the bonded area was free of embrittled zones and possessed a uniform wrought structure without metallurgical discontinuities.

22. Cooke, V.W. and Levy, A., "Solid Phase Bonding of Aluminum Alloys to Steel", Journal of Metals, Vol. 28(35), November 1949, pp 28-35.

Three procedures for solid-phase bonding of aluminum alloys to various steels have been investigated and found capable of producing high bond strengths. The twist and shear methods are characterized by low bonding temperatures and considerable deformation. The hot-press method employs slightly higher temperatures and no external lateral movement. Variables investigated were bonding temperature, pressure, surface preparation, deformation, composition and subsequent heat treatment.

Regardless of initial bonding technique, strengths of as bonded assembles were found to be increased as much as 100 pct by subsequent annealing. Both 32S and B18S alloys bonded to 18-8 stainless steel frequently could be strengthend by solution heat treatment and aging, without lowering of bond strengths.

23. Cowan, G.R. and Holtzman, A.H., "Flow Configurations in Colliding Plates: Explosive Bonding", Journal of Applied Physics, Vol. 34(4), April 1963, pp 928-939.

The collision of plates at high velocity sometimes causes them to be metallurgically bonded. A study has been made of the nature of the bonds and of the conditions required to produce bonding. A necessary requirement is the formation of a jet in the space ahead of the region of impact. When the collision region moves along the plates at a velocity which exceeds the bulk sound velocity of both materials, the relative velocity of the plates must exceed a critical value for jetting. Clarification of these critical conditions in symmetric collisions, and a correct extension of asymmetric collisions have been obtained by consideration of the effect of downstream boundary conditions on the configuration of the shock waves attached to the collision line in the jetless case. When the velocity of the collision is subsonic, bonding is obtained when the elastic strength of the material is exceeded. Metallographic examination shows that three types of bond may be formed: (1) a direct bond, (2) a uniform layer of solidified melt, and (3) a wavy interface with discrete regions of solidified melt alternating with regions of direct bond. Consideration of the flow indicates the following: (1) the direct bond results from the removal of the surface layers as part of the jet, (2) the alloy results from the melting caused by entrapment of the high velocity jet between the plates, and (3) the wavy interface is caused by an oscillation in the jet flow which produces the mixed type of bonding. The thickness of the continuous alloy layer, which greatly exceeds the calculated jet thickness, indicates that entrapment of the jet dissipates most of the kinetic energy lost in the collision. Analysis of the layer indicates a composition and structure which is expected from the rapid quenching of a well-mixed melt.

24. Crane, C.H., Lovell, D.T. and Baginski, W.A., "Research Study for Development of Techniques for Joining of Dissimilar Metals", The Boeing Company, Seattle, Washington, for NASA, Huntsville, Alabama, Contract NAS8-11307

Quarterly Progress Report 1, October 15, 1964
Quarterly Progress Report 2, January 15, 1965
Quarterly Progress Report 3, April 15, 1965
Quarterly Progress Report 4, July 15, 1965
Literature Survey - "Joining of Dissimilar Metals", October 1964

A research program was conducted to: (1) study and investigate potential methods for joining 2219 aluminum alloy to 321 stainless steel and (2) demonstrate the feasibility of adapting the most promising methods to production requirements, i.e, 20 to 50-inch cylindrical assemblies capability of cryogenic service.

State-of-the-art cognizance was established by a comprehensive literature survey and analysis of present technology. The three most promising methods- diffusion bonding, brazing and fusion welding - were selected for further study and development.

This evaluation proved diffusion bonding to be the best method for joining 2219 aluminum alloy to 321 stainless steel. The unique bonding method produced high strength, ductile joints and utilized diffusion aids as well as low processing temperatures and short times to effectively control formation of embrittling phases at the joint interface.

Successful diffusion bonding was accomplished at (1) temperatures of 500°F to 600°F, (2) pressures of 20 to 25 ksi and (3) times of 2 to 4 hours. The joint faying surfaces were electroplated with solder prior to bonding. The silver prevented the formation of oxide-film barriers and controlled formation of embrittling phases.

Processing techniques for diffusion bonding of large diameter assemblies were successfully developed and demonstrated by fabrication and testing of four 20-inch diameter joints. A unique diffusion bonding method was developed utilizing simple differential thermal expansion tooling. The method can be economically adapted to production requirements.

It was concluded that diffusion bonding is the most satisfactory method for joining large diameter stainless steel to aluminum alloy cylinders and is superior in strength and reliability to welding or brazing.

25. Davies, R.J. and Stephenson, N., "Diffusion Bonding of Nimonic 90 Nickel-Chromium-Cobalt Alloy", British Welding Journal, Vol. 9(3), March 1962, pp 139-148.

Techniques were sought for joining components of Nimonic 99 Ni-Cr-Co alloy for applications in which the strength of the joint is required to match, or at least approach that of the parent material, but where marked deformation of the components is unacceptable, and conventional fusion-and resistance-welding processes are unsuitable. The procedures examined were (i) hot- or cold-pressing, using soft metal or alloy interlayers, followed by heat treatment causing diffusion in the solid state, and (ii) pressure brazing, also followed by diffusion treatment. The interlayer materials and brazing fillers used were types likely to alloy with the parent material during diffusion treatment.

Butt joints, having good stress-rupture strength at 1500°F were made by pressure brazing in a protective atmosphere with a Ni-Mn-Pd filler alloy, followed by diffusion and aging treatments without pressure. Joints similarly

silver fittings and tubing to silver storage vessels. The diffusion bonding was conducted at temperatures between 380° and 720°F. Prior to bonding, material having an as-rolled surface was cleaned with methanol. Specimens (lap joint) were prepared by placing the material between two dies while being heated in a muffle furnace. After reaching the desired temperature, the dies were removed and placed in a hydraulic press. Pressure was applied to reduce the joint thickness by 50%. Shear testing showed that the 720°F temperature gave the best bonded joints.

28. Dulin, C.H., "Alcoa Pressure Bonding Process", Alcoa Green Letter, August 1960.

A pressure bonding process (U.S. Patent 2,908,073) is described for bonding of aluminum to stainless steel, carbon and alloy steels and copper. Various applications for this process are illustrated.

29. Eckel, J.F., "Diffusion Across Dissimilar Metal Joints", Welding Journal, April 1964, pp 170s-178s.

The review and study of element migration across a ferritic and austenitic diffusion couple are discussed. The experience on dissimilar welded joints in power generating equipment has shown that the migration of carbon from the ferritic material to the austenitic material is a major problem.

Studies of diffusion bonded joints between the dissimilar alloys, AISI 304 (.06C) and SA 212 (.25C), have shown that C migrates from ferritic steels across the interface in the direction of the alloy (304) having the higher chromium content. This migration of interstitial carbon results in extensive precipitation of carbides. Accompanying the migration of interstitial C is a migration of the substitutional atoms Fe, Cr and Ni. Evidence was obtained indicating that Fe diffuses into an austenitic steel from a ferritic steel, that Ni diffuses into the ferritic steel and that Cr diffuses away from the interface in both directions. Interposition of a Ni barrier between a ferritic and austenitic stainless steel reduces but does not prevent C migration.

As the carbon content increased in the AISI 304 steel, the following carbides were formed in order: $(Cr, Fe)_4C$, $(Cr, Fe)_7C_3$, $(Cr, Fe)_3C$. The effect of more rapid grain boundary diffusion was apparent in that martensite (caused by nickel migration in the SA 212 steel) extended beyond the volume diffusion front in the SA 212 steel and isolation of ferrite grains occurred. Diffusion studies were conducted in helium and vacuum atmospheres.

30. Elliott, R.P., "Diffusion in Titanium and Titanium Alloys", USAF Report ASD-TDR-62-561, October 1962.

The self-diffusion of titanium and the interdiffusion of aluminum, zirconium, molybdenum, vanadium, and oxygen in titanium have been investigated in the temperature range 600°-1300°C. Diffusion couples were prepared by roll-bonding or press-bonding techniques. Electron microprobe methods were used to determine the penetration of the substitutionally dissolved solutes; vacuum fusion analysis was used to determine the penetration of interstitially dissolved oxygen. The electron microprobe analysis could not be used to determine the penetration curves of aluminum in titanium because of the very high absorption of characteristic aluminum X-radiation by titanium.

The self-diffusion of titanium was investigated by studying penetration of Ti^{44}, formed by bombarding scandium with protons. Diffusion couples were formed by dissolving Ti^{44}-enriched TiO_2 into the titanium. The self-diffusion coefficients of alpha Ti and beta Ti and the interdiffusion coefficients of Zr, Mo, V and O in alpha Ti and beta Ti were determined and the data presented.

31. Evans, R.M., "Notes on the Diffusion Bonding of Metals", Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, DMIC Memo 53, April 1960.

Notes from a literature survey on diffusion bonding are presented. Most of the practical development work has been limited to the application of diffusion bonding to particular products such as nuclear reactor components. A definition is given for diffusion bonding and applicable diffusion bonding processes are reviewed. Various aspects of diffusion bonding are discussed with the subject divided on the basis of two joint systems: metal-to-metal with intermediate materials in the joint area and metal-to-metal without intermediate materials. It is pointed out that the metals joining industry is in need of basic research programs in this area.

32. Fairlie, J., "Explosive Welding and Forming Open Another Door to Industry", Welding Engineer, April 1959, pp 61-64.

Possible applications of explosive forming and welding are presented. Preliminary welds have been made on materials such as: aluminum to aluminum, aluminum to Inconel, aluminum to stainless steel, stainless steel to itself and aluminum sandwiched between stainless steel.

33. Feduska, W., "The Nature of the Diffusion of Brazing Alloy Elements in Heat Resisting Alloys", Welding Journal, February 1961, pp 81s-89s.

A microstructural and microhardness study was made of the diffusion of single and binary combinations of elements, present in commercial high temperature brazing alloys, into heat-resisting alloys. Base metals used were AISI 410, AISI 347, Alloy 3, Alloy 4 and Alloy 5. Data obtained on 105 diffusion samples isolated the effects of individual diffusion elements during the interface reactions which take place between the brazing alloy and base metal.

34. Feinstein, L., "Diffusion Bonding", Stanford Research Institute, Menlo Park, Calif. Presented at the ASM Sponsored 1964 Golden Gate Metals Conference, San Francisco, Calif., Feb. 1964.

Diffusion bonding is defined and the features which distinguish diffusion bonding from brazing are described. Diffusion mechanisms are discussed and examples given of diffusion in bonding of similar and dissimilar metals. Since diffusivity is temperature dependent, the bond will be formed faster with higher temperatures. When a liquid phase is present at the interface, diffusion rates are greatly increased. With a well designed system is is possible to form at relatively low temperatures a bond which has a melting point and bond strength approaching those of the base metal.

35. Gaiennie, B., "Diffusion Bonding: The State of the Art", Machinery, March 1965, pp 139-143.

The general aspects of diffusion bonding are presented. The state-of-the-art is fairly advanced as indicated by prototype production in several areas. General research is directed toward optimizing temperature, pressure and time combinations, interface preparation, joint design, interface catalyst and development of bonding techniques and equipment. It was found that maximum diffusion of the interfaces could be obtained at approximately one-half the melting temperature of the metal involved. It was also determined that pressure and time elements used, can vary inversely through a wide range without affecting bonding results.

36. Gatsek, L.F., "Bonding and Welding of Dissimilar Metals", Light Metal Age, April 1965, pp 10-13.

A summary of dissimilar metal joining techniques is presented with emphasis placed on aluminum to stainless steel joining. The processes discussed include brazing, diffusion-bonding, resistance-welding, soldering, percussion stud-welding, ultrasonic welding and roll bonding. Brazing and diffusion

bonding are the two processes of practical application to large diameter tube joining. Brazing of 6061 aluminum to 304L stainless steel is accomplished by hot-tinning the steel and dip brazing using Alcoa 718 alloy filler. The tin on the 304L alloy serves as a barrier material even though it is in a molten state at the brazing temperature. An interface material is applied to both aluminum and stainless steel when diffusion bonding is used. Silver and copper have been used as interface material for diffusion bonding aluminum to aluminum in an argon-gas atmosphere.

37. Hess, W.F., and Nippes, E.G., "A Method for Welding Sheet Aluminum to SAE 4140 Steel", Welding Journal, March 1946, pp 129s-148s.

The joining of aluminum to steel by resistance welding was investigated. The application was for joining aluminum cooling fins to SAE 4140 steel aircraft engine cylinders. The authors determined that the resistance welding had to be accomplished without melting of the steel because of the formation of brittle iron-aluminide phases at the interface. It was also necessary to create a weld (or bond) without heating the steel above its austenizing temperature to prevent a martensitic structure from forming during cooling of the weld (or bond).

An interface metal was required to obtain a satisfactory weld. Tin, zinc, chromium, cadmium, copper and silver were electroplated to the steel. Of these metals, silver was the most satisfactory providing high-strength, ductile welds over a wide range of welding current and plating thickness.

38. Hirano, K., Agarwala, R.P., and Cohen, M., "Diffusion of Iron, Nickel, and Cobalt in Aluminum", Acta Metallurgia, Vol. 10, Sept. 1962, pp 857-863.

Interdiffusion coefficients of iron, nickel and cobalt in aluminum have been determined over a temperature range of 660° to 1170°F, using radio-active tracers and the residual-activity technique. The experimentally determined frequency factors and activation energies are quite small compared to those for zinc diffusion in aluminum and for self-diffusion in aluminum. This contrast in behavior is explained on the basis of the extremely low solid solubilities of iron, nickel and cobalt in aluminum, which reduce the flux through the lattice to the point where diffusion along short-circuiting paths becomes controlling. The appropriate solution of the diffusion equation and the quantitative results obtained suggest that normal concentrations of dislocations can provide the necessary short- circuiting paths.

39. Hollander, M.B., "Welding Metals by Friction", Materials in Design Engineering, February 1962, pp 79-81.

A summary of friction welding is given. This process involves rotating one work piece against the other, developing frictional heat at the interface. When interface softening occurs, rotation is stopped and the pieces are upset forged together. The basic process variables are axial pressure, surface sliding speed and time. Materials joined by this method include the various steel alloys and selected light metals. Primary application has been joining oil well drill pipe.

40. Hughson, R.V., "New Process for Ti-Clad Steel Plate", Chemical Engineering, Vol. 68(10), May 15, 1961, pp 194-198.

A process developed by Lukens Steel Company for producing titanium clad steel plate is described. An enclosed sandwich of titanium sheet and A-204 low carbon manganese steel plate is flushed continuously with argon while being heated before rolling, to eliminate impurities that interfere with the bond. Two clad plates with the titanium back to back are roll bonded in one sandwich. Preheat temperature limit before rolling is 1700° to 1750°F. A reduction of at least three to one is required for good bonding. No intermediate material is used. Method of forming, cutting and welding of Ti-clad steel are discussed.

41. Kinzel, A.B., "Adams Lecture - Solid Phase Welding", Welding Journal, Vol. 23 (12), December 1944, pp 1124-1144.

A comprehensive review of solid-phase welding is presented. This process is broadly defined as joining without the formation of a liquid phase during the process. The best criteria for evaluation of a solid-phase weld is elimination of the original interface, this occurs by crystal growth and diffusion. Phase transformation was shown to have an important effect on the weld. Temperature plays a major and even dominant role in solid-state welding. For ferritic steels the temperature must be above the critical temperature for trans-interface crystallization in order to provide a satisfactory bond. Theoretical consideration of diffusion and related variables is presented for application to solid-state welding.

42. Kuper, A.B., Lazarus, D., Manning, J.R., and Tomizuka, C.G., "Diffusion in Ordered and Disordered Copper-Zinc", Physical Review, Vol. 104(6), December 1956, pp 1536-1541.

The diffusivities of Cu^{64}, Zu^{65}, and Sb^{124} in single crystals of 47-48 atomic per cent zinc copper-zinc (beta brass) have been measured over the temperature range 510°-1500°F, by using sectioning techniques. The diffusion coefficients

show a striking dependence on the degree of long-range order at temperatures below the critical temperature 874°F. A slight dependence of the diffusion coefficient on short-range order is noted above the critical temperature. The diffusion coefficients obey an Arrhenius equation only in the fully disordered phase, with temperature dependences given by $D_{Cu} = 0.011 \exp(-22000/RT)$ cm^2-sec, $D_{Zn} = 0.0035 \exp(-18,800/RT)$ cm^2/sec; $D_{Sb} = 0.08 \exp(-23,500/RT)$ cm^2/sec. The variation of the diffusion coefficients with temperature in the ordered phase is considered in terms of a simple elastic model. Excellent agreement is obtained by using the measured elastic constants and assuming that the energy for motion of the imperfection is simply related to the smallest (110) shear modulus. In the disordered phase Sb diffuses faster than Zn or Cu, while in the ordered phase Sb diffuses at the same rate as Zn, which is faster than Cu. This result is shown to be inconsistent with an interchange, interstitial, or nearest-neighbor vacancy mechanism for diffusion. The result is consistent with an interstitialcy mechanism.

43. Lamb, H. J., and Wheeler, M.J., "The Identification of Intermetallic Layers Formed on Aluminized Steel by Means of the Electron Probe Microanalyzer" Journal of the Institute of Metals, Vol. 92, 1963-64, pp 150-152.

An investigation was conducted of the nature of aluminum coating on aluminized steel containing a double intermetallic layer. The layers were identified by compositional means to be Fe_2Al_5 adjacent to the steel and $Fe Al_3$ adjacent to the aluminum.

44. LeClaire, A.D. and Bear, I.J., "The Interdiffusion of Uranium and Aluminum", J. Nuclear Energy, Vol. 2, 1956, pp 229-242.

Results are given of measurements of the width, as a function of temperature and pressure, of the diffusion zone formed by the interdiffusion of uranium and aluminum and of the relative penetration of uranium into aluminum and of aluminum into uranium.

The experiments are unusual among diffusion measurements in showing an appreciable accelerating effect of pressure on the rate of interdiffusion. This is not marked for temperatures below 1000°F. The penetration of the uranium into the aluminum is about 2-1/4 times faster than that of the aluminum into the uranium.

The results of a microscopical and x-ray examination of the diffusion zone are presented, and a discussion is given of the possible origins of the pressure effect.

39. Hollander, M.B., "Welding Metals by Friction", Materials in Design Engineering, February 1962, pp 79-81.

A summary of friction welding is given. This process involves rotating one work piece against the other, developing frictional heat at the interface. When interface softening occurs, rotation is stopped and the pieces are upset forged together. The basic process variables are axial pressure, surface sliding speed and time. Materials joined by this method include the various steel alloys and selected light metals. Primary application has been joining oil well drill pipe.

40. Hughson, R.V., "New Process for Ti-Clad Steel Plate", Chemical Engineering, Vol. 68(10), May 15, 1961, pp 194-198.

A process developed by Lukens Steel Company for producing titanium clad steel plate is described. An enclosed sandwich of titanium sheet and A-204 low carbon manganese steel plate is flushed continuously with argon while being heated before rolling, to eliminate impurities that interfere with the bond. Two clad plates with the titanium back to back are roll bonded in one sandwich. Preheat temperature limit before rolling is 1700° to 1750°F. A reduction of at least three to one is required for good bonding. No intermediate material is used. Method of forming, cutting and welding of Ti-clad steel are discussed.

41. Kinzel, A.B., "Adams Lecture - Solid Phase Welding", Welding Journal, Vol. 23 (12), December 1944, pp 1124-1144.

A comprehensive review of solid-phase welding is presented. This process is broadly defined as joining without the formation of a liquid phase during the process. The best criteria for evaluation of a solid-phase weld is elimination of the original interface, this occurs by crystal growth and diffusion. Phase transformation was shown to have an important effect on the weld. Temperature plays a major and even dominant role in solid-state welding. For ferritic steels the temperature must be above the critical temperature for trans-interface crystallization in order to provide a satisfactory bond. Theoretical consideration of diffusion and related variables is presented for application to solid-state welding.

42. Kuper, A.B., Lazarus, D., Manning, J.R., and Tomizuka, C.G., "Diffusion in Ordered and Disordered Copper-Zinc", Physical Review, Vol. 104(6), December 1956, pp 1536-1541.

The diffusivities of Cu^{64}, Zu^{65}, and Sb^{124} in single crystals of 47-48 atomic per cent zinc copper-zinc (beta brass) have been measured over the temperature range 510°-1500°F, by using sectioning techniques. The diffusion coefficients

show a striking dependence on the degree of long-range order at temperatures below the critical temperature 874°F. A slight dependence of the diffusion coefficient on short-range order is noted above the critical temperature. The diffusion coefficients obey an Arrhenius equation only in the fully disordered phase, with temperature dependences given by $D_{Cu} = 0.011 \exp(-22000/RT)$ cm^2-sec, $D_{Zn} = 0.0035 \exp(-18,800/RT)$ cm^2/sec; $D_{Sb} = 0.08 \exp(-23,500/RT)$ cm^2/sec. The variation of the diffusion coefficients with temperature in the ordered phase is considered in terms of a simple elastic model. Excellent agreement is obtained by using the measured elastic constants and assuming that the energy for motion of the imperfection is simply related to the smallest (110) shear modulus. In the disordered phase Sb diffuses faster than Zn or Cu, while in the ordered phase Sb diffuses at the same rate as Zn, which is faster than Cu. This result is shown to be inconsistent with an interchange, interstitial, or nearest-neighbor vacancy mechanism for diffusion. The result is consistent with an interstitialcy mechanism.

43. Lamb, H. J., and Wheeler, M.J., "The Identification of Intermetallic Layers Formed on Aluminized Steel by Means of the Electron Probe Microanalyzer" Journal of the Institute of Metals, Vol. 92, 1963-64, pp 150-152.

An investigation was conducted of the nature of aluminum coating on aluminized steel containing a double intermetallic layer. The layers were identified by compositional means to be Fe_2Al_5 adjacent to the steel and $Fe Al_3$ adjacent to the aluminum.

44. LeClaire, A.D. and Bear, I.J., "The Interdiffusion of Uranium and Aluminum", J. Nuclear Energy, Vol. 2, 1956, pp 229-242.

Results are given of measurements of the width, as a function of temperature and pressure, of the diffusion zone formed by the interdiffusion of uranium and aluminum and of the relative penetration of uranium into aluminum and of aluminum into uranium.

The experiments are unusual among diffusion measurements in showing an appreciable accelerating effect of pressure on the rate of interdiffusion. This is not marked for temperatures below 1000°F. The penetration of the uranium into the aluminum is about 2-1/4 times faster than that of the aluminum into the uranium.

The results of a microscopical and x-ray examination of the diffusion zone are presented, and a discussion is given of the possible origins of the pressure effect.

45. Loenstein, P. and Tuffin, W.B., "Metallurgical Bonding of Dissimilar Metals by Co-Extrusion", Nuclear Metals, West Concord, Mass.

The co-extrusion process lends itself to the production of high quality metallurgical bonded shapes of several dissimilar metal combinations. Mechanical aspects and metallurgical aspects of bonding are described. The importance of bond layer thickness, when brittle compounds form, is discussed. Specific illustrations of applications of the process to rods, shapes, tubes and tubular transition joints, are given. Joining of refractory and reactive metals to ferrous alloys or alloys containing nickel are particularly cited.

46. McEwan, K.J.B. and Miller, D.R., "Pressure Welding of Dissimilar Metals!, British Welding Journal, Vol. 9(7), July 1962, pp 406-420.

The roll bonding of dissimilar metals has been studied and related to previous experience with autogenous pressure welding. The metal pairs studied were divided into the four groups: Immiscible; partially miscible and intermetallic forming.

The immiscible pairs studied were Cd, Fe, Fe-Pb, Cu-Pb and Cu-Mo; partially miscible were Cu-Fe, Cu-Ag, and Al-Zn; miscible were Cu-Ni, Fe-Ni and Mg-Cd; intermetallic forming were Cu-Al, Fe-Al, Ca-Pb, Mg-Al, Ag-Al and Fe-Mo.

If the temperature of welding was sufficiently low, so that no appreciable interdiffusion occurred, the only significant difference from autogenous welding was that relative movement occurred at the weld interface, owing to the different deformation characteristics of the two metals, and this enhanced bonding.

On welding at high temperatures, or on post-heat treatment, the properties of the joint were determined by the extent and effect of interdiffusion. Immiscible and slightly miscible systems gave stable welds. Some miscible metals exhibited diffusional porosity resulting in serious weakening of the bond. With intermetallic forming systems two types of behavior were observed. In the majority of cases, associated with a brittle intermetallic layer, the bond was strong if the layer was maintained below a critical thickness, but weak if it grew above this thickness. The critical thickness at which the transition occurred varied with the system under consideration, probably being dependent upon the existence of a very small amount of ductility in the intermetallic layer. If the interface layer was ductile the joint was strong and failure occurred in the weaker metal.

47. McGowan, P. R., William, N.R., and Allyn, J.I., "Diffusion Bonded Titanium Alloy Honeycomb Panels", Interim Report IR-8-212, Douglas Aircraft Company, Long Beach, Calif., October 1964.

A summary of development of diffusion bonded titanium alloy honeycomb is presented. The alloys used were titanium 8Al-1Mo-1V and commercially pure Ti-75A. Bonding parameters of 1750°F for four hours were selected on the basis of satisfactory bonds in four inch square panels. Panel assemblies are enclosed in a vacuum tight stainless steel envelope (10^{-5} to 10^{-6} torr). To prevent crushing of the core due to this vacuum, the fixture or outer envelope is evacuated to 29.5 inches Hg. Glassrock insulation, strip heaters, refrasil, internally cooled copper platens and slip sheets are placed on both sides of the honeycomb envelope. Pressure is applied by a vacuum pressure bag between the tooling. Low pressure (creep controlled) bonding was used due to crushing of the core at high pressure.

48. Metcalfe, A.G., "Modern Diffusion Bonding Meets Space-Age Needs", SAE Journal, April 1964, pp 53-57.

Describes developments in diffusion bonding processes for joining Ta, W, TD nickel, superalloys, T-111 Ta alloy and Mo and Cb and their alloys for aerospace applications. Comparison of different diffusion bonding processes: yield stress controlled bonding (or pressure welding), diffusion controlled bonding and creep controlled bonding. Diffusion bonding is a method of low temperature bonding that is particularly applicable to dissimilar metals and metals that can be damaged or embrittled by high temperatures.

49. Miller, M.A. and Oyler, G.W., "Pressure Welding Aluminum at Various Temperatures", Welding Journal, Vol. 30, October 1951, pp 486s-498s.

Pressure welding is defined as the formation of a solid-phase weld between metallic materials, by the application of a deforming pressure, at any temperature below the melting point of the components. The three major factors in the pressure welding of aluminum, assuming optimum surface preparation and suitable die design, are temperature, pressure and time. These factors are closely interdependent and capable of graphical representation.

At temperatures below about 500°F, the extent of deformation during welding determines weld efficiency. At elevated temperatures, diffusion is also an important factor in the establishment of metallurgical bonds. Requires unit pressures decrease rapidly as temperatures increase above 600°F, and approach the solidus temperature of the alloy being welded.

The advantages and disadvantages of using low temperatures and high unit pressures, as contrasted to the use of elevated temperatures and low unit pressures, have been discussed.

45. Loenstein, P. and Tuffin, W.B., "Metallurgical Bonding of Dissimilar Metals by Co-Extrusion", Nuclear Metals, West Concord, Mass.

The co-extrusion process lends itself to the production of high quality metallurgical bonded shapes of several dissimilar metal combinations. Mechanical aspects and metallurgical aspects of bonding are described. The importance of bond layer thickness, when brittle compounds form, is discussed. Specific illustrations of applications of the process to rods, shapes, tubes and tubular transition joints, are given. Joining of refractory and reactive metals to ferrous alloys or alloys containing nickel are particularly cited.

46. McEwan, K.J.B. and Miller, D.R., "Pressure Welding of Dissimilar Metals!, British Welding Journal, Vol. 9(7), July 1962, pp 406-420.

The roll bonding of dissimilar metals has been studied and related to previous experience with autogenous pressure welding. The metal pairs studied were divided into the four groups: Immiscible; partially miscible and intermetallic forming.

The immiscible pairs studied were Cd, Fe, Fe-Pb, Cu-Pb and Cu-Mo; partially miscible were Cu-Fe, Cu-Ag, and Al-Zn; miscible were Cu-Ni, Fe-Ni and Mg-Cd; intermetallic forming were Cu-Al, Fe-Al, Ca-Pb, Mg-Al. Ag-Al and Fe-Mo.

If the temperature of welding was sufficiently low, so that no appreciable interdiffusion occurred, the only significant difference from autogenous welding was that relative movement occurred at the weld interface, owing to the different deformation characteristics of the two metals, and this enhanced bonding.

On welding at high temperatures, or on post-heat treatment, the properties of the joint were determined by the extent and effect of interdiffusion. Immiscible and slightly miscible systems gave stable welds. Some miscible metals exhibited diffusional porosity resulting in serious weakening of the bond. With intermetallic forming systems two types of behavior were observed. In the majority of cases, associated with a brittle intermetallic layer, the bond was strong if the layer was maintained below a critical thickness, but weak if it grew above this thickness. The critical thickness at which the transition occurred varied with the system under consideration, probably being dependent upon the existence of a very small amount of ductility in the intermetallic layer. If the interface layer was ductile the joint was strong and failure occurred in the weaker metal.

47. McGowan, P. R., William, N.R., and Allyn, J.I., "Diffusion Bonded Titanium Alloy Honeycomb Panels", Interim Report IR-8-212, Douglas Aircraft Company, Long Beach, Calif., October 1964.

A summary of development of diffusion bonded titanium alloy honeycomb is presented. The alloys used were titanium 8Al-1Mo-1V and commercially pure Ti-75A. Bonding parameters of 1750°F for four hours were selected on the basis of satisfactory bonds in four inch square panels. Panel assemblies are enclosed in a vacuum tight stainless steel envelope (10^{-5} to 10^{-6} torr). To prevent crushing of the core due to this vacuum, the fixture or outer envelope is evacuated to 29.5 inches Hg. Glassrock insulation, strip heaters, refrasil, internally cooled copper platens and slip sheets are placed on both sides of the honeycomb envelope. Pressure is applied by a vacuum pressure bag between the tooling. Low pressure (creep controlled) bonding was used due to crushing of the core at high pressure.

48. Metcalfe, A.G., "Modern Diffusion Bonding Meets Space-Age Needs", SAE Journal, April 1964, pp 53-57.

Describes developments in diffusion bonding processes for joining Ta, W, TD nickel, superalloys, T-111 Ta alloy and Mo and Cb and their alloys for aerospace applications. Comparison of different diffusion bonding processes: yield stress controlled bonding (or pressure welding), diffusion controlled bonding and creep controlled bonding. Diffusion bonding is a method of low temperature bonding that is particularly applicable to dissimilar metals and metals that can be damaged or embrittled by high temperatures.

49. Miller, M.A. and Oyler, G.W., "Pressure Welding Aluminum at Various Temperatures", Welding Journal, Vol. 30, October 1951, pp 486s-498s.

Pressure welding is defined as the formation of a solid-phase weld between metallic materials, by the application of a deforming pressure, at any temperature below the melting point of the components. The three major factors in the pressure welding of aluminum, assuming optimum surface preparation and suitable die design, are temperature, pressure and time. These factors are closely interdependent and capable of graphical representation.

At temperatures below about 500°F, the extent of deformation during welding determines weld efficiency. At elevated temperatures, diffusion is also an important factor in the establishment of metallurgical bonds. Requires unit pressures decrease rapidly as temperatures increase above 600°F, and approach the solidus temperature of the alloy being welded.

The advantages and disadvantages of using low temperatures and high unit pressures, as contrasted to the use of elevated temperatures and low unit pressures, have been discussed.

50. Miller, M.A., "Joining Aluminum to Other Metals", Welding Journal, Vol. 32, August 1953, pp 730-740.

Methods of joining aluminum to other metals by fusion welding, pressure welding, brazing, soldering, diffusion welding and resin bonding are discussed. Of the welding processes, arc and flash welding are of more general usefulness than are torch or resistance brazing. Brazing methods, while of limited usefulness in the joining of aluminum to copper and copper-base alloys, except by the use of transition joints, are of considerable usefulness for joining aluminum to ferrous alloys, particularly if the ferrous parts are given a suitable surface preparation, the best of which appears to be an aluminum coating.

Non-fusion methods such as diffusion welding and pressure welding are discussed for joining aluminum to other metals. Either pressing or rolling may be used to join metals by these methods. Silver-plated aluminum may be bonded to pure silver, certain silver alloys and to any metal that can be silver plated, by heating the parts together at 500-600°F for a period of time under pressure; silver readily diffuses across the interface and results in a good joint.

Pressure welding, either at room or elevated temperature, under conditions to give proper deformation, is becoming increasingly important for joining aluminum to metals such as copper and steel.

51. Moore, D.C., "Titanium Clad and Titanium Process Equipment", Welding and Metal Fabrication, July 1963, pp 276-282.

Methods of lining processing equipment with titanium are presented. This can be done by lining a steel vessel with titanium or fabricating the vessel from titanium clad steel. The bimetal plate can be produced by roll bonding, brazing or explosive cladding. The rolling technique does not employ intermediate metals and is accomplished at temperatures below brittle compound formation. A copper/silver alloy of eutectic composition is used in brazing titanium to steel. The explosive method has not been used for production applications and apparently does not employ intermediate metals. Vanadium and silver are mentioned as interlayer metals to provide a suitable metallurgical transition when joining clad material by welding.

52. Niemann, J.T., Sopher, R.R., and Rieppel, P.J., "Diffusion Bonding Below 1000°F", Welding Journal, Vol. 37, August 1958, pp 337s-342s.

Techniques and metal systems investigated to obtain diffusion bonded joints between beryllium copper and Monel. Results showed that bonding can be accomplished at 650°F or perhaps lower. Good joints were obtained with

the following intermediate metal combinations: Au-Cu, Au-Ag, Au-Pb and Au-Al. Superior bonds strengths (13,000 psi shear) were exhibited by Au-Cu and Au-Ag combinations while the Au-Pb and Au-Al were found to be quite brittle. The diffusion bonding technique permits the joining of the Be-Cu alloy cover sheet and the Monel block of a hypersonic wind-tunnel throat at the age-hardening temperature of the Be-Cu alloy.

53. Orysh, M.S., Betz, I.G., and Hussey, F.W., "Joining of Steel and Other Wear Resistant Metals to Aluminum Alloys", Frankford Arsenal Technical Memorandum M64-8-1, August 1963.

Joining of steel and other wear-resistant metals to aluminum by arc welding and diffusion bonding were studied. The steel members used had a coating of either silver brazing alloy, zinc, or aluminum. Samples of commercial products consisting of aluminum brazed to steel by proprietary processes and aluminum bonded to steel in sheet, plate, and tube form were included in the study. Plates of 2024 aluminum alloy overlaid with two metallized coatings and three experimental hard-surfacing aluminum alloys were also evaluated. It was found that 2024 aluminum alloy can be welded to steel which has been coated with either zinc, aluminum, or a silver alloy, provided the welding arc is directed toward the aluminum member of the joint. The diffusion-bonding process can be used to join 2024 aluminum alloy to silver-alloy-coated steel. The surface hardness of aluminum alloy plates can be increased through the application of an experimental hard-surfacing aluminum alloy or a metallized coating.

54. Paprocki, S.J., Hodge, E.S., and Gripshover, P.J., "Gas Pressure Bonding", Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, DMIC Report 159, September 1961.

A critical review of the literature is presented on the gas-pressure bonding process. This solid-state bonding technique has been successfully utilized for joining, cladding and densifying many material systems.

The gas-pressure bonding process employs a gas at high pressure and elevated temperature in order to join and fabricate metallic or ceramic materials. Temperatures are held well below those required in sintering operation and therefore resulting grain growth is held to a minimum.

Examples are cited of typical nuclear fuel elements and various structural components of interest for aircraft and missile application. Bonding parameters including temperatures, pressures and times are discussed.

55. Parks, J.M., "Recrystallization Welding", Welding Journal, Vol. 32, May 1953, pp 209s-222s.

Recrystallization is established as the mechanism of solid phase welding and the author concludes that the pressure welding process should more rightly be known as recrystallization welding. The principal factors controlling recrystallization are discussed and related to welding. Shear strengths of recrystallization welds are discussed. A basic relationship between recrystallization temperature and degree of deformation is derived and analyzed. The importance of clean cold-worked surfaces for recrystallization welding is emphasized.

56. Pearson, J. and Hayes, G.A., "Research in Explosive Welding", ASTME Technical Paper SP6397, 1962-63.

A review of explosive welding is presented. Studies have been mainly devoted to understanding the mechanisms of the process. A few commercial applications have been investigated, these include: cladding of large flat plates, lining of long tubes and rocket nozzles and joining of dissimilar metal billets. A "surface jetting" phenomenon may occur at the joint resulting in an irregular or saw tooth surface. Buffer plates are frequently used to protect the weld plate surface and transmit uniform pressure. Extensive plastic flow is generally required to accomplish a satisfactory explosive weld. Nineteen various similar and dissimilar metal combinations have been joined explosively on an experimental basis. These include representative aluminum, steel, super and refractory alloys.

57. Sawatzky, A. and Jaumont, F.E., "Diffusion of the Elements of the IB and IIB Subgroups in Silver", Transactions of AIME, 1957; Journal of Metals, October 1957, pp 1207-1210.

Data are given for the diffusion of the elements of the IB and IIB subgroups in single crystals of silver. The sectioning technique and high specific activity isotopes were used to determine the diffusion coefficients of Cu and Hg in Ag in the present investigation and of Zn, Cd, Au and Ag in Ag in previous investigations.

With the exception of those for mercury in silver, the data indicate that the activation energies for diffusion of the atoms of a given subgroup in the same solvent are similar, but the frequency factors differ. From this, it is concluded that atomic size, provided solid solutions are formed, probably does not affect the activation energy. The relation of the present results to several of the more popular generalizations concerning diffusion is discussed.

58. Schwartzbart, H., "What is Diffusion Bonding", Welding Engineer, November 1962, pp 46-47.

A general description and definition of diffusion bonding is given. It is described as a group of welding process with appropriate temperature and joint deformation limitations. The characteristic feature of diffusion bonded joints is that the sharply outlined filler metal layer evident in conventional brazed joints is essentially obliterated. Reference is made to diffusion bonding Zircaloy plate-type fuel elements with intermediate layers of copper, iron or nickel.

59. Storchheim, S., "Hot Pressure Bonding", Metal Progress, Vol. 72, July 1957, pp 97-101.

Investigation was conducted on the diffusion bonding, by the press bonding process, of several metallic couples without the benefit of intermediate metals. Emphasis was placed on diffusion systems having aluminum as one-half of the couple. Studies were conducted using Al-Ni, Al-Cu, Al-Fe and Al-Zr couples. The variables of time, temperature and bonding pressure were studied with regard to joint strength and metallographic structure. The effect of time, temperature and pressure on joint strength and intermetallic alloy zone formation are discussed.

60. Stroup, P.T. and Purdy, G.A., "Aluminum Coating of Steel - A Comparison of Various Processes", Metals Progress, Vol. 57, January 1950, pp 59-63, 128-130.

Steel can be coated with aluminum by hot-dipping, electroplating, spraying, chemical reaction and calorizing. The authors discuss the coatings produced by each of these methods. Particular emphases is given to the importance of controlling the thickness of iron-aluminum compound that forms between pure aluminum surface layer and steel base. The six methods of coating are compared on the basis of structure and cost.

61. Tylecote, R.F., "Investigations on Pressure Welding", British Welding Journal, Vol. 1(3), March 1954, pp 117-138.

The object of this work was to establish certain of the principles involved in the process of pressure or solid-phase welding. It is particularly concerned with the connection between the weldability of various metals at room temperature and the physical properties of the oxide film. The effect of post heat-treatment of welds has been investigated and the results are interpreted in the light of oxide-film solubility and the formation of intermetallic compounds.

Work has also been done on the welding of deoxidized copper in hydrogen to prevent the formation of an oxide film. The results show that the nature of the film is undoubtedly responsible for the poor weldability of copper at room temperature.

The effect of orientation on the weldability of single crystals of aluminum has been determined. The particular crystallographic plane brought into contact has a marked effect on the degree of transinter-facial grain growth upon recrystallization.

62. Tylecote, R.F., "Pressure Welding in Practice", British Welding Journal, Vol. 4(3), March 1957, pp 113-120.

The practical applications of pressure welding during the ten years from 1946 to 1956 are summarized. The main applications lie in two fields: (1) those relating to the butt welding of tubes and sections in steel and (2) the joining of overlapping sheet material in copper and aluminum alloys by pressing or rolling.

The techniques used are discussed, and an attempt is made to assess the advantages of the process.

63. Vicars, E.E., "An Efficient Joining Technique: Diffusion Bonding", Metal Progress, April 1965, pp 125-130.

Methods of diffusion bonding honeycomb panels are discussed. The general advantages over alternative methods are presented as well as the general processing used. Stop-weld materials such as: TiO_2, MgO and ZrO_2 are used to prevent bonding during honeycomb joining. The use of intermediate metal at the joint is preferred as removal of stop-weld materials is eliminated. Mention is made of accelerating diffusion by cold working which increases the number of vacancies and the use of high frequency current which increases mobility of surface atoms.

64. Wood, C.L., "A Technical Report on Duranel - Stainless-Clad Aluminum", Aluminum Company of America, January 1963.

A new stainless steel clad aluminum sheet product marketed by Alcoa under the tradename "Duranel" is described. Properties and applications for the laminated sheet are discussed. Methods for forming, joining and finishing of the clad sheet are described in detail.

65. Young, J.G. and Smith, A.A., "Joining Dissimilar Metals", Welding and Metal Fabrication, July 1959, pp 275-281.

Methods of joining dissimilar metals are reviewed. Principles and applications of fusion welding, brazing, resistance welding, pressure welding and solid state diffusion bonding are discussed. The metallurgical principles in joining dissimilar metals are discussed and consideration is also given to such factors as cracking and dilution and uniformity of joint composition.

66. Young, W.R. and Jones, E.S., "Joining of Refractory Metals by Brazing and Diffusion Bonding", Air Force Technical Document Report No. ASD-TDR-63-88, January 1963.

A discussion of joining several alloy combinations by diffusion bonding in vacuum, using high temperature and pressures is presented. Alloy combinations that were successfully bonded and produced ductile joints were Cb-1Zr alloy to Mo-0.5Ti molybdenum alloy, copper to Cb-1Zr alloy, copper to 316 stainless steel and Mo-0.5Ti molybdenum alloy to Rene' 41.

67. "Astroweld--Diffusion Bonded Honeycomb", Hexcel Products, Inc., Berkeley, Calif., R&D Technical Report 101, May 1963.

The "Astroweld" process of diffusion bonding honeycomb sandwich is presented. Bonding of core materials is accomplished with or without an intermediate material. Successful solid state bonding has been accomplished with the following materials: steel, copper alloys, stainless steel, super-alloys and refractory alloys. Bonding of the skin members to core material requires application of a high purity intermediate metal on the honeycomb cell edges. These intermediate metals are placed on the honeycomb nodes in micron thicknesses. At bonding temperatures this material tends to yield and absorbs initial surface irregularities.

68. "Diffusion Bonding" 'Cool' Newcomer Makes Joints Disappear", Steel, Vol. 150(14), April 2, 1962, pp 117-120.

A brief summary of diffusion bonding experience within the Aero-space industry is given. Specific applications include: Type 321 stainless honeycomb Rene' 41, titanium alloys, tungsten, beryllium-copper and beryllium. In many intermediate layers are used to promote bonding.

69. "Joining Steel to Aluminum", Solar Aircraft Co., San Diego, Calif., A Division of International Harvester Company, RDR 12584, February 1965.

The Solar Bimetal Joining Process is described. Any aluminum alloy with a solidus temperature of 1100°F or higher may be joined to most stainless steel

and superalloys. The essential elements of the process include conditioning the stainless steel by a patented process and brazing it to the aluminum alloy. Typical assemblies produced are stainless steel bellows joined to aluminum rings. Tubular test specimens have been subjected to thermal cycling (160°F to -320°F), helium pressure leak test, pressure surge test at -320°F, Gimbal cyclic test, vibration test and helium leak test without evidence of failure. Corrosion resistance of bimetal joints is similar to brazed aluminum joints. Other dissimilar metal joints which have been joined by brazing are: 6061 aluminum to AMS 6439 steel, beryllium to stainless steel and titanium, titanium to alloy and stainless steel and magnesium to steel.

70. "Roll Bonded Sandwich Structures", Douglas Aircraft Co. and Battelle Memorial Institute, November 1963.

A new technique for producing titanium alloy sandwich structures by roll bonding is described. Titanium sandwich with the voids filled with a dissimilar metal is completely encased in a dissimilar metal pack. The face sheets are diffusion bonded to the core by hot rolling of the metal pack. After forming of the sandwich to the desired shape, the dissimilar metal inserts are removed by chemical means. This method of making sandwich structure is believed to be less costly than welding and the joints have strength equivalent to that of the base metal. Data on properties of typical roll-bonded sandwich structure of Ti 6Al 4V alloy are presented.

71. U.S. Patent 2,908,073, "Method of Bonding Aluminum Metal to Dissimilar Metal", C.H. Dulin, Assignor to the Aluminum Company of America, October 13, 1959.

Methods are described for pressure bonding of aluminum alloys to steel and copper alloys. The methods outlined are adaptable for joining flat plates of aluminum to steel for use in manufacture of electric flat irons and cooking utensils.

72. Cottrell, A.H., "Theoretical Structural Metallurgy", St. Martin's Press Inc., New York, 1957.

This text presents a review of theoretical structural metallurgy based on the electron theory of metals and statistical thermodynamics of metals and alloys. It is written by a metallurgist for metallurgical students relating the salient features of theoretical physics to the structure of metals and alloys. Of primary interest is Chapter XII, "Diffusion in Metals and Alloys".

73. Shewmon, P.G., "Diffusion in Solids", McGraw-Hill Book Co., Inc., New York, 1963.

This text presents the background and logical development of diffusion in solids. Experimental results and theoretical explanations are presented to aid in the understanding of the physical meaning and implications of the concepts which apply to diffusion in all crystalline solids.

74. LeClaire, A.D., "Diffusion in Metals", The Journal of the Iron and Steel Institute, Vol. 174, July 1953.

A review is given of the principal results that have been obtained from experimental and theoretical work on diffusion in metals. From consideration of those results, suggestions are made on the type of experiments most likely to further an understanding of the subject.

75. Bradt, R.C., et al, "Kirkendall - Effect Densification in a Sintered Tungsten-Molybdenum Powder Compact", ACTA Metallurgica, Letters to the Editor, Vol. 14, 1966, pp 553-554.

Experimental results on a sintered tungsten-molybdenum powder compact are presented which clearly illustrate the Kirkendall effect by porosity changes at the interface.

76. Buehler, W.J. and Wiley, R.C., "TiNi-Ductile Intermetallic Compound", Transactions of the ASM Volume 55, 1962, pp 269-276.

The intermetallic compound TiNi was found to exist at room temperature as a ductile and impact resistant material with unique vibration damping properaties. Further, TiNi and Ni-rich TiNi alloys are quench-hardenable, paramagnetic, resistant to corrosion, abrasion and oxidation, and capable of maintaining their hardness at elevated temperatures.

77. Buehler, W.J. and Wang, F.E., "Martensitic Transformations in the TiNi Compound", Paper presented at the 5th International Symposium on the Reactivity of Solids, Munich, August 5-8, 1964.

Alloys near stoichiometric TiNi composition were found to undergo two transformations from 380°C to room temperature. The lower temperature transformation is a diffusionless type and, in a 50.3 at .% alloy, exhibits a M_s temperature between 35° and 45°C. The ductility and other unusual phenomena associated with these alloys are attributed to the unique structural behavior during the transformations, namely, the co-existence of an ordered TiNi phase with the " δ1" and " δ2" phases in the 45°-350°C temperature range, and the occurrence of a diffusionless transformation without change in the relative amount of the phases involved.

78. Hauser, D, et al, "Fundamentals of Solid State Welding and Their Application to Beryllium, Aluminum and Stainless Steel", Battelle Memorial Institute for U.S. Army Missile Command, Redstone Aresenal, Alabama, Contract DA-01-021-AMC-11706 (Z).

This report presents the results of a state-of-the-art survey of solid state diffusion welding and roll welding of aerospace metals. Particular emphasis is given to beryllium, high-strength aluminum alloys, and 321 stainless steel.

The report is divided into four major categories:

(1) A general survey of solid state diffusion welding, including a description of a real surface, factors influencing microscopic plastic flow, diffusion, grain growth, dissimilar metal welding, and use of intermediate materials.

(2) A description of solid state welding methods, including roll welding, roll-welding theory, advantages and limitations of welding methods, and joint designs that are suitable for diffusion welding and roll welding.

(3) Nondestructive testing techniques for solid state welded joints and their applicability.

(4) A survey of similar and dissimilar metal diffusion welding the selected metals.

On the basis of the information obtained, general areas in which future research is desirable are presented.

79. Mueller, W.M., "Energetics in Metallurgical Phenomena", Volume 1, Gordon and Breach, Publishers, New York, 1965.

The formal theory of diffusion is presented as well as experimental techniques and results. It is shown that experimental basis for understanding diffusion in solids is on far firmer footing than the theory.

APPENDIX B

SUMMARY OF CLEANING PROCEDURES

SUMMARY OF CLEANING PROCEDURES

Alloy	Cleaning Solution	Solution Temperature	Time in Solution
321 SS Inconel 718 Inconel 600	Vapor degrease: alkaline clean: pickle in Nitric-Hydrofluoric acid [1]	80°-130°F	30 min.
Ti-8Al-1Mo-1V Ti-5Al-2.5Sn			5 min.
2219 Al 7106 Al	Vapor degrease: alkaline clean: pickle in ACP #2 [2]	Room	15 min.

[1] Nitric-Hydrofluoric (100 gal)

HNO_3	18 gal
HCL	16 gal
HF	4.5 gal
CH_3COOH	2.4 gal
$(COOH)_2$	2 lbs
Na_2HPO_4	1 lb
H_2O	Remainder

[2] ACP #2 (100 gal)

ACP #2	37 lbs
HNO_3	10 gal
HF (60%)	.02 gal
H_2O	Remainder

APPENDIX C

PLATING PROCEDURE

APPENDIX C

PLATING PROCEDURE

I. Procedure for Plating 321 Stainless Steel, Inconel 600 and Inconel 718

A. Copper Plate .0005/.0007" Thick

1. Vapor degrease.
2. Cathodic clean in alkaline electrocleaner.
3. Anodic clean in 60% H_2SO_4-45 seconds.
4. Strike in all chloride nickel strike - 30 seconds.
5. Copper plate in conventional Rochelle salt copper cyanide plating solution.

B. Silver Plate .0005/.0007" Thick

1. Perform steps 1 through 4 in paragraph I.A.
2. Copper strike in conventional Rochelle salt copper cyanide plating solution.
3. Silver plate in Lea-Ronal proprietary silver plating solution.

C. Nickel Plate

1. Perform steps 1 through 4 in paragraph I.A.
2. Nickel plate in conventional Watts nickel plating bath.

II. Procedure for Plating Bare 2219 and 7106 Aluminum Alloys

A. Copper Plate .0005/.0007" Thick

1. Vapor degrease.
2. Soak clean in non-silicated aluminum cleaner.
3. Deoxidize at room temperature.
4. Dip in nitric-hydrofluoric acid - 5 seconds.
5. Zincate (conventional zinc immersion bath for aluminum).
6. Remove zinc by dipping in concentrated nitric acid.
7. Repeat step 5.
8. Copper plate in conventional Rochelle salt copper cyanide plating solution with 10.0-10.5 pH.

B. Silver Plate .0005/.0007" Thick

1. Perform steps 1 through 7 in paragraph II.A.
2. Copper strike .00002" thick using solution in step 8 in paragraph II.A.
3. Silver plate in Lea-Ronal proprietary silver plating solution.

III. Procedure for Plating Anodized 2219 and 7106 Aluminum Alloys

A. Anodize 2219 and 7106 Aluminum Alloys

1. Solvent clean.
2. Alkaline etch in 5% sodium hydroxide solution.
3. Desmut in 35% nitric acid solution.
4. Anodize in 4% phosphoric acid solution at 60°F, 100 volts DC for 30 minutes.

B. Copper Plating .0007/.001" Thick

1. Anodize per paragraph III.A.
2. Copper plate in conventional copper sulfate-sulfuric acid bath operated at room temperature and with a current density of 100 ASF.

C. Nickel Plating .0007/.001" Thick

1. Anodize per paragraph III.A.
2. Nickel strike using conventional Woods nickel strike bath at room temperature and at 40 ASF.
3. Nickel plate using conventional sulfamate nickel bath at 140°F and with a current density of 75 ASF.

D. Silver Plating .0007/.001" Thick

1. Anodize per paragraph III.A.
2. Silver strike using conventional silver strike bath.
3. Silver plate using a conventional silver cyanide bath at room temperature and with a current density of 10 ASF.

IV. Procedure for Plating Bare Ti-5Al-2.5Sn and Ti-8Al-1Mo-1V

A. Copper Plating .0007/.001" Thick

1. Solvent clean.
2. Alkaline clean.

3. Etch in nitric acid-hydrofluoric acid solution.

4. Activate by immersion in boiling concentrated hydrochloric acid for 60 seconds.

5. Copper plate with conventional copper sulfate-sulfuric acid bath at room temperature and with a current density of 100 ASF.

B. Nickel Plate .0007/.001" Thick

1. Perform steps 1 through 4 in paragraph IV.A.

2. Nickel strike using conventional Woods nickel strike bath at room temperature and with a current density of 40 ASF.

3. Nickel plate using conventional sulfamate nickel bath at 140°F and with a current density of 75 ASF.

C. Silver Plating .0007/.001" Thick

1. Perform steps 1 through 4 in paragraph IV.A.

2. Silver strike using conventional silver strike bath.

3. Silver plate using a conventional silver cyanide bath at room temperature and with a current density of 10 ASF.

V. Procedure for Plating Anodized Ti-5Al-2.5Sn and Ti-8Al-1Mo-1V

A. Anodize

1. Solvent clean.

2. Alkaline clean.

3. Etch in nitric-hydrofluoric acid solution.

4. Anodize in a solution of 7 parts by volume acetic and one part hydrofluoric acid (70%) and at a current density of 7.5 ASF.

B. Copper Plate .0007/.001" Thick

1. Anodize per paragraph V.A.

2. Copper plate with conventional copper sulfate-sulfuric acid bath and at a current density of 100 ASF.

C. Nickel Plate .0007/.001" Thick

1. Anodize per paragraph V.A.

2. Nickel strike using conventional Woods nickel strike bath at room temperature and a current density of 40 ASF.

3. Nickel plate using conventional sulfomate nickel bath at 140°F and at a current density of 75 ASF.

D. Silver Plate .0007/.001" Thick

1. Anodize per paragraph V.A.

2. Silver strike using conventional silver strike bath.

3. Silver plate using conventional silver cyanide bath at room temperature and with a current density of 10 ASF.

APPENDIX D

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
1	2219	.127		1		700	45,000	50 min.	20 min.	.042	Passed	Brittle Low Strength	Partially Bonded	Subscale specimens used to achieve high deformation. Press Ram bottomed against stop immediately after applying pressure
	321	.082								000				
2	2219	.127				950	45,000	65 min.	5 min.	.050	Failed	–	Partially Bonded	
	321	.082								000				
3	2219	.126				950	45,000	65 min.	5 min.	.054	Passed	Brittle Low Strength	Partially Bonded	
	321	.082								.001				
4	7106	.060				950	7,500	60 min.	20 min.	.0046	Passed	Ductile Fair Strength	Partially Bonded	
	321	.082								000				
5	7106	.062			2	950	7,500	60 min.	24 hr.	.0215	Passed	Brittle Good Strength	Almost Completely Bonded	
	321	.082								000				
6	7106	.060				950	7,500	60 min.	60 min.	.0214	Passed	Brittle Fair Strength	Partially Bonded	
	321	.082								000				
7	321	.082				1625	20,000	2 hr.	5 min.	000	–	–	No Bonding	
	Ti-8Al-1Mo-1V	.058								.016			Ti Surface Oxidized	
8	2219	.057				915	12,000	10 min.	2 hr.	.0095	Passed	Ductile Fair Strength	Almost Completely Bonded	Press Ram bottomed against stop in 2 min. Retort temperature reached 1000°F for 2 min.
	Ti-5Al-2.5Sn	.056								000				
9	2219	.057				915	12,000	10 min.	2 hr.	.010	Passed	Low Strength	Partially Bonded	
	321	.082								000				
10	7106	.061	None			915	12,000	10 min.	2 hr.	.008	Passed	Brittle Low Strength	Faying Surface Smooth-Grey Color – 100% Bonded	
	321	.082								000				
11	Inconel 600	.063				1610	15,000	10 min.	30 min.	.001	Material separated when removing from retort.		Surfaces Appeared Bonded Shiny Grey & Brittle	Press ram bottomed against stop 7 min. after 15,000 PSI pressure was applied
	Ti-8Al-1Mo-1V	.059								.005				
12	321	.063				1610	15,000	10 min.	30 min.	.005	Passed	Ductile High Strength	Almost Completely Bonded	
	Rene' 41	.082								000				
13	321	.082				1810	15,000	10 min.	30 min.	.005	Material Separated when removing from retort		Completely Bonded Shiny Grey & Brittle	
	Ti-8Al-1Mo-1V	.059								.004				
14	321	.083				700	15,000	5 min.	24 hr.	.0015	–	–	No Bonding	
	2219	.058								.002				
15	2219	.058				700	15,000	5 min.	24 hr.	.002	–	–	No Bonding	
	Ti-5Al-2.5Sn	.056								.001				
16	7106	.061			3	700	15,000	5 min.	24 hr.	.004	Failed	–	Partially Bonded	
	321	.083								.001				
17	321	.083				1000	15,000	5 min.	24 hr.	000	Material Not Bonded			Bonding pressure too low
	Rene' 41	.063								000				
18	Inconel 600	.063				1000	15,000	5 min.	24 hr.	000	Passed	Brittle Low Strength	Partially Bonded	
	Ti-8Al-1Mo-1V	.059								000				
19	321	.082				1000	15,000	5 min.	24 hr.	000	Failed	–	Small Amount Bonding	
	Ti-8Al-1Mo-1V	.058								000				
20	Inconel 600	.062				1610	12,000	10 min.	5 min.	000	Passed	Brittle Good Strength	Completely Bonded	
	Ti-8Al-1Mo-1V	.059								000				

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
21	321	.082	None	1	3	1615	12,000	10 min.	5 min.	.000	Passed	Brittle Low Strength	Partially Bonded	
	René' 41	.063								.000				
22	321	.083	None			1615	12,000	10 min.	5 min.	.0015	Passed	Brittle Fair Strength	Almost Completely Bonded	
	Ti-8Al-1Mo-1V	.059								.000				
23	321	.082	None			1875	7,500	10 min.	5 min.	.001	Passed	Brittle Low Strength	Partial Bonding	
	René' 41	.063								.000				
24	321	.083	Copper foil .005			1875	7,500	10 min.	5 min.	.000	Material not bonded		Copper foil bonded to René' 41 But not to 321 steel	
	René' 41	.063								.000				
25	321	.082	Nickel foil .0078			1875	7,500	10 min.	5 min.	.000	Passed	Material Completely Bonded Impossible to Peel Joint		
	René' 41	.063								.000				
26	321	.082	None			1640	12,000	7 min.	5 min.	.003	Passed	Brittle Good Strength	Glossy - Grey Surface 100% Bonded	
	Ti-8Al-1Mo-1V	.059								.0015				
27	321	.082	None			1640	10,500	7 min.	5 min.	.001	Passed	Brittle Good Strength	Glossy - Grey Surface 100% Bonded	
	Ti-8Al-1Mo-1V	.059								.001				
28	321	.083	Nickel foil .0078			1640	10,500	7 min.	5 min.	.001	Passed	Ductile High Strength	Failed Randomly through foil to 321 and René' 41 interfaces	
	René' 41	.063								.000				
29	2219	.058	None			700	17,000	6 min.	5 min.	.0015	–	–	No Bonding	
	Ti-5Al-2.5Sn	.054								.000				
30	2219	.058	None			700	17,000	6 min.	5 min.	.0015	–	–	No Bonding	
	321	.082								.000				
31	7106	.061	None			700	17,000	6 min.	5 min.	.0025	Failed	–	Slightly Bonded	
	321	.082								.000				
32	2219	.058	None			950	9,000	8 min.	5 min.	.007	Passed	Ductile Good Strength	Completely Bonded	
	Ti-5Al-2.5Sn	.054								.000				
33	2219	.058	None			950	9,000	8 min.	5 min.	.005	Passed	Ductile Fair Strength	Almost Completely Bonded	
	321	.082								.000				
34	7106	.061	None			950	9,000	8 min.	5 min.	.007	Passed	Ductile Good Strength	Completely Bonded	
	321	.082								.000				

D3

1> All material chemically cleaned. Immediately prior to bonding the faying surfaces of the material were sanded with 80 grit abrasive paper and wiped with acetone.

2> Tests 1 through 10 were conducted in a sand sealed retort and argon atmosphere. Some oxidation occured during bonding.

3> Tests 11 through 34 were conducted in a welded retort and argon atmosphere. No oxidation occurred.

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME Min. HEATUP	TIME Min. AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
35	321	.082	NONE	▷	ARGON GAS	1200	17,000	5	5	.000	FAILED	~	SMALL AMOUNT OF WELDING	
	RENE 41	.062								.000				
36	321	.082	▲	▲	▲	1200	17,000	5	5	.000	PASSED	BRITTLE LOW STRENGTH	PARTIALLY WELDED	
	Ti-8Al-1Mo-1V	.059								.000				
37	INCONEL 600	.059				1200	17,000	5	5	.000	PASSED	BRITTLE LOW STRENGTH	PARTIALLY WELDED	
	Ti-8Al-1Mo-1V	.063								.001				
38	321	.082				1400	14,000	5	5	.000	PASSED	LOW STRENGTH	SMALL AMOUNT OF WELDING	
	RENE 41	.062								.000				
39	321	.083				1400	14,000	5	5	.000	PASSED	BRITTLE- LOW STRENGTH	PARTIALLY WELDED	
	Ti-8Al-1Mo-1V	.059								.002				
40	INCONEL 600	.063				1400	14,000	5	5	.000	PASSED	BRITTLE LOW STRENGTH	PARTIALLY WELDED	
	Ti-8Al-1Mo-1V	.059								.0015				
41	2219	.058				900	6,250	7	20	.013	PASSED	LOW STRENGTH AND DUCTILITY	PARTIALLY WELDED	PRESS RAM BOTTOMED AFTER THE 6,250 PSI PRESSURE WAS APPLIED FOR 15 MIN.
	321	.082								.000				
42	7106	.061				900	6,250	7	20	.005	PASSED	MEDIUM STRENGTH AND DUCTILITY	GLOSSY GREY SURFACES	
	321	.083								.000				
43	2219	.058				900	6,250	7	20	.015	PASSED	HIGH STRENGTH AND DUCTILITY	DULL GREY SMOOTH SURFACES	
	Ti-5Al-2.5Sn	.054								.000				
44	2219	.058				800	5,250	7	60	.004	—	~	~	DID NOT WELD
	321	.082								.000				
45	7106	.062				800	5,250	7	60	.001	FAILED	~	SMALL AMOUNT OF WELDING	
	321	.082								.000				
46	2219	.058				800	5,250	7	60	.004	PASSED	LOW STRENGTH	PARTIALLY WELDED	
	Ti-5Al-1Mo-1V	.054								.000				
47	INCONEL 600	.062				1450	12,500	10	15	.001	PASSED	BRITTLE- MEDIUM STRENGTH	SMOOTH - GREY SURFACES, COMPLETELY WELDED	
	Ti-8Al-1Mo-1V	.053								.000				
48	321	.082				1450	12,500	10	15	.0005	PASSED	BRITTLE- MEDIUM STRENGTH	SMOOTH - GREY SURFACES, COMPLETELY WELDED	
	Ti-8Al-1Mo-1V	.055								.001				
49	321	.082				1450	12,500	10	15	.000	PASSED	MEDIUM STRENGTH AND DUCTILITY	ALMOST COMPLETELY WELDED	
	RENE 41	.063								.000				
50	INCONEL 600	.062				1400	16,500	8	30	.000	PASSED	BRITTLE - MEDIUM STRENGTH	SMOOTH - GREY SURFACES, COMPLETELY WELDED	
	Ti-8Al-1Mo-1V	.054								.002				
51	321	.082				1400	16,500	8	30	.000	PASSED	BRITTLE- MEDIUM STRENGTH	SMOOTH- GREY SURFACES, COMPLETELY WELDED	
	Ti-8Al-1Mo-1V	.053								.001				
52	321	.082				1400	16,500	8	30	.0005	PASSED	LOW STRENGTH AND DUCTILITY	PARTIALLY WELDED	
	RENE 41	.062								.000				
53	INCONEL 600	.062	▼	▼	▼	1300	20,000	8	15	.000	PASSED	BRITTLE- MEDIUM STRENGTH	SMOOTH - GREY SURFACES, COMPLETELY WELDED	
	Ti-8Al-1Mo-1V	.057								.000				
54	321	.082	NONE	▷	ARGON GAS	1300	20,000	8	15	.000	PASSED	BRITTLE- MEDIUM STRENGTH	PARTIALLY WELDED	
	Ti-8Al-1Mo-1V	.057								.0005				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP					
55	321 / RENE 41	.082 / .062	NONE	▷	ARGON GAS	1300	20,000	8	15	.000 / .000	PASSED	LOW STRENGTH	PARTIALLY WELDED	
56	INCONEL 600 / Ti-8Al-1Mo-1V	.062 / .056	▲	▲	▲	1200	21,000	5	30	.000 / .000	PASSED	LOW STRENGTH	PARTIALLY WELDED	
57	321 / Ti-8Al-1Mo-1V	.082 / .056				1200	21,000	5	30	.000 / .0005	PASSED	LOW STRENGTH	PARTIALLY WELDED	
58	321 / RENE 41	.082 / .062				1200	21,000	5	30	.000 / .000	—	—	—	DID NOT WELD
59	INCONEL 600 / Ti-8Al-1Mo-1V	.062 / .056				1200	20,000	5	120	.000 / .001	PASSED	BRITTLE-MEDIUM STRENGTH	SMOOTH-GREY SURFACES, COMPLETELY WELDED	
60	321 / Ti-8Al-1Mo-1V	.082 / .055				1200	20,000	5	120	.0005 / .001	PASSED	BRITTLE-LOW STRENGTH	ALMOST COMPLETELY WELDED	
61	321 / RENE 41	.082 / .063				1200	20,000	5	120	.0005 / .000	PASSED	LOW STRENGTH	PARTIALLY WELDED	
62	INCONEL 600 / Ti-8Al-1Mo-1V	.062 / .056				1300	20,000	7	90	.000 / .003	PASSED	BRITTLE-HIGH STRENGTH	SMOOTH-GREY SURFACES, COMPLETELY WELDED	
63	321 / Ti-8Al-1Mo-1V	.082 / .056				1300	20,000	7	90	.0015 / .002	PASSED	BRITTLE-MEDIUM STRENGTH	GREY SURFACES COMPLETELY WELDED	
64	321 / RENE 41	.082 / .063				1300	20,000	7	90	.002 / .000	PASSED	LOW STRENGTH	PARTIALLY WELDED	
65	321 / RENE 41	.081 / .063				1300	21,000	16	180	.002 / .000	PASSED	MEDIUM STRENGTH - LOW DUCTILITY	ALMOST COMPLETELY WELDED	
66	321 / Ti-8Al-1Mo-1V	.081 / .057				1300	21,000	16	180	.002 / .0015	PASSED	BRITTLE-MEDIUM STRENGTH	GREY SURFACES - COMPLETELY WELDED	
67	INCONEL 600 / Ti-8Al-1Mo-1V	.062 / .059				1100	24,000	9	120	.000 / .0015	PASSED	BRITTLE LOW STRENGTH	GREY SURFACES, NOT COMPLETELY WELDED	
68	321 / Ti-8Al-1Mo-1V	.082 / .058				1100	24,000	9	120	.001 / .001	PASSED	LOW STRENGTH	PARTIALLY WELDED	
69	INCONEL 600 / Ti-8Al-1Mo-1V	.061 / .056				1200	20,000	5	60	.0015 / .0005	PASSED	BRITTLE-MEDIUM STRENGTH	GREY SURFACES COMPLETELY WELDED	
70	321 / Ti-8Al-1Mo-1V	.082 / .058				1200	20,000	5	60	.0005 / .001	PASSED	BRITTLE MEDIUM STRENGTH	GREY SURFACES COMPLETELY WELDED	
71	INCONEL 600 / Ti-8Al-1Mo-1V	.062 / .057				1200	12,500	5	120	.000 / .0005	PASSED	BRITTLE LOW STRENGTH	GREY SURFACES NOT COMPLETELY WELDED	
72	321 / Ti-8Al-1Mo-1V	.082 / .058				1200	12,500	5	120	.000 / .000	PASSED	LOW STRENGTH	GREY SURFACES 90% WELDED	
73	INCONEL 600 / Ti-8Al-1Mo-1V	.062 / .058	▼	▼	▼	1200	12,500	5	60	.000 / .000	PASSED	BRITTLE MEDIUM STRENGTH	GREY SURFACES COMPLETELY WELDED	
74	321 / Ti-8Al-1Mo-1V	.082 / .058	NONE	▷	ARGON GAS	1200	12,500	5	60	.000 / .000	PASSED	LOW STRENGTH	75% WELDED	

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
75	Inconel 600	.062	None	▷	Argon Gas	1200	12,500	5	240	.000	Passed	Brittle - Low strength	Grey - smooth surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.000				
76	321	.082	▲	▲	▲	1200	12,500	5	240	.000	Passed	Low strength	80% welded	
	Ti-8Al-1Mo-1V	.057								.000				
77	Inconel 600	.061				1200	20,000	4	120	.000	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.001				
78	321	.082				1200	20,000	4	120	.001	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.001				
79	Inconel 600	.062				1200	30,000	8	240	.005	Passed	Brittle - medium strength	Smooth-grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.054								.003				
80	321	.082				1200	30,000	8	240	.007	Passed	Brittle - medium strength	Smooth-grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.003				
81	Inconel 600	.062				1200	30,000	10	120	.0025	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.002				
82	321	.082				1200	30,000	10	120	.003	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.0025				
83	Inconel 600	.062				1200	20,000	5	240	.001	Passed	Brittle - medium strength	Smooth, grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.0015				
84	321	.082				1200	20,000	5	240	.0005	Passed	Brittle - medium strength	Smooth, grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.057								.0025				
85	Inconel 600	.062				1200	30,000	8	60	.002	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.003				
86	321	.082				1200	30,000	8	60	.000	Passed	Brittle medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.056								.003				
87	Inconel 600	.058				1350	20,000	7	120	.003	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.008				
88	321	.082				1350	20,000	7	120	.003	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.009				
89	Inconel 600	.062				1350	30,000	6	60	.010	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	The deformation of the specimens welded at 30,000 psi varied considerably throughout the specimens. This was caused by uneven lateral flow of the retort top and bottom.
	Ti-8Al-1Mo-1V	.056								.008				
90	321	.082				1350	30,000	6	60	.010	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.007				
91	Inconel 600	.061				1350	30,000	8	120	.016	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.057								.012				
92	321	.082				1350	30,000	8	120	.018	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.057								.013				
93	Inconel 600	.062	▼	▼	▼	1350	30,000	4	10	.004	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.058								.003				
94	321	.082	None	▷	Argon Gas	1350	30,000	4	10	.003	Passed	Brittle - medium strength	Smooth - grey surfaces, completely welded	
	Ti-8Al-1Mo-1V	.057								.004				

SUMMARY OF DIFFUSION WELDING DI VELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
95	Inconel 600	.062	None	▷	Argon Gas	1350	20,000	5	60	.006	Passed	Brittle-Medium Strength	Smooth-Shiny Grey Surfaces, Completely Welded	
	Ti-8Al-1Mo-1V	.057								.004				
96	321	.082	↑	↑	↑	1350	20,000	5	60	.004	Passed	Brittle-Medium Strength	Smooth-Shiny Grey Surfaces, Completely Welded	
	Ti-8Al-1Mo-1V	.057								.005				
97	Inconel 600	.062				1350	12,500	5	120	.0015	Passed	Brittle-Medium Strength	Smooth-Shiny Grey Surfaces, Completely Welded	
	Ti-8Al-1Mo-1V	.058								.001				
98	321	.082				1350	12,500	5	120	.0015	Passed	Brittle-Medium Strength	Smooth-Shiny Grey Surfaces, Completely Welded	
	Ti-8Al-1Mo-1V	.057								.0015				
99	Inconel 600	.062				1350	20,000	8	10	.002	Passed	Brittle-Medium Strength	Smooth-Shiny Grey Surfaces, Completely Welded	
	Ti-8Al-1Mo-1V	.057								.001				
100	321	.082				1350	20,000	8	10	.002	Passed	Low Strength	Grey Surfaces 90% Welded	
	Ti-8Al-1Mo-1V	.058								.001				
101	Inconel 600	.062				1350	12,500	6	10	.000	Passed	Low Strength	Grey Surfaces 80% Welded	
	Ti-8Al-1Mo-1V	.058								.001				
102	321	.082				1350	12,500	6	10	.000	Passed	Low Strength	70% Welded	
	Ti-8Al-1Mo-1V	.058								.001				
103	Inconel 600	.062				1350	12,500	3	60	.0015	Passed	Brittle Medium Strength	Grey-Smooth Surfaces Completely Welded	
	Ti-8Al-1Mo-1V	.057								.001				
104	321	.082				1350	12,500	3	60	.0015	Passed	Brittle Low Strength	Grey-Smooth Surfaces Completely Welded	
	Ti-8Al-1Mo-1V	.056								.0005				
105	Inconel 600	.062				1450	30,000	4	10	.011	Passed			All specimens welded at 1450°F failed in a brittle manner and with a medium strength. After peeling the surfaces of the specimens exhibited a smooth-shiny grey surface. The deformation of the specimens welded at high pressures varied considerably throughout the specimens. This was caused by uneven lateral flow of the retort top and bottom.
	Ti-8Al-1Mo-1V	.058								.009				
106	321	.082				1450	30,000	4	10	.010	Passed			
	Ti-8Al-1Mo-1V	.057								.007				
107	Inconel 600	.062				1450	30,000	18	120	.028	Passed			
	Ti-8Al-1Mo-1V	.058								.016				
108	321	.082				1450	30,000	18	120	.015	Passed			
	Ti-8Al-1Mo-1V	.058								.019				
109	Inconel 600	.063				1450	12,500	5	10	.0005	Passed			
	Ti-8Al-1Mo-1V	.057								.002				
110	321	.082				1450	12,500	5	10	.0005	Passed			
	Ti-8Al-1Mo-1V	.058								.002				
111	Inconel 600	.062				1450	12,500	5	120	.003	Passed			
	Ti-8Al-1Mo-1V	.058								.008				
112	321	.082				1450	12,500	5	120	.005	Passed			
	Ti-8Al-1Mo-1V	.058								.005				
113	Inconel 600	.062				1450	30,000	7	60	.020	Passed			
	Ti-8Al-1Mo-1V	.058								.018				
114	321	.082	None	▷	Argon Gas	1450	30,000	7	60	.015	Passed			
	Ti-8Al-1Mo-1V	.057								.017				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
115	Inconel 600	.063	None	▷	Argon Gas	1450	20,000	3	60	.010	Passed			See notes on previous page.
	Ti-8Al-1Mo-1V	.058								.008				
116	321	.081				1450	20,000	3	60	.005	Passed			
	Ti-8Al-1Mo-1V	.057								.007				
117	Inconel 600	.061				1450	20,000	7	120	.020	Passed			
	Ti-8Al-1Mo-1V	.058								.020				
118	321	.080				1450	20,000	7	120	.015	Passed			
	Ti-8Al-1Mo-1V	.057								.028				
119	Inconel 600	.061				1450	12,500	5	60	.002	Passed			
	Ti-8Al-1Mo-1V	.058								.004				
120	321	.081				1450	12500	5	60	.002	Passed			
	Ti-8Al-1Mo-1V	.058								.004				
121	Inconel 600	.062				1450	20,000	5	10	.001	Passed			
	Ti-8Al-1Mo-1V	.059								.001				
122	321	.080				1450	20,000	5	10	.001	Passed			
	Ti-8Al-1Mo-1V	.058								.001				
123	2219	.057				850	9,250	9	120	.010	Failed	~	Small amount of welding	
	321	.080								.000				
124	7106	.060				850	9,250	9	120	.006	Failed	~	Small amount of welding	
	321	.081								.000				
125	2219	.057				850	9,250	9	120	.007	Passed	Low strength and ductility	Partially welded	
	Ti-5Al-2.5Sn	.054								.000				
126	2219	.057				900	5,500	11	60	.0035	Passed	Low strength and ductility	Partially welded	
	321	.080								.000				
127	7106	.060				900	5,500	11	60	.003	Passed	Low strength and ductility	Partially welded	
	321	.081								.000				
128	2219	.057				900	5,500	11	60	.002	Passed	Medium strength and ductility	Appeared 90% welded	
	Ti-5Al-2.5Sn	.054								.000				
129	2219	.057				900	7,500	10	120	.013	Passed	Low strength and ductility	Partially welded	
	321	.081								.000				
130	7106	.060				900	7,500	10	120	.010	Passed	Medium strength and ductility	Glossy grey surfaces	Difficult to peel
	321	.081								.000				
131	2219	.057				900	7,500	10	120	.011	Passed	High strength	~	Could not peel
	321	.054								.000				
132	2219	.057				900	3,500	7	120	.001	Failed	~	Small amount of welding	Welding pressure too low for complete welding
	321	.081								.000				
133	7106	.060				900	3,500	7	120	.002	Passed	Low strength	Partially welded	
	321	.080								.000				
134	2219	.057	None	▷	Argon Gas	900	3,500	7	120	.001	Passed	Low strength	Partially welded	
	Ti-5Al-2.5Sn	.054								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEM	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
135	2219	.057	NONE	▷	ARGON GAS	900	3,500	7	240	.001	FAILED	—	SMALL AMOUNT OF WELDING	
	321	.081								.000				
136	7106	.060	▲	▲	▲	900	3,500	7	240	.002	PASSED	LOW STRENGTH	10% WELDED	
	321	.081								.000				
137	2219	.057				900	3,500	7	240	.001	PASSED	HIGH STRENGTH AND DUCTILITY	TITANIUM SURFACE APPEARED TO CONTAIN ALUMINUM	DIFFICULT TO PEEL
	Ti-5Al-2.5Sn	.055								.002				
138	2219	.057				900	5,500	5	120	.003	FAILED	—	SMALL AMOUNT OF WELDING	
	321	.081								.000				
139	7106	.060				900	5,500	5	120	.005	PASSED	MEDIUM STRENGTH AND DUCTILITY	SURFACE OF 7106 APPEARED SLIGHTLY CRAZED	
	321	.081								.000				
140	2219	.057				900	5,500	5	120	.003	PASSED	MEDIUM STRENGTH AND DUCTILITY	TITANIUM SURFACE APPEARED TO CONTAIN ALUMINUM	
	Ti-5Al-2.5Sn	.054								.000				
141	2219	.057				900	7,500	5	240	.011	PASSED	LOW STRENGTH	PARTIALLY WELDED	
	321	.081								.000				
142	7106	.060				900	7,500	5	240	.014	PASSED	MEDIUM STRENGTH AND DUCTILITY	COMPLETELY WELDED GLOSSY-GREY SURFACES	
	321	.080								.000				
143	2219	.057				900	7,500	5	240	.015	PASSED	HIGH STRENGTH AND DUCTILITY	COULD NOT PEEL	
	Ti-5Al-2.5Sn	.055								.000				
144	2219	.057				900	7,500	10	60	.003	FAILED	—	SMALL AMOUNT OF WELDING	
	321	.081								.000				
145	7106	.060				900	7,500	10	60	.005	PASSED	LOW STRENGTH AND DUCTILITY	GREY SURFACES	
	321	.081								.000				
146	2219	.057				900	7,500	10	60	.006	PASSED	MEDIUM STRENGTH AND DUCTILITY	TITANIUM APPEARED TO CONTAIN ALUMINUM	
	Ti-5Al-2.5Sn	.055								.000				
147	2219	.058				900	5,500	5	240	.003	FAILED	—	SMALL AMOUNT OF WELDING	
	321	.081								.000				
148	7106	.060				900	5,500	5	240	.005	PASSED	MEDIUM STRENGTH AND DUCTILITY	GREY SURFACES SOME CRAZING	
	321	.081								.000				
149	2219	.057				900	5,500	5	240	.003	PASSED	HIGH STRENGTH AND DUCTILITY	TITANIUM APPEARED TO CONTAIN ALUMINUM	
	Ti-5Al-2.5Sn	.054								.000				
150	321	.057				900	3,500	5	60	.001	FAILED	—		SPECIMENS DID NOT EXHIBIT ADEQUATE WELDING. PRESSURE TOO LOW FOR 60 MINUTE WELDING TIME.
	321	.081								.000				
151	7106	.060				900	3,500	5	60	.001	FAILED	—		
	321	.081								.000				
152	2219	.057				900	3,500	5	60	.001	FAILED	—		
	Ti-5Al-2.5Sn	.055								.000				
153	2219	.057	▼	▼	▼	950	5,500	4	60	.005	PASSED	LOW STRENGTH AND DUCTILITY	PARTIALLY WELDED	
	321	.080								.000				
154	7106	.060	NONE	▷	ARGON GAS	950	5,500	4	60	.005	PASSED	MEDIUM STRENGTH AND DUCTILITY	GLOSSY GREY SURFACES	
	321	.081								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
155	2219	.057	NONE	▷	ARGON GAS	950	5,500	4	60	.008	PASSED	HIGH STRENGTH AND DUCTILITY	SHINY, ALUMINUM COLOR	DIFFICULT TO PEEL
	Ti-5Al-2.5Sn	.054								.000				
156	2219	.057	▲	▲	▲	950	5,500	7	120	.006	PASSED	LOW STRENGTH AND DUCTILITY	NOT COMPLETELY WELDED	
	321	.081								.000				
157	7106	.060				950	5,500	7	120	.007	PASSED	MEDIUM STRENGTH AND DUCTILITY	GLOSSY-GREY SURFACE	
	321	.081								.000				
158	2219	.057				950	5,500	7	120	.007	PASSED	MEDIUM STRENGTH AND DUCTILITY	TITANIUM CONTAINED PARTICLES OF ALUMINUM	
	Ti-5Al-2.5Sn	.054								.000				
159	2219	.057				950	7,500	5	120	.017	PASSED	LOW STRENGTH AND DUCTILITY	DULL GREY COLOR NOT COMPLETELY WELDED	
	321	.081								.000				
160	7106	.060				950	7,500	5	120	.018	PASSED	MEDIUM STRENGTH AND DUCTILITY	GLOSSY-GREY SURFACES	
	321	.081								.000				
161	2219	.057				950	7,500	5	120	.016	PASSED	HIGH STRENGTH AND DUCTILITY	TITANIUM CONTAINED PARTICLES OF ALUMINUM	DIFFICULT TO PEEL 2219 BROKE DURING PEELING
	Ti-5Al-2.5Sn	.054								.000				
162	2219	.057				950	3,500	10	120	.002	PASSED	LOW STRENGTH	PARTIALLY WELDED	
	321	.081								.000				
163	7106	.060				950	3,500	10	120	.003	PASSED	MEDIUM STRENGTH AND DUCTILITY	GLOSSY-GREY SURFACES	
	321	.080								.000				
164	2219	.057				950	3,500	10	120	.003	PASSED	MEDIUM STRENGTH AND DUCTILITY	ALUMINUM SURFACE APPEARED SLIGHTLY CRAZED	
	Ti-5Al-2.5Sn	.055								.000				
165	2219	.057				950	7,500	5	60	.012	PASSED	LOW STRENGTH AND DUCTILITY	DULL GREY SURFACES	
	321	.081								.000				
166	7106	.060				950	7,500	5	60	.015	PASSED	MEDIUM STRENGTH AND DUCTILITY	GLOSSY-GREY SURFACES	
	321	.081								.000				
167	2219	.057				950	7,500	5	60	.011	PASSED	HIGH STRENGTH AND DUCTILITY	PARTICLES ON SURFACE OF TITANIUM-ALUMINUM SURFACE CRAZED	
	Ti-5Al-2.5Sn	.054								.000				
168	2219	.057				950	7,500	5	30	.007	PASSED	LOW STRENGTH	PARTIALLY WELDED	
	321	.081								.000				
169	7106	.060				950	7,500	5	30	.008	PASSED	MEDIUM STRENGTH LOW DUCTILITY	GLOSSY-GREY SURFACES	
	321	.081								.000				
170	2219	.057				950	7,500	5	30	.007	PASSED	MEDIUM STRENGTH AND DUCTILITY	TITANIUM SURFACE CONTAINED ALUMINUM PARTICLES	
	Ti-5Al-2.5Sn	.054								.008				
171	2219	.057				950	5,500	7	30	.002	FAILED	—	SMALL AMOUNT OF WELDING	
	321	.081								.000				
172	7106	.060				950	5,500	7	30	.003	PASSED	MEDIUM STRENGTH LOW DUCTILITY	90% WELDED	
	321	.081								.000				
173	2219	.057	▼	▼	▼	950	5,500	7	30	.004	PASSED	LOW STRENGTH	75% WELDED	
	Ti-5Al-2.5Sn	.054								.000				
174	2219	.057	NONE	▷	ARGON GAS	950	3,500	5	30	.001	FAILED	—	SMALL AMOUNT OF WELDING	
	321	.081								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
175	7106	.060	NONE	▷	ARGON GAS	950	3,500	5	30	.002	PASSED	MEDIUM STRENGTH LOW DUCTILITY	GLOSSY - GREY SURFACES	
	321	.081								.000				
176	2219	.057	▲	▲	▲	950	3,500	5	30	.001	PASSED	MEDIUM STRENGTH LOW DUCTILITY	TITANIUM CONTAINED PARTICLES OF ALUMINUM	
	Ti-5Al-2.5Sn	.055								.000				
177	2219	.057				950	3,500	6	60	.0015	FAILED	—	SMALL AMOUNT OF WELDING	
	321	.081								.000				
178	7106	.060				950	3,500	6	60	.002	PASSED	MEDIUM STRENGTH LOW DUCTILITY	GLOSSY - GREY SURFACES	
	321	.081								.000				
179	2219	.057				950	3,500	6	60	.0015	PASSED	MEDIUM STRENGTH LOW DUCTILITY	SOME ALUMINUM ON SURFACE OF TITANIUM	
	Ti-5Al-2.5Sn	.054								.000				
180	2219	.057				1000	7,500	7	120	.019	PASSED	LOW STRENGTH AND DUCTILITY	DULL GREY SURFACES COMPLETELY WELDED	
	321	.081								.000				
181	7106	.060				1000	7,500	7	120	.025	PASSED	LOW STRENGTH AND DUCTILITY	GLOSSY GREY SURFACES	
	321	.081								.000				
182	2219	.057				1000	7,500	7	120	.023	PASSED	LOW STRENGTH AND DUCTILITY	SMOOTH - GREY SURFACES	
	Ti-5Al-2.5Sn	.054								.000				
183	2219	.058				1000	5,500	5	120	.016	PASSED	LOW STRENGTH AND DUCTILITY	DULL GREY SURFACES	
	321	.081								.000				
184	7106	.060				1000	5,500	5	120	.015	FAILED	~	GLOSSY - GREY SURFACES	
	321	.081								.000				
185	2219	.057				1000	5,500	5	120	.014	PASSED	MEDIUM STRENGTH AND DUCTILITY	SMOOTH GREY SURFACES	
	Ti-5Al-2.5Sn	.053								.000				
186	2219	.057				1000	3,500	10	120	.004	PASSED	LOW STRENGTH AND DUCTILITY	DULL GREY SMOOTH SURFACES	
	321	.081								.000				
187	7106	.060				1000	3,500	10	120	.005	FAILED	~	GLOSSY - GREY SURFACES	
	321	.080								.000				
188	2219	.057				1000	3,500	10	120	.004	PASSED	LOW STRENGTH AND DUCTILITY	SMOOTH GREY SURFACES	
	Ti-5Al-2.5Sn	.054								.000				
189	2219	.057				1000	7,500	7	60	.019	PASSED	LOW STRENGTH AND DUCTILITY	DULL GREY SMOOTH SURFACES	
	321	.081								.000				
190	7106	.060				1000	7,500	7	60	.012	FAILED	~	GLOSSY - GREY SMOOTH SURFACES	
	321	.081								.000				
191	2219	.057				1000	7,500	7	60	.017	PASSED	MEDIUM STRENGTH AND DUCTILITY	TITANIUM SURFACE ROUGH. ALUMINUM SURFACE CRAZED	
	Ti-5Al-2.5Sn	.054								.000				
192	2219	.057				1000	5,500	6	60	.009	PASSED	MEDIUM STRENGTH AND DUCTILITY	DULL GREY SMOOTH SURFACE	
	321	.081								.000				
193	7106	.060	▼	▼	▼	1000	5,500	6	60	.010	FAILED	~	GLOSSY GREY SURFACE	
	321	.081								.000				
194	2219	.057	NONE	▷	ARGON GAS	1000	5,500	6	60	.011	PASSED	MEDIUM STRENGTH AND DUCTILITY	SMOOTH GREY SURFACES	
	Ti-5Al-2.5Sn	.054								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
195	2219	.057	NONE	▷	ARGON GAS	1000	3,500	5	60	.003	PASSED	LOW STRENGTH	DULL GREY SMOOTH SURFACE	
	321	.081								.000				
196	7106	.060	▲	▲	▲	1000	3,500	5	60	.004	FAILED	~	GLOSSY GREY SURFACES	
	321	.081								.000				
197	2219	.057				1000	3,500	5	60	.002	PASSED	LOW STRENGTH AND DUCTILITY	GLOSSY GREY ALUMINUM CRAZED	
	Ti-5Al-2.5Sn	.054								.000				
198	2219	.057				1000	7,500	7	30	.014	PASSED	LOW STRENGTH AND DUCTILITY	DULL GREY SMOOTH SURFACES	
	321	.081								.000				
199	7106	.060				1000	7,500	7	30	.018	PASSED	LOW STRENGTH AND DUCTILITY	GLOSSY GREY SURFACES	
	321	.081								.000				
200	2219	.057				1000	7,500	7	30	.000	PASSED	MEDIUM STRENGTH AND DUCTILITY	SMOOTH GREY SURFACES	
	Ti-5Al-2.5Sn	.055								.012				
201	2219	.057				1000	5,500	5	30	.007	PASSED	LOW STRENGTH	DULL GREY SMOOTH SURFACES	
	321	.080								.000				
202	7106	.060				1000	5,500	5	30	.006	FAILED	~	GLOSSY GREY SURFACES	
	321	.081								.000				
203	2219	.058				1000	5,500	5	30	.008	PASSED	MEDIUM STRENGTH & DUCTILITY	GLOSSY GREY SURFACES, ALUMINUM CRAZED	
	Ti-5Al-2.5Sn	.055								.000				
204	2219	.057				1000	3,500	6	30	.002	FAILED	~	PARTIALLY WELDED	
	321	.081								.000				
205	7106	.060				1000	3,500	6	30	.003	PASSED	LOW STRENGTH & DUCTILITY	GLOSSY GREY SURFACES	
	321	.081								.000				
206	2219	.057				1000	3,500	6	30	.001	PASSED	LOW STRENGTH & DUCTILITY	GLOSSY GREY SURFACES, ALUMINUM CRAZED	
	Ti-5Al-2.5Sn	.054								.000				
207	INCONEL 718	.061				1600	12,500	5	30	.001	PASSED	HIGH STRENGTH AND DUCTILITY	SMOOTH - LIGHT GREY COLOR	DIFFICULT TO PEEL
	321	.081								.002				
208	INCONEL 718	.061				1600	17,500	6	30	.007 TOTAL	PASSED	~	~	IMPOSSIBLE TO PEEL
	321	.081												
209	INCONEL 718	.061				1600	22,500	4	30	.012 TOTAL	PASSED	~	~	IMPOSSIBLE TO PEEL
	321	.081												
210	INCONEL 718	.061				1600	22,500	5	60	.025 TOTAL	PASSED	~	~	IMPOSSIBLE TO PEEL
	321	.081												
211	INCONEL 718	.061				1600	17,500	4	60	.003	PASSED	HIGH STRENGTH AND DUCTILITY	SMOOTH - LIGHT GREY COLOR	DIFFICULT TO PEEL
	321	.081								.007				
212	INCONEL 718	.061				1600	12,500	21	60	.002	PASSED	HIGH STRENGTH AND DUCTILITY	SMOOTH - LIGHT GREY COLOR	DIFFICULT TO PEEL
	321	.081								.002				
213	INCONEL 718	.061	▼	▼	▼	1600	22,500	7	120	.030 TOTAL	PASSED	~	~	IMPOSSIBLE TO PEEL
	321	.081												
214	INCONEL 718	.061	NONE	▷	ARGON GAS	1600	17,500	7	120	.012	PASSED	HIGH STRENGTH AND DUCTILITY	SMOOTH LIGHT GREY COLOR	DIFFICULT TO PEEL
	321	.081								.011				

SUMMARY OF DIFFUSION WELDING DEV :LOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
215	INCONEL 718	.061	NONE	▷	ARGON GAS	1600	12,500	11	120	.003	PASSED	HIGH STRENGTH AND DUCTILITY	SMOOTH - LIGHT GREY COLOR	DIFFICULT TO PEEL
	321	.081								.005				
216	INCONEL 718	.061	▲	▲	▲	1325	27,500	5	60	.0005	PASSED	LOW STRENGTH	50% WELDED	HIGHER PRESSURES WOULD PROBABLY INCREASE JOINT STRENGTH OF THE 1325 °F SERIES
	321	.080								.0005				
217	INCONEL 718	.061				1325	22,500	5	60	.0005	PASSED	LOW STRENGTH	20% WELDED	
	321	.081								.0005				
218	INCONEL 718	.061				1325	17,500	5	60	.0005	PASSED	LOW STRENGTH	20% WELDED	
	321	.081								.001				
219	INCONEL 718	.061				1325	27,500	4	120	.0015	PASSED	LOW STRENGTH	50% WELDED	
	321	.081								.001				
220	INCONEL 718	.061				1325	22,500	9	120	.0005	PASSED	LOW STRENGTH	50% WELDED	
	321	.081								.001				
221	INCONEL 718	.061				1325	17,500	7	120	.001	PASSED	LOW STRENGTH	20% WELDED	
	321	.081								.0005				
222	INCONEL 718	.061				1325	27,500	7	240	.0015	PASSED	MEDIUM STRENGTH & DUCTILITY	90% WELDED	
	321	.081								.002				
223	INCONEL 718	.061				1325	22,500	6	240	.000	PASSED	LOW STRENGTH	25% WELDED	
	321	.081								.001				
224	INCONEL 718	.061				1325	17,500	6	240	.0005	PASSED	LOW STRENGTH	20% WELDED	
	321	.081								.001				
225	INCONEL 718	.061				1750	17,500	4	10	.005	PASSED	HIGH STRENGTH AND DUCTILITY	SMOOTH - LIGHT GREY SURFACES	DIFFICULT TO PEEL
	321	.081								.007				
226	INCONEL 718	.061				1750	12,500	5	10	.004	PASSED	HIGH STRENGTH AND DUCTILITY	SMOOTH - LIGHT GREY SURFACES	
	321	.081								.004				
227	INCONEL 718	.061				1750	7,500	5	10	.000	PASSED	HIGH STRENGTH AND DUCTILITY	90% WELDED	
	321	.081								.001				
228	INCONEL 718	.061				1750	17,500	4	30	.019 TOTAL	PASSED	~	~	IMPOSSIBLE TO PEEL
	321	.081												
229	INCONEL 718	.061				1750	12,500	8	30	.008	PASSED	HIGH STRENGTH & DUCTILITY	SMOOTH - LIGHT GREY SURFACES	DIFFICULT TO PEEL
	321	.081								.006				
230	INCONEL 718	.061				1750	7,500	5	30	.0015	PASSED	HIGH STRENGTH & DUCTILITY	SMOOTH - LIGHT GREY SURFACES	
	321	.081								.002				
231	INCONEL 718	.061				1750	17,500	4	60	.040 TOTAL	PASSED	~	~	IMPOSSIBLE TO PEEL
	321	.081												
232	INCONEL 718	.061	▼	▼	▼	1750	12,500	4	60	.013	PASSED	HIGH STRENGTH & DUCTILITY	SMOOTH - LIGHT GREY SURFACES	DIFFICULT TO PEEL
	321	.081								.015				
233	INCONEL 718	.061	NONE	▷	ARGON GAS	1750	7,500	5	60	.003	PASSED	HIGH STRENGTH & DUCTILITY	SMOOTH - LIGHT GREY SURFACES	
	321	.081								.006				

▷ ALL MATERIAL CHEMICALLY CLEANED PER APPENDIX A. PRIOR TO WELDING MATERIAL WAS ABRASIVELY CLEANED

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
234	Inconel 600	.046	None	25% C.W.	Argon	1350	20,000	6	10	.001	Passed	Medium Strength Brittle	Smooth - Grey Surfaces - Completely Welded	
	Ti-8Al-1Mo-1V	.042								.001				
235	Inconel 600	.062		Anneal				6	10	.001				
	Ti-8Al-1Mo-1V	.057								.0015				
236	321	.061		25% Cold Reduced				6	10	.001				
	Ti-8Al-1Mo-1V	.043								.0005				
237	321	.080		No Cold Reduction				6	10	.001				
	Ti-8Al-1Mo-1V	.057								.001				
238	Inconel 600	.047		25% Cold Reduced				4	60	.001				
	Ti-8Al-1Mo-1V	.042								.001				
239	Inconel 600	.062		No Cold Reduction				4	60	.002				
	Ti-8Al-1Mo-1V	.058								.002				
240	321	.060		25% Cold Reduced				4	60	.002				
	Ti-8Al-1Mo-1V	.042								.001				
241	321	.081		No Cold Reduction				4	60	.005				
	Ti-8Al-1Mo-1V	.057								.002				
242	Inconel 600	.047		25% Cold Reduced				8	120	.001				
	Ti-8Al-1Mo-1V	.042								.004				
243	Inconel 600	.062		No Cold Reduction				8	120	.002				
	Ti-8Al-1Mo-1V	.054								.002				
244	321	.061		25% Cold Reduction				8	120	.003				
	Ti-8Al-1Mo-1V	.043								.0015				
245	321	.080		No Cold Reduction				8	120	.004				
	Ti-8Al-1Mo-1V	.058								.002				
246	Inconel 718	.043		25% Cold Reduction		1600	12,500	8	10	.0005		Low-Medium Strength	Light Grey 90% Welded	
	321	.061								.0005				
247	Inconel 718	.061		No Cold Reduction		1600	12,500	8	10	.0005		Low-Medium Strength	Light Grey 90% Welded	
	321	.080								.001				
248	Inconel 718	.044		25% Cold Reduction		1600	12,500	6	60	.0015		Medium Strength and Ductility	Smooth - Light Grey Color	
	321	.061								.002				
249	Inconel 718	.061		No Cold Reduction		1600	12,500	6	60	.001		Medium Strength and Ductility	Smooth - Light Grey Color	
	321	.081								.002				
250	Inconel 718	.043		25% Cold Reduction		1600	12,500	6	120	.002		High Strength and Ductility	Smooth - Light Grey Color	Difficult to Peel
	321	.061								.003				
251	Inconel 718	.061		No Cold Reduction		1600	12,500	6	120	.004		High Strength and Ductility	Smooth - Light Grey Color	
	321	.081								.003				
252	321	.080		No Cold Reduction		1450	20,000	6	10	.006		Medium Strength Brittle	Smooth - Dull Grey	
	Ti-8Al-1Mo-1V	.059								.004				
253	321	.073	None	10% Cold Reduction	Argon	1450	20,000	6	10	.005	Passed	Medium Strength Brittle	Smooth - Dull Grey	
	Ti-8Al-1Mo-1V	.053								.004				

SUMMARY OF DIFFUSION WELDING D VELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
254	321	.080	NONE	25% COLD REDUCTION	ARGON	1450	20,000	7	10	.006	PASSED	MEDIUM STRENGTH BRITTLE	SMOOTH DULL GREY	
	Ti-8Al-1Mo-1V	.043								.004				
255	321	.040	↑	50% C.R.	↑	↑	↑	6	10	.007	↑	↑	↑	
	Ti-8Al-1Mo-1V	.059		NONE C.R.						.004				
256	321	.080		NO COLD REDUCTION				4	60	.010				
	Ti-8Al-1Mo-1V	.059								.005				
257	321	.073		10% COLD REDUCTION				4	60	.013				
	Ti-8Al-1Mo-1V	.053								.008				
258	321	.060		25% COLD REDUCTION				4	60	.012				
	Ti-8Al-1Mo-1V	.043								.008				
259	321	.041		50% C.R.				4	60	.004				
	Ti-8Al-1Mo-1V	.060		NO C.R.						.009				
260	321	.080		NO COLD REDUCTION				5	120	.010				
	Ti-8Al-1Mo-1V	.057								.009				
261	321	.073		10% COLD REDUCTION				5	120	.010				
	Ti-8Al-1Mo-1V	.053								.010				
262	321	.060		25% COLD REDUCTION	↓	↓	↓	5	120	.013		↓	↓	
	Ti-8Al-1Mo-1V	.049								.015				
263	321	040		50% C.R.	ARGON	1450	20,000	5	120	.009		MEDIUM STRENGTH BRITTLE	SMOOTH DULL GREY	
	Ti-8Al-1Mo-1V	.062		NO C.R.						.016				
264	2219	.056		ABRASIVE 80 GRIT	AIR	950	7,500	6	30	.008		LOW STRENGTH AND DUCTILITY	PARTIALLY WELDED	SPECIMENS HEATED TO WELDING TEMPERATURE IN AN AIR ATMOSPHERE PRIOR TO APPLYING 7.5 KSI PRESSURE
	321	.080								.000				
265	2219	.056		POLISHED ¼ M	↑	↑	↑	6	30	.007		LOW STRENGTH AND DUCTILITY	CENTER COULD NOT BE PEELED. EDGES NOT WELDED.	
	321	.080								.000				
266	7106	.059		ABRASIVE 80 GRIT				6	30	.008		MEDIUM STRENGTH AND DUCTILITY	COMPLETELY WELDED SURFACE GREY AND CRAZED	
	321	.080								.000				
267	7106	.058		POLISHED ¼ M				6	30	.006		MEDIUM STRENGTH AND DUCTILITY	DIFFICULT TO PEEL SURFACES RETAINED MIRROR FINISH	
	321	.080								.000				
268	2219	.055		ABRASIVE 80 GRIT				6	30	.009		HIGH STRENGTH AND DUCTILITY	COULD NOT PEEL	
	Ti-5Al-2.5Sn	.053								.000				
269	2219	.054		POLISHED ¼ M				6	30	.008	↓	LOW STRENGTH AND DUCTILITY	SURFACES RETAINED MIRROR FINISH	
	Ti-5Al-2.5Sn	.054								.000				
270	2219	.055		ABRASIVE 80 GRIT				80	30	.011	PASSED	MEDIUM STRENGTH AND DUCTILITY	90% WELDED BRIGHT GREY SURFACES	7.5 KSI PRESSURE APPLIED PRIOR TO HEATING PARTS IN AN AIR ATMOSPHERE
	321	.079								.000				
271	2219	.056		POLISHED ¼ M				80	30	.008	FAILED	—	SMALL AMOUNT OF WELDING. SURFACES RETAINED MIRROR FINISH	
	321	.080								.000				
272	7106	.059	↓	ABRASIVE 80 GRIT	↓	↓	↓	80	30	.009	PASSED	MEDIUM STRENGTH AND DUCTILITY	100% WELDED ALUMINUM SURFACE CRAZED	
	321	.078								.000				
273	7106	.058	NONE	POLISHED ¼ M	AIR	950	7,500	80	30	.016	PASSED	MEDIUM STRENGTH AND DUCTILITY	100% WELDED BOTH SURFACES CRAZED	
	321	.080								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
274	2219	.055	None	80 GRIT	AIR	950	7,500	80	30	.009	PASSED	HIGH STRENGTH AND DUCTILITY	DIFFICULT TO PEEL	PRESSURE APPLIED PRIOR TO HEATING TO TEMP. IN AIR.
	Ti-5Al-2.5Sn	.053								.000				
275	2219	.056		POLISHED 1/4 M				80	30	.007	FAILED	—	NO VISIBLE WELDING MIRROR FINISH RETAINED	
	Ti-5Al-2.5Sn	.054								.000				
276	2219	.055		ABRASIVE 1/4 M				75	10	.004	FAILED	—	NO WELDING	PRESSURE APPLIED PRIOR TO HEATING TO TEMP. IN AIR.
	321	.080								.000				
277	7106	.058		ABRASIVE 1/4				75	10	.003	PASSED	MEDIUM STRENGTH AND DUCTILITY	GREY- GRAZED SURFACES	
	321	.080								.000				
278	2219	.055		ABRASIVE 80 GRIT				75	10	.005	PASSED	HIGH STRENGTH	EDGES PARTIALLY WELDED - COULD NOT PEEL REMAINDER	
	Ti-5Al-2.5Sn	.054								.000				
279	2219	.056		ABRASIVE 80 GRIT				8	10	.004	PASSED	LOW STRENGTH	20% WELDED	SPECIMENS HEATED TO TEMPERATURE IN AIR. LOAD APPLIED.
	321	.080								.000				
280	7106	.058		ABRASIVE 80 GRIT				8	10	.003	PASSED	MEDIUM STRENGTH & DUCTILITY	EDGES DID NOT WELD. COMPLETELY AT CENTER	
	321	.080								.000				
281	2219	.055		ABRASIVE 80 GRIT				8	10	.004	FAILED	—	TITANIUM SLIGHTLY OXIDIZED — NO WELDING	
	Ti-5Al-2.5Sn	.054								.000				
282	2219	.056		ABRASIVE 80 GRIT				10	60	.013	PASSED	LOW STRENGTH	SMALL AMOUNT OF WELDING SOME OXIDATION	HEAT TO TEMPERATURE IN AIR. LOAD APPLIED
	321	.080								.000				
283	7106	.057		ABRASIVE 80 GRIT				10	60	.015	PASSED	LOW STRENGTH	SOME WELDING AT CENTER OF SPECIMEN	
	321	.080								.000				
284	2219	.056		ABRASIVE 80 GRIT				10	60	.015	PASSED	MEDIUM STRENGTH & DUCTILITY	EDGES NOT WELDED	
	Ti-5Al-2.5Sn	.054								.000				
285	2219	.056		ABRASIVE 80 GRIT				80	60	.016	FAILED	—	STEEL SLIGHTLY OXIDIZED	PRESSURE APPLIED PRIOR TO HEATING TO TEMPERATURE IN AIR.
	321	.080								.000				
286	7106	.058		ABRASIVE 80 GRIT				80	60	.016	PASSED	LOW STRENGTH	WELDED IN CENTER ONLY	
	321	.080								.000				
287	2219	.056		ABRASIVE 80 GRIT		950	7,500	80	60	.009	PASSED	LOW STRENGTH	WELDED IN CENTER ONLY	
	Ti-5Al-2.5Sn	.054								.000				
288	INCONEL 718	.061		ABRASIVE 80 GRIT		1600	12,500	7	10	.002	PASSED	LOW STRENGTH	LIGHT GREY OXIDE ON SURFACES	HEAT TO TEMPERATURE IN AIR - APPLY LOAD
	321	.080								.001				
289	INCONEL 718	.060		POLISH 1/4 M				7	10	.001	PASSED	LOW STRENGTH	SHINY - BRIGHT BLUE SURFACES	
	321	.080								.003				
290	INCONEL 718	.060		ABRASIVE 80 GRIT				15	60	.003	PASSED	LOW STRENGTH	DARK GREY OXIDE SURFACES	
	321	.080								.004				
291	INCONEL 718	.059		POLISH 1/4 M				15	60	.004	PASSED	LOW STRENGTH	LIGHT GREY SURFACES - SOME WELDING	
	321	.079								.003				
292	INCONEL 718	.060		ABRASIVE 80 GRIT				130	10	.002	PASSED	LOW STRENGTH	GREY OXIDE SURFACES	PRESSURE APPLIED PRIOR TO HEATING TO TEMPERATURE IN AIR
	321	.080								.003				
293	INCONEL 718	.059	None	POLISH 1/4 M	AIR	1600	12,500	130	10	.006 TOTAL	PASSED	HIGH STRENGTH	DIFFICULT TO PEEL COMPLETELY WELDED	
	321	.079												

SUMMARY OF DIFFUSION WELDIN 3 DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP	MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
294	Inconel 718	.056	None	Abrasive 80 grit	Air	1600	12,500	140	60	.001	Passed	Low strength	Light grey oxide surfaces	Applied load prior to heating to temperature
	321	.080								.003				
295	Inconel 718	.057		Polish ¼ M	Air	1600	12,500	140	60	.003 Total	Passed	Could not peel	—	
	321	.080												
296	2219	.056		Abrasive 80 grit	Argon	950	7,500	5	30	.005	Passed	Low strength	70% welded	
	321	.080								.000				
297	2219	.056		Chemical clean				5	30	.006	Passed	High strength & ductility	Surface of steel retained aluminum	
	321	.079								.000				
298	2219	.055		Polish ¼ M				5	30	.006	Failed	—	Mirror image surfaces retained	
	321	.079								.000				
299	2219	.056		Machined				5	30	.006	Passed	Low strength	Partial welding	
	321	.079								.000				
300	2219	.055		Abrasive 80 grit				7	60	.012	Passed	Low strength	Partially welded	
	321	.080								.000				
301	2219	.057		Chemical clean				7	60	.010	Passed	High s strength	Steel surface retained alum.	
	321	.081								.000				
302	2219	.056		Polish ¼ M				7	60	.009	Passed	High strength	Mirror like finish. Some alum. retained on s.s	
	321	.080								.000				
303	2219	.056		Machined				7	60	.010	Passed	Low strength	Partially welded	
	321	.079								.000				
304	7106	.060		Abrasive 80 grit				5	30	.008	Passed	Medium strength and ductility	Aluminum surface crazed	
	321	.081								.000				
305	7106	.060		Chemical clean				5	30	.007	Passed	High strength	Could not peel	
	321	.080								.000				
306	7106	.060		Polish ¼ M				5	30	.007	Passed	Medium strength & ductility	Mirror surfaces retained - some crazing	
	321	.080								.000				
307	7106	.060		Machined				5	30	.008	Passed	Medium strength	Aluminum surface crazed	
	321	.078								.000				
308	7106	.060		Abrasive 80 grit				5	60	.005	Passed	Medium strength	Aluminum surface crazed	
	321	.081								.000				
309	7106	.060		Chemical clean				5	60	.010	Passed	High strength	Difficult to peel aluminum crazed	
	321	.080								.000				
310	7106	.060		Polish ¼ M				5	60	.011	Passed	Medium strength	Shiny - smooth crazed surfaces	
	321	.081								.000				
311	7106	.060		Machined				5	60	.013	Passed	Medium strength	Aluminum crazed	
	321	.079								.000				
312	2219	.057		Abrasive 80 grit				5	30	.003	Passed	Medium-high strength	Aluminum surface crazed	
	Ti-5Al-2.5Sn	.054								.000				
313	2219	.056	None	Chemical clean	Argon	950	7,500	5	30	.002	Passed	Low strength	Some crazing rogue not welded	
	Ti-5Al-2.5Sn	.054								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
314	2219	.056	NONE	POLISH ¼ M	ARGON	950	7,500	5	30	.002	PASSED	HIGH STRENGTH AND DUCTILITY	COULD NOT PEEL WITHOUT FRACTURING	ALUM
	Ti-5Al-2.5Sn	.054								.000				
315	2219	.055		MACHINED		950	7,500	5	30	.002		MEDIUM STRENGTH	SOME ALUMINUM RETAINED ON Ti.	
	Ti-5Al-2.5Sn	.055								.000				
316	2219	.056		ABRASIVE 80 GRIT		950	7,500	7	60	.005		HIGH STRENGTH & DUCTILITY	DIFFICULT TO PEEL ALUMINUM CRAZED	
	Ti-5Al-2.5Sn	.054								.000				
317	2219	.056		CHEMICAL CLEAN		950	7,500	7	60	.004		HIGH STRENGTH & DUCTILITY	DIFFICULT TO PEEL ALUMINUM CRAZED	
	Ti-5Al-2.5Sn	.054								.000				
318	2219	.056		POLISH ¼ M		950	7,500	7	60	.004		HIGH STRENGTH & DUCTILITY	ALMOST IMPOSSIBLE TO PEEL	
	Ti-5Al-2.5Sn	.053								.000				
319	2219	.054		MACHINED		950	7,500	7	60	.002		MEDIUM STRENGTH	TITANIUM SURFACE CONTAINED ALUM. PARTICLES	
	Ti-5Al-2.5Sn	.055								.000				
320	INCONEL 600	.062		ABRASIVE 80 GRIT		1350	20,000	5	10	.001		MEDIUM STRENGTH-BRITTLE	SMOOTH-GREY SURFACES	
	Ti-8Al-1Mo-1V	.060								.002				
321	INCONEL 600	.062		CHEMICAL CLEAN		1350	20,000	5	10	.0015				
	Ti-8Al-1Mo-1V	.059								.002				
322	INCONEL 600	.062		POLISH ¼ M		1350	20,000	5	10	.002				
	Ti-8Al-1Mo-1V	.059								.0005				
323	INCONEL 600	.061		MACHINED		1350	20,000	5	10	.002				
	Ti-8Al-1Mo-1V	.059								.001				
324	INCONEL 600	.062		ABRASIVE 80 GRIT		1350	20,000	6	60	.002				
	Ti-8Al-1Mo-1V	.059								.002				
325	INCONEL 600	.062		CHEMICAL CLEAN		1350	20,000	6	60	.004				
	Ti-8Al-1Mo-1V	.059								.004				
326	INCONEL 600	.061		POLISH ¼ M		1350	20,000	6	60	.005				
	Ti-8Al-1Mo-1V	.059								.004				
327	INCONEL 600	.060		MACHINED		1350	20,000	6	60	.003				
	Ti-8Al-1Mo-1V	.059								.003				
328	321	.080		ABRASIVE 80 GRIT		1450	20,000	10	10	.002				
	Ti-8Al-1Mo-1V	.060								.004				
329	321	.080		CHEMICAL CLEAN		1450	20,000	10	10	.006				
	Ti-8Al-1Mo-1V	.060								.003				
330	321	.080		POLISH ¼ M		1450	20,000	10	10	.007				
	Ti-8Al-1Mo-1V	.058								.004				
331	321	.077		MACHINED		1450	20,000	10	10	.005				
	Ti-8Al-1Mo-1V	.059								.002				
332	321	.081		ABRASIVE 80 GRIT		1450	20,000	5	60	.005				
	Ti-8Al-1Mo-1V	.059								.008				
333	321	.081	NONE	CHEMICAL CLEAN	ARGON	1450	20,000	5	60	.015	PASSED	MEDIUM STRENGTH-BRITTLE	SMOOTH-GREY SURFACES	
	Ti-8Al-1Mo-1V	.059								.012				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP.					
334	321	.081	NONE	POLISH 1/4 M	ARGON	1450	20,000	5	60	.012	PASSED	MEDIUM STRENGTH-BRITTLE	SMOOTH - GREY SURFACES	
	Ti-8Al-1Mo-1V	.059								.009				
335	321	.078		MACHINED		1450	20,000	5	60	.012	PASSED	MEDIUM STRENGTH-BRITTLE	SMOOTH - GREY SURFACES	
	Ti-8Al-1Mo-1V	.059								.005				
336	INCONEL 718	.060		ABRASIVE 80 GRIT		1600	12,500	5	10	.000	PASSED	MEDIUM STRENGTH	SOME SANDING MARKS VISIBLE	SPECIMENS PEELED USING PLIERS
	321	.081								.001				
337	INCONEL 718	.060		CHEMICAL CLEAN		1600	12,500	5	10	.001	PASSED	MEDIUM STRENGTH	DULL GREY SURFACES	
	321	.081								.001				
338	INCONEL 718	.061		POLISH 1/4 M		1600	12,500	5	10	.001	PASSED	MEDIUM STRENGTH	DULL GREY SURFACES	
	321	.081								.001				
339	INCONEL 718	.062		MACHINED		1600	12,500	5	10	.002	PASSED	MEDIUM STRENGTH	SOME MACHINING MARKS VISIBLE	
	321	.081								.001				
340	INCONEL 718	.061		ABRASIVE 80 GRIT		1600	12,500	5	60	.002	PASSED	HIGH STRENGTH	DULL GREY SURFACES	CHISEL REQUIRED TO PEEL SPECIMENS
	321	.081								.002				
341	INCONEL 718	.061		CHEMICAL CLEAN		1600	12,500	5	60	.002	PASSED	HIGH STRENGTH	DULL GREY SURFACES	
	321	.081								.004				
342	INCONEL 718	.061		POLISH 1/4 M		1600	12,500	5	60	.002	PASSED	HIGH STRENGTH	SURFACES SHINY AND SMOOTH	
	321	.080								.003				
343	INCONEL 718	.062	NONE	MACHINED		1600	12,500	5	60	.005	PASSED	HIGH STRENGTH	DULL GREY SURFACES	
	321	.080								.004				
344	INCONEL 600	.062	SILVER FOIL .001"	ABRASIVE CLEAN 80 GRIT		1000	20,000	5	60	.000	PASSED	LOW STRENGTH	SILVER ADHERED TO TITANIUM. POOR ADHERENCE TO INCO 600	
	Ti-8Al-1Mo-1V	.060								000				
345	321	.081	SILVER FOIL .001"			1000	20,000	5	60	.000	PASSED	LOW STRENGTH	SILVER ADHERED TO TITANIUM. POOR ADHERENCE TO 321 SS	
	Ti-8Al-1Mo-1V	.059								.000				
346	INCONEL 718	.061	SILVER FOIL .001"			1000	20,000	5	60	.000	PASSED	LOW STRENGTH	SILVER HAD POOR ADHERENCE TO 718 AND 321	
	321	.081								.000				
347	INCONEL 600	.062	SILVER FOIL .001"			1300	20,000	5	10	.000	PASSED	MEDIUM STRENGTH	SILVER ADHERED TO TITANIUM AND APPROX 50% OF INCO 600	
	Ti-8Al-1Mo-1V	.059								.000				
348	321	.081	SILVER FOIL .001"			1300	20,000	5	10	.000	PASSED	MEDIUM STRENGTH	SILVER ADHERED TO TITANIUM AND APPROX. 75% OF 321 SURFACE	
	Ti-8Al-1Mo-1V	.059								.000				
349	INCONEL 718	.061	SILVER FOIL .001"			1300	20,000	5	10	.000	PASSED	MEDIUM STRENGTH	SILVER ADHERED TO APPROX. 75% OF SURFACES	
	321	.080								.000				
350	INCONEL 600	.061	SILVER FOIL .001"			1500	20,000	8	10	.010	PASSED	MEDIUM STRENGTH	SILVER RANDOMLY PEELED FROM BOTH SURFACES	
	Ti-8Al-1Mo-1V	.059								.003				
351	321	.080	SILVER FOIL .001"			1500	20,000	8	10	.002	PASSED	MEDIUM STRENGTH	SILVER FAILED AT 321 SURFACE AND AT SILVER INTERFACE	
	Ti-8Al-1Mo-1V	.059								.009				
352	INCONEL 718	.062	SILVER FOIL .001"			1500	20,000	8	10	.001	PASSED	MEDIUM STRENGTH	SILVER PEELED FROM BOTH SURFACES RANDOMLY	
	321	.081								.002				
353	INCONEL 600	.062	GOLD FOIL .001"	ABRASIVE CLEAN 80 GRIT	ARGON	1000	20,000	6	60	.000	—	—	FOIL DID NOT ADHERE TO INCO 600 GOOD ADHERENCE TO Ti.	
	Ti-8Al-1Mo-1V	.059								.000				

D 19

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
354	321	.080	GOLD FOIL .001"	ABRASIVE CLEAN 80 GRIT	ARGON	1000	20,000	6	60	.000	—	~	FOIL DID NOT WELD TO 321. GOOD ADHERENCE TO TITANIUM	
	Ti-8Al-1Mo-1V	.059								.000				
355	INCONEL 718	.061	↑	↑	↑	1000	↑	6	60	.000	~	~	NO WELDING OF FOIL TO 321 OR 718	
	321	.081								.000				
356	INCONEL 600	.062				1300		5	10	.000	PASSED	LOW STRENGTH BRITTLE	GOLD PEELED FROM TITANIUM. Ti SURFACE DARK GREY	
	Ti-8Al-1Mo-1V	.058								.000				
357	321	.080				1300		5	10	.000	PASSED	LOW STRENGTH BRITTLE	TITANIUM SURFACE VERY DARK	
	Ti-8Al-1Mo-1V	.059								.000				
358	INCONEL 718	.062				1300		5	10	.000	PASSED	LOW-MEDIUM STRENGTH	GOLD FOIL PEELED FROM 718 - WAS SILVER IN COLOR	
	321	.081								.000				
359	INCONEL 600	.062				1200		5	10	.000	—	~	GOLD DID NOT WELD TO INCO 600. AU LIGHT IN COLOR	
	Ti-8Al-1Mo-1V	.059								.000				
360	321	.080				1200		5	10	.000	~	~	GOLD DID NOT WELD TO 321. AU HAD LIGHT BRASS COLOR	
	Ti-8Al-1Mo-1V	.059								.000				
361	INCONEL 718	.061	GOLD FOIL .001"			1200		5	10	.000	~	~	FOIL LIGHT IN COLOR. DID NOT WELD	
	321	.080								.000				
362	INCONEL 600	.062	NICKEL FOIL .002"			1000		7	60	.000	~	~	FOIL DID NOT WELD TO INCO 600. SOME WELDING TO Ti	
	Ti-8Al-1Mo-1V	.060								.000				
363	321	.081	↓			1000		7	60	.000	~	~	FOIL DID NOT WELD TO 321 SS. SOME WELDING TO Ti	
	Ti-8Al-1Mo-1V	.059								.000				
364	INCONEL 718	.061				1000		7	60	.000	~	~	NO WELDING	
	321	.081								.000				
365	INCONEL 600	.062				1300		5	10	.000	PASSED	LOW STRENGTH & DUCTILITY	NICKEL FOIL PEELED PRIMARILY FROM INCO 600	THIS COMBINATIONS HAVE BETTER DUCTILITY THAN BARE COMBINATIONS
	Ti-8Al-1Mo-1V	.060								.001				
366	321	.080				1300		5	10	.000	PASSED	MEDIUM STRENGTH Low DUCTILITY	NICKEL FOIL PEELED PRIMARILY FROM 321	
	Ti-8Al-1Mo-1V	.059								.000				
367	INCONEL 718	.062				1300		5	10	.000	PASSED	LOW STRENGTH	PARTIAL WELDING TO 718 & 321	
	321	.080								.001				
368	INCONEL 600	.061				1300		5	60	.001	PASSED	MEDIUM STRENGTH - LOW DUCTILITY	RANDOM FAILURE THROUGH FOIL AND METAL SURFACES	
	Ti-8Al-1Mo-1V	.059								.001				
369	321	.079				1300		5	60	.001	PASSED	MEDIUM STRENGTH- LOW DUCTILITY	RANDOM FAILURE. THROUGH FOIL AND METAL SURFACES	
	Ti-8Al-1Mo-1V	.059								.002				
370	INCONEL 718	.061				1300		5	60	.001	PASSED	LOW STRENGTH	PARTIAL WELDING OF FOIL TO INCO 718	
	321	.081								.002				
371	INCONEL 600	.061				1500		6	10	.003	PASSED	MEDIUM STRENGTH BRITTLE	FAILED AT TITANIUM INTERFACE	FAILED SIMILAR TO BARE METAL COMBINATIONS
	Ti-8Al-1Mo-1V	.058								.007				
372	321	.080				1500		6	10	.010	PASSED	MEDIUM STRENGTH BRITTLE	FAILED AT TITANIUM INTERFACE	
	Ti-8Al-1Mo-1V	059	↓	↓	↓		↓			.006				
373	INCONEL 718	.061	NICKEL FOIL .002"	ABRASIVE CLEAN 80 GRIT	ARGON	1500	20,000	6	10	.002	PASSED	HIGH STRENGTH & DUCTILITY	FAILED AT INCO 718 INTERFACE	
	321	.080								.003				

D20

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
374	Inconel 600	.062	Copper Foil .001"	Abrasive Bo Grit	Argon	1300	10,000	5	60	.000	Passed	Low strength brittle	Dull grey- Cu apparently peeled from Inco 600	Better ductility than bare metal combinations
	Ti-8Al-1Mo-1V	.059								.001				
375	321	.080				1300	10,000	5	60	.001	Passed	Low strength brittle	Dull grey random failure	
	Ti-8Al-1Mo-1V	.059								.002				
376	Inconel 718	.061				1300	10,000	5	60	.001	Passed	Medium strength & ductility	Appeared similar to copper brazed joint	
	321	.080								.001				
377	Inconel 600	.061				1500	10,000	7	10	.005	—	~	Parts separated - dark grey surfaces	
	Ti-8Al-1Mo-1V	.058								.010				
378	321	.081				1500	10,000	7	10	.015	—	~	Parts separated - dark grey surfaces	
	Ti-8Al-1Mo-1V	.060								.006				
379	Inconel 718	.063				1500	10,000	7	10	.002	Passed	Medium strength & ductility	Appeared similar to copper brazed joint	
	321	.081								.003				
380	Inconel 600	.061				1700	12,500	5	10	.010	~	~	Parts separated - no evidence of Cu foil	
	Ti-8Al-1Mo-1V	.059								.020				
381	321	.080				1700	12,500	5	10	.015	~	~	Parts separated no evidence of Cu foil	
	Ti-8Al-1Mo-1V	.059								.018				
382	Inconel 718	.061	Copper Foil .001"			1700	12,500	5	10	.030 Total	Passed	High strength	Could not peel	
	321	.080												
383	Inconel 600	.062	Titanium Foil .001"			1500	20,000	5	10	.002	Passed	Medium strength - brittle	Shiny - grey surfaces	Strength & appearance similar to bare material
	Ti-8Al-1Mo-1V	.060								.005				
384	321	.081				1500	20,000	5	10	.010	Passed	Medium strength- brittle	Shiny- grey surfaces	
	Ti-8Al-1Mo-1V	.059								.005				
385	Inconel 600	.062				1300	20,000	5	60	.000	Passed	Medium strength brittle	Dull grey surfaces	
	Ti-8Al-1Mo-1V	.060								.002				
386	321	.081				1300	20,000	5	60	.004	Passed	Medium strength brittle	Dull grey surfaces	
	Ti-8Al-1Mo-1V	.059								.001				
387	Inconel 600	.062				1300	20,000	5	10	.000	Passed	Low strength	Incomplete welding	
	Ti-8Al-1Mo-1V	.060								.001				
388	321	.080				1300	20,000	5	10	.001	Passed	Low strength	Incomplete welding	
	Ti-8Al-1Mo-1V	.060								.000				
389	Inconel 600	.061				1000	20,000	5	60	.000	~	~	Foil did not adhere to Ti.	
	Ti-8Al-1Mo-1V	.059								.000				
390	321	.080	Titanium Foil .001"			1000	20,000	5	60	.000	~	~	Foil did not adhere to Ti.	
	Ti-8Al-1Mo-1V	.060								.000				
391	Inconel 600	.062	Vanadium Foil .002"			1300	20,000	5	10	.000	Passed	Low strength	Foil did not adhere to Ti alloy.	
	Ti-8Al-1Mo-1V	.060								.000				
392	321	.081	Vanadium Foil .002"			1300	20,000	5	10	.001	Passed	Low strength	Foil did not adhere to Ti alloy.	
	Ti-8Al-1Mo-1V	.059								.000				
393	Inconel 600	.062	Vanadium Foil .002"	Abrasive Bo Grit	Argon	1300	20,000	5	60	.000	Passed	Low strength	Foil did not completely weld to Ti alloy	
	Ti-8Al-1Mo-1V	.060								.002				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP.					
394	321	.081	VANADIUM FOIL .002"	ABRASIVE 80 GRIT	ARGON	1300	20,000	5	60	.002	PASSED	LOW STRENGTH	FOIL NOT COMPLETELY WELDED TO Ti ALLOY	
	Ti-8Al-1Mo-1V	.061								.002				
395	INCONEL 600	.062	VANADIUM FOIL .002"			1500	20,000	6	10	.003	PASSED	HIGH STRENGTH MED. DUCTILITY	FOIL PEELED RANDOMLY FROM BOTH SURFACES	
	Ti-8Al-1Mo-1V	.062								.008				
396	321	.080	VANADIUM FOIL .002"			1500	20,000	6	10	.010	PASSED	HIGH STRENGTH MED. DUCTILITY	FOIL PEELED RANDOMLY FROM BOTH SURFACES	
	Ti-8Al-1Mo-1V	.059								.005				
397	INCONEL 600	.062	VANADIUM FOIL .002"			1700	12,500	5	10	.008	PASSED	HIGH STRENGTH MED. DUCTILITY	FOIL NOT VISIBLE AFTER PEELING	
	Ti-8Al-1Mo-1V	.060								.015				
398	321	.080	VANADIUM FOIL .002"			1700	12,500	5	10	.025	PASSED	HIGH STRENGTH MED. DUCTILITY	FOIL NOT VISIBLE AFTER PEELING	
	Ti-8Al-1Mo-1V	.060								.010				
399	INCONEL 718	.061	IRON FOIL .001"			1000	20,000	5	60	.000	~	~	FOIL DID NOT WELD TO EITHER ALLOY	
	321	.081								.000				
400	INCONEL 718	.061	IRON FOIL .001"			1300	20,000	8	10	.000	~	~	FOIL WELDED TO 321 ALLOY ONLY	
	321	.081								.001				
401	INCONEL 718	.061	IRON FOIL .001"			1500	20,000	5	60	.002	PASSED	LOW STRENGTH	INCOMPLETE WELDING TO 718 ALLOY	
	321	.080								.002				
402	INCONEL 718	.061	IRON FOIL .001"	ABRASIVE 80 GRIT	ARGON	1500	20,000	5	10	.001	PASSED	LOW STRENGTH	SMALL AMOUNT OF WELDING TO 718 ALLOY	
	321	.081								.001				
403	2219	.055	NONE	POLISH DONE 1/4 M	VACUUM	950	7,500	12	30	.010	FAILED	~	MIRROR FINISH RETAINED	
	321	.080								.000				
404	7106	.059		POLISH 1/4 M				12	30	.014	PASSED	MEDIUM STRENGTH BRITTLE	SMOOTH GREY SURFACES	
	321	.081								.000				
405	2219	.055		POLISH 1/4 M				12	30	.008	PASSED	HIGH STRENGTH	IMPOSSIBLE TO PEEL	
	Ti-5Al-2.5Sn	.054								.000				
406	2219	.056		ABRASIVE 80 GRIT				10	30	.011	PASSED	LOW STRENGTH	NOT COMPLETELY WELDED	
	321	.081								.000				
407	7106	.059		ABRASIVE 80 GRIT				10	30	.010	PASSED	MEDIUM STRENGTH LOW DUCTILITY	SMOOTH GREY SURFACES	
	321	.080								.000				
408	2219	.055		ABRASIVE 80 GRIT				10	30	.009	PASSED	HIGH STRENGTH MED DUCTILITY	ALUMINUM ADHERED TO TITANIUM	
	Ti-5Al-2.5Sn	.054								000				
409	2219	.055		POLISH 1/4 M				14	60	.014	PASSED	LOW STRENGTH	SHINY MIRROR FINISH	
	321	.080								.000				
410	7106	.059		POLISH 1/4 M				14	60	.016	FAILED	~	SHINY GREY SURFACES	
	321	.080								.000				
411	2219	.055		POLISH 1/4 M				14	60	.011	PASSED	HIGH STRENGTH	COULD NOT PEEL	
	Ti-5Al-2.5Sn	.054								.000				
412	2219	.065		ABRASIVE 80 GRIT				6	60	.010	PASSED	MEDIUM STRENGTH	TITANIUM APPEARED	
	321	.081								.000				
413	7106	.060	NONE	ABRASIVE 80 GRIT	VACUUM	950	7,500	6	60	.015	FAILED	~	SMOOTH - SHINY SURFACES	
	321	.080								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
414	2219	.056	NONE	ABRASIVE 80 GRIT	VACUUM	950	7,500	6	60	.010	PASSED	HIGH STRENGTH MED. DUCTILITY	ALUMINUM ADHERED TO TITANIUM	
	Ti-5Al-2.5Sn	.054								.000				
415	INCONEL 600	.062	↑	↑	↑	1350	20,000	10	10	.000	PASSED	HIGH STRENGTH BRITTLE	SMOOTH GREY SURFACES	
	Ti-8Al-1Mo-1V	.059								.001				
416	321	.080				1350	↑	10	10	.000	PASSED	LOW STRENGTH	NOT COMPLETELY WELDED	
	Ti-8Al-1Mo-1V	.059								.001				
417	INCONEL 718	.060				1350		10	10	.000	~	~	NO WELDING	
	321	.080								.000				
418	INCONEL 600	.061				1350		8	30	.001	PASSED	MEDIUM STRENGTH BRITTLE	DULL GREY SURFACES	
	Ti-8Al-1Mo-1V	.058								.002				
419	321	.080				1350		8	30	.001	PASSED	MEDIUM STRENGTH BRITTLE	DULL GREY SURFACES	
	Ti-8Al-1Mo-1V	.058								.004				
420	INCONEL 718	.060				1350		8	30	.001	PASSED	MEDIUM STRENGTH & DUCTILITY	LIGHT GREY SURFACES	
	321	.080								.001				
421	INCONEL 600	.062				1450		12	10	.001	PASSED	MEDIUM STRENGTH BRITTLE	DULL GREY SURFACES	
	Ti-8Al-1Mo-1V	.059								.001				
422	321	.080				1450		12	10	.001	PASSED	MEDIUM STRENGTH BRITTLE	DULL GREY SURFACES	
	Ti-8Al-1Mo-1V	.059								.002				
423	INCONEL 718	.061				1450		12	10	.001	PASSED	LOW STRENGTH	PARTIALLY WELDED	
	321	.080								.001				
424	INCONEL 600	.062				1450		10	30	.003	PASSED	MEDIUM STRENGTH BRITTLE	DULL GREY SURFACES	
	Ti-8Al-1Mo-1V	.058								.005				
425	321	.081	↓	↓	↓	1450	↓	10	30	.010	PASSED	MEDIUM STRENGTH BRITTLE	DULL GREY SURFACES	
	Ti-8Al-1Mo-1V	.058								.004				
426	INCONEL 718	.060	NONE	ABRASIVE 80 GRIT	VACUUM	1450	20,000	10	30	.005 TOTAL	PASSED	HIGH STRENGTH	COULD NOT PEEL	
	321	.081												
427	2219	.058	COPPER PLATE	ABRASIVE ISO GRIT	ARGON	500	25,000	10	60	.001	PASSED	LOW STRENGTH	NO COMPLETELY WELDED. COPPER TARNISHED	COPPER AND SILVER PLATING WERE APPLIED TO BARE ALUMINUM AND TITANIUM ON SPECIMENS No. 427 THROUGH No. 450
	321	.083								.000				
428	7106	.061	↑	↑	↑	500	25,000	10	60	.004	PASSED	MEDIUM STRENGTH	NOT COMPLETELY WELDED. COPPER TARNISHED.	
	321	.081								.000				
429	2219	.058				500	25,000	10	60	.003	PASSED	LOW STRENGTH	COPPER STRIPPED VERY EASILY (FROM Ti)	
	Ti-5Al-2.5Sn	.056								.000				
430	2219	.058				500	25,000	8	120	001	PASSED	LOW STRENGTH	INCOMPLETE WELDING COPPER TARNISHED	
	321	.082								000				
431	7106	.061				500	25,000	8	120	.002	PASSED	LOW STRENGTH	INCOMPLETE WELDING COPPER TARNISHED	
	321	.083								.000				
432	2219	.058	↓	↓	↓	500	25,000	8	120	.002	PASSED	LOW STRENGTH	COPPER STRIPPED FROM TITANIUM	
	Ti-5Al-2.5Sn	.056								.000				
433	2219	.058	COPPER PLATE	ABRASIVE ISO GRIT	ARGON	700	17,500	6	10	.003	PASSED	MEDIUM STRENGTH & DUCTILITY	PEELED AT COPPER TO 2219 INTERFACE	
	321	.083								.000				

D23

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
434	7106	.061	COPPER PLATE	ABRASIVE ISO GRIT	ARGON	700	17,500	6	10	.008	PASSED	HIGH STRENGTH MOD. DUCTILITY	PEELED AT COPPER TO 7106 INTERFACE	
	2219	.083								.000				
435	2219	.058	↑	↑	↑	700	17,500	6	10	.002	↑	LOW STRENGTH	COPPER STRIPPED FROM TITANIUM	
	Ti-5Al-2.5Sn	.056								.000				
436	2219	.058	↕			700	17,500	5	60	.002		MEDIUM STRENGTH & DUCTILITY	COPPER FRACTURED AT ALUMINUM INTERFACE	
	321	.082								.000				
437	7106	.061	↓			700	17,500	5	60	.012		MEDIUM STRENGTH & DUCTILITY	COPPER FRACTURED AT ALUMINUM INTERFACE	
	321	.083								.000				
438	2219	.057	COPPER PLATE			700	17,500	5	60	.004		LOW STRENGTH	COPPER STRIPPED FROM TITANIUM	
	Ti-5Al-2.5Sn	.056								.000				
439	2219	.058	SILVER PLATE			500	25,000	6	60	.001		MEDIUM STRENGTH	FAILED AT SILVER TO SILVER INTERFACE	
	321	.083								.000				
440	7106	.062	↑			500	25,000	6	60	.002		MEDIUM STRENGTH	FAILED AT SILVER TO SILVER INTERFACE	
	321	.083								.000				
441	2219	.058				500	25,000	6	60	.001		LOW STRENGTH	SILVER STRIPPED FROM TITANIUM	
	Ti-5Al-2.5Sn	.057								.000				
442	2219	.058				500	25,000	5	120	.002		MEDIUM STRENGTH	FAILED AT SILVER TO SILVER INTERFACE	
	321	.082								.000				
443	7106	.062				500	25,000	5	120	.006		MEDIUM STRENGTH	FAILED AT SILVER TO SILVER INTERFACE	
	321	.082								.000				
444	2219	.058				500	25,000	5	120	.002		LOW STRENGTH	SILVER STRIPPED FROM TITANIUM	
	Ti-5Al-2.5Sn	.056								.000				
445	2219	.058				700	17,500	10	10	.002		MEDIUM STRENGTH	FAILED AT SILVER TO 2219 INTERFACE	
	321	.083								.000				
446	7106	.062				700	17,500	10	10	.006		MEDIUM STRENGTH	FAILED AT SILVER TO 7106 INTERFACE	
	321	.083								.000				
447	2219	.058				700	17,500	10	10	.002		LOW STRENGTH	SILVER STRIPPED FROM TITANIUM	
	Ti-5Al-2.5Sn	.057								.000				
448	2219	.059				700	17,500	8	60	.005	↓	MEDIUM STRENGTH	FAILED AT SILVER TO 2219 INTERFACE	
	321	.083								.000				
449	7106	.063	↓			700	17,500	8	60	.008	PASSED	MEDIUM STRENGTH	FAILED AT SILVER TO 7106 INTERFACE	
	321	.083								.000				
450	2219	.058	SILVER PLATE			700	17,500	8	60	.005	~	~	SILVER PARTED FROM TITANIUM	
	Ti-5Al-2.5Sn	.057								.000				
451	2219	.059	COPPER PLATE			500	25,000	5	60	.003	PASSED	LOW STRENGTH	SMALL AMOUNT OF WELDING. COPPER TARNISHED	
	321	.082								.000				
452	7106	.063	COPPER PLATE	↓	↓	500	25,000	5	60	.003	PASSED	MEDIUM STRENGTH	PARTIALLY WELDED COPPER TARNISHED	
	321	.082								.000				
453	2219	.058	COPPER PLATE	ABRASIVE ISO GRIT	ARGON	500	25,000	5	60	.002	PASSED	LOW STRENGTH	PARTIALLY WELDED SOME COPPER STRIPPED FROM Ti	
	Ti-5Al-2.5Sn	.057								.000				

SUMMARY OF DIFFUSION WELDING DEVELC PMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
454	2219	.058	COPPER PLATE	ABRASIVE 150 GRIT	ARGON	500	25000	5	120	.001	PASSED	LOW STRENGTH	PARTIALLY WELDED SOME COPPER PEELED FROM 2219	COPPER AND SILVER PLATING WAS APPLIED TO ANODIZED ALUMINUM AND TO ANODIZED (TiF) TITANIUM OD SPECIMENS No. 451 THROUGH No. 482
	321	.083								.000				
455	7106	.062				500	25,000	5	120	.004		LOW STRENGTH	COPPER PEELED FROM ANODIZED 7106	
	321	.083								.000				
456	2219	.058				500	25,000	5	120	.002		LOW STRENGTH	COPPER PEELED FROM TITANIUM SURFACE	
	Ti-5Al-2.5Sn	.056								.000				
457	2219	.058				700	17,500	6	10	.002		MEDIUM STRENGTH	COPPER & ANODIZED SURFACE LIFTED FROM 2219	
	321	.083								.000				
458	7106	.062				700	17,500	6	10	.005		MED-LOW STRENGTH	COPPER LIFTED FROM ANODIZED SURFACE OF 7106	
	321	.082								.000				
459	2219	.058				700	17,500	6	10	.002		LOW STRENGTH	COPPER LIFTED FROM TITANIUM SURFACE	
	Ti-5Al-2.5Sn	.057								.000				
460	2219	.058				700	17,500	5	60	.002		LOW STRENGTH	COPPER AND ANODIZED SURFACE LIFTED FROM 2219	
	321	.082								.000				
461	7106	.061				700	17,500	5	60	.010		LOW STRENGTH	COPPER PEELED FROM ANODIZED SURFACE OF 7106	
	321	.082								.000				
462	2219	.058	COPPER PLATE			700	17,500	5	60	.005		LOW STRENGTH	COPPER PEELED FROM TITANIUM	
	Ti-5Al-2.5Sn	.057								.000				
463	2219	.058	SILVER PLATE			500	25,000	5	60	.001		LOW STRENGTH	SILVER LIFTED FROM ANODIZED SURFACE OF 2219	
	321	.082								.000				
464	7106	.062				500	25,000	5	60	.004		LOW STRENGTH	SILVER LIFTED FROM SURFACE OF 7106	
	321	.081								.000				
465	2219	.062				500	25,000	5	60	.002		LOW STRENGTH	SILVER LIFTED FROM SURFACE OF TITANIUM	
	Ti-5Al-2.5Sn	.057								.000				
466	2219	.058				500	25,000	7	120	.002		LOW STRENGTH	SILVER LIFTED FROM ANODIZED SURFACE OF 2219	
	321	.083								.000				
467	7106	.062				500	25,000	7	120	.004		LOW STRENGTH	SILVER LIFTED FROM ANODIZED SURFACE OF 7106	
	321	.083								.000				
468	2219	.058				500	25000	7	120	.004		LOW STRENGTH	SILVER LIFTED FROM TITANIUM	
	Ti-5Al-2.5Sn	.057								.000				
469	2219	.058				700	17,500	5	10	.004	PASSED	LOW STRENGTH	SILVER PEELED FROM ANODIZED SURFACE	
	321	.082								.000				
470	7106	.063				700	17,500	5	10	.008	PASSED	LOW STRENGTH	SILVER PEELED FROM ANODIZED SURFACE	
	321	.083								.000				
471	2219	.058				700	17,500	5	10	.000	~	~	PARTS SEPARATED SILVER STRIPPED FROM Ti	
	Ti-5Al-2.5Sn	.056								.002				
472	2219	.058				700	17,500	5	60	.002	PASSED	LOW STRENGTH	SILVER PEELED FROM ANODIZED SURFACE	
	321	.083								.000				
473	7106	.063	SILVER PLATE	ABRASIVE 150 GRIT	ARGON	700	17,500	5	60	.008	PASSED	LOW STRENGTH	SILVER PEELED FROM ANODIZED SURFACE	
	321	.082								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
474	2219	.058	SILVER PLATE	ABRASIVE 150 GRIT	ARGON	700	17,500	5	60	.002	PASSED	LOW STRENGTH	SILVER LIFTED FROM TITANIUM SURFACE	
	Ti-5Al-1Mo-1V	.056								.000				
475	2219	.058	NICKEL PLATE			900	7,500	6	10	.004	PASSED	LOW STRENGTH	NICKEL PEELED FROM ANODIZED SURFACE	
	321	.062								.000				
476	7106	.062	SILVER PLATE			900	7,500	6	10	.005	PASSED	LOW STRENGTH	SILVER PEELED FROM ANODIZED SURFACE	
	321	.082								.000				
477	2219	.058	SILVER PLATE			900	7,500	6	10	.006	PASSED	LOW STRENGTH	SILVER PEELED FROM ANODIZED SURFACE	
	Ti-5Al-1.5Sn	.057								.000				
478	2219	.058	NICKEL PLATE			900	7,500	6	10	.005	FAILED	~	NICKEL LIFTED FROM TITANIUM	
	Ti-5Al-1Mo-1V	.057								.000				
479	2219	.057	NICKEL PLATE			900	7,500	8	60	.004	PASSED	MEDIUM STRENGTH LOW DUCTILITY	FAILED AT NICKEL TO 2219 SURFACE	
	321	.082								.000				
480	7106	.062	SILVER PLATE			900	7,500	8	60	.005	PASSED	LOW STRENGTH	FAILED AT SILVER TO 7106	
	321	.083								.000				
481	2219	.058	SILVER PLATE			900	7,500	8	60	.003	PASSED	MEDIUM STRENGTH LOW DUCTILITY	FAILED AT SILVER TO 2219 SURFACE	
	Ti-5Al-2.5Sn	.057								.000				
482	2219	.058	NICKEL PLATE			900	7,500	8	60	.005	PASSED	LOW STRENGTH	FAILED AT NICKEL TO 2219 SURFACE	
	Ti-5Al-2.5Sn	.057								.000				
483	INCONEL 600	.061	TUNGSTEN MARKER .0005 D.			1450	20,000	10	60	.000	~	~	~	SPECIMENS USED FOR DIFFUSION STUDIES
	Ti-8Al-1Mo-1V	.059								.003				
484	321	.081	TUNGSTEN MARKER .0005 D.			1450	20,000	10	60	.001	~	~	~	
	Ti-8Al-1Mo-1V	.057								.003				
485	INCONEL 600	.063	CU PLATE ON BARE Ti			900	20,000	5	60	.000	PASSED	LOW STRENGTH	PARTIALLY WELDED AT Cu TO Cu	
	Ti-8Al-1Mo-1V	.060								.000				
486	INCONEL 600	.063	AG PLATE ON BARE Ti			900	20,000	5	60	.000	PASSED	LOW STRENGTH	PARTIALLY WELDED AT AG TO AG	
	Ti-8Al-1Mo-1V	.061								.000				
487	INCONEL 600	.063	Ni PL. ON BARE Ti.			900	20,000	5	60	.000	FAILED	~	NICKEL PLATE LIFTED FROM TITANIUM	
	Ti-8Al-1Mo-1V	.060								.000				
488	INCONEL 600	.063	CU PLATE ON ANODIZED Ti			900	20,000	6	60	.000	FAILED	~	COPPER PLATING CONTAMINATED. DID NOT WELD	
	Ti-8Al-1Mo-1V	.060								.000				
489	INCONEL 600	.063	AG PLATE ON ANODIZED TITANIUM			900	20,000	6	60	.000	FAILED	~	SILVER CONTAMINATED DID NOT WELD	
	Ti-8Al-1Mo-1V	.060								.000				
490	INCONEL 600	.064	Ni PLATE ON ANODIZED Ti			900	20,000	6	60	.000	PASSED	LOW STRENGTH	NICKEL PEELED FROM TITANIUM	
	Ti-8Al-1Mo-1V	.055								.000				
491	INCONEL 600	.063	CU PLATE ON BARE Ti			1100	20,000	5	10	.000	PASSED	LOW STRENGTH	COPPER PLATING PARTIALLY WELDED	
	Ti-8Al-1Mo-1V	.059								.000				
492	INCONEL 600	.063	AG PLATE ON BARE Ti			1100	20,000	5	10	.000	PASSED	LOW STRENGTH	SILVER STRIPPED FROM TITANIUM	
	Ti-8Al-1Mo-1V	.059								.000				
493	INCONEL 600	.063	Ni PLATE ON BARE Ti	ABRASIVE 150 GRIT	ARGON	1100	20,000	5	10	.000	PASSED	LOW STRENGTH	NICKEL PEELED RANDOMLY FROM INCO 600 AND Ti.	
	Ti-8Al-1Mo-1V	.062								.000				

D 26

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP					
494	INCONEL 600	.063	Cu PLATE ON	ABRASIVE	ARGON	1100	20,000	6	10	.000	PASSED	LOW STRENGTH	SMALL AMOUNT OF WELDING - Cu CONTAMINATED	
	Ti-8Al-1Mo-1V	.059	ANODIZED Ti	150 GRIT						.000				
495	INCONEL 600	.062	Ag PLATE ON	↑	↑	1100	20,000	6	10	.000	↑	LOW STRENGTH	FAILED AT Ag-Ag AND AT Ag-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.060	ANODIZED Ti							.000				
496	INCONEL 600	.064	Ni PLATE ON			1100	20,000	6	10	.000		LOW STRENGTH	Ni PEELED FROM Ti - NOT COMPLETELY WELDED	
	Ti-8Al-1Mo-1V	.060	ANODIZED Ti							.000				
497	INCONEL 600	.064	Cu PLATE ON			1300	20,000	5	10	.000		MEDIUM STRENGTH LOW-MED DUCTILITY	FAILED AT Cu-Cu AND Cu-Ti INTERFACE.	
	Ti-8Al-1Mo-1V	.059	BARE Ti							.001				
498	INCONEL 600	.063	Ag PLATE ON			1300	20,000	5	10	.000		MEDIUM STREN. LOW-MED. DUCTILITY	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.060	BARE Ti							.000				
499	INCONEL 600	.063	Ni PLATE ON			1300	20,000	5	10	.000		LOW STRENGTH & DUCTILITY	NICKEL PEELED FROM TITANIUM	
	Ti-8Al-1Mo-1V	.061	BARE Ti							.001				
500	INCONEL 600	.064	Cu PLATE ON			1300	20,000	7	10	.000		MED. STREN. LOW-MED. DUCTILITY	FAILED AT Cu-Cu INTERFACE	
	Ti-8Al-1Mo-1V	.061	BARE Ti							.001				
501	INCONEL 600	.063	Ag PLATE ON			1300	20,000	7	10	.000		MED. STREN. LOW-MED DUCTILITY	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.060	BARE Ti							.000				
502	INCONEL 600	.064	Ni PLATE ON			1300	20,000	7	10	.001		MED. STREN LOW-MED DUCTILITY	FAILED AT NICKEL TO Ti INTERFACE	
	Ti-8Al-1Mo-1V	.060	ANODIZED Ti							.001				
503	INCONEL 600	.063	Cu PLATE ON			1500	20,000	5	10	.004		MED - STREN. LOW DUCTILITY	FAILED AT Cu-Cu AND Cu-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.059	BARE Ti							.002				
504	INCONEL 600	.064	Ag PLATE ON			1500	20,000	5	10	.003		MED. STREN MED. DUCTILITY	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.060	BARE Ti							.004				
505	INCONEL 600	.063	Ni PLATE ON			1500	20,000	5	10	.002		MED. STREN LOW DUCTILITY	FAILED AT Ni TO Ti INTERFACE	
	Ti-8Al-1Mo-1V	.059	BARE Ti							.001				
506	INCONEL 600	.062	Cu PLATE ON			1500	20,000	5	10	.001		MED. STREN. LOW DUCTILITY	FAILED AT Cu-Cu AND Cu-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.060	ANODIZED Ti							.006				
507	INCONEL 600	.064	Ag PLATE ON			1500	20,000	5	10	.003	↓	MED. STREN. MED. DUCTILITY	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.058	ANODIZED Ti							.006				
508	INCONEL 600	.064	Ni PLATE ON			1500	20,000	5	10	.002	PASSED	MED. STREN. LOW-MED DUCT.	FAILED AT Ni-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.059	ANODIZED Ti							.008				
509	321	.081	Cu PLATE ON			900	20,000	6	60	.000	~	~	PLATING DID NOT ADHERE TO Ti.	
	Ti-8Al-1Mo-1V	.060	BARE Ti							.000				
510	321	.082	Ag PLATE ON			900	20,000	6	60	.000	~	~	PLATING DID NOT ADHERE TO Ti.	
	Ti-8Al-1Mo-1V	.060	BARE Ti							.000				
511	321	.082	Ni PLATE ON			900	20,000	6	60	.000	~	~	PLATING DID NOT ADHERE TO Ti.	
	Ti-8Al-1Mo-1V	.061	BARE Ti							.000				
512	321	.083	Cu PLATE ON			900	20,000	6	60	.000	PASSED	LOW STRENGTH	PARTIAL WELDING OF PLATED SURFACE	
	Ti-8Al-1Mo-1V	.059	ANODIZED Ti							.000				
513	321	.082	Ag PLATE ON	ABRASIVE 150 GRIT	ARGON	900	20,000	6	60	.000	PASSED	LOW STRENGTH	PARTIAL WELDING OF PLATED SURFACES	
	Ti-8Al-1Mo-1V	.060	ANODIZED Ti							.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP.					
S14	321	.082	Ni PLATE ON ANODIZED Ti	ABRASIVE 150 GRIT	ARGON	900	20000	6	60	.000	PASSED	VERY LOW STRENGTH	PARTIALLY WELDED	
	Ti-8Al-1Mo-1V	.060								.000				
S15	321	.083	Cu PLATE ON BARE Ti			1100		5	10	.000		LOW STRENGTH	PARTIALLY WELDED. COPPER CONTAMINATED	
	Ti-8Al-1Mo-1V	.059								.000				
S16	321	.082	Ag PLATE ON BARE Ti			1100		5	10	.000		LOW STRENGTH	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.060								.000				
S17	321	.083	Ni PLATE ON BARE Ti			1100		5	10	.000		LOW STRENGTH	NICKEL PEELED FROM TITANIUM	
	Ti-8Al-1Mo-1V	.061								.000				
S18	321	.084	Cu PLATE ANODIZED Ti			1100		5	10	.000		MED STRENGTH LOW-MED. DUCT.	FAILED AT COPPER-COPPER INTERFACE	
	Ti-8Al-1Mo-1V	.061								.000				
S19	321	.083	Ag PLATE ANODIZED Ti			1100		5	10	.000		MED. STRENGTH MED. DUCTILITY	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.059								.000				
S20	321	.082	Ni PLATE ANODIZED Ti			1100		5	10	.000		MED STRENGTH LOW-MED DUCT.	FAILED AT Ni-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.059								.000				
S21	321	.082	Cu PLATE ON BARE Ti			1300		5	10	.000		MED. STREN. MED-LOW DUCT.	FAILED AT Cu-Cu AND Cu-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.060								.001				
S22	321	.082	Ag PLATE ON BARE Ti			1300		5	10	.001		MED. STREN. MED. DUCT.	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.059								.000				
S23	321	.081	Ni PLATE ON BARE Ti			1300		5	10	.0005		MED. STREN. LOW DUCT.	FAILED AND Ni-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.060								.001				
S24	321	.083	Cu PL. ANODIZED Ti			1300		5	10	.000		MED STREN. MED DUCT.	FAILED AT Cu-Cu INTERFACE	
	Ti-8Al-1Mo-1V	.059								.0005				
S25	321	.082	Ag PLATE ANODIZED Ti			1300		5	10	.001		MED. STREN. MED. DUCT.	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.060								.001				
S26	321	.081	Ni PLATE ANODIZED Ti			1300		5	10	.0005		MED. STREN LOW DUCTILITY	FAILED AT Ni-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.061								.000				
S27	321	.083	Cu PLATE ON BARE Ti			1500		5	10	.002		MED. STREN. LOW DUCT.	FAILED AT Cu-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.059								.002				
S28	321	.082	Ag PLATE ON BARE Ti			1500		5	10	.003		MED. STREN. MED. DUCT.	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.060								.004				
S29	321	.082	Ni PLATE ON BARE Ti			1500		5	10	.001		MED. STREN. LOW DUCT.	FAILED AT Ni-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.060								.004				
S30	321	.082	Cu PLATE ON ANODIZED Ti			1500		5	10	.001		MED. STREN. LOW DUCT.	FAILED AT Cu-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.060								.004				
S31	321	.083	Ag PLATE ON ANODIZED Ti			1500		5	10	.002		MED STREN. MED. DUCT.	FAILED AT Ag-Ag INTERFACE	
	Ti-8Al-1Mo-1V	.061								.003				
S32	321	.082	Ni PLATE ON ANODIZED Ti	ABRASIVE 150 GRIT	ARGON	1500	20,000	5	10	.001	PASSED	MED STREN. LOW DUCT	FAILED AT Ni-Ti INTERFACE	
	Ti-8Al-1Mo-1V	.061								.003				

SUMMARY OF DIFFUSION WELDIN G DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
533	INCONEL 718	.062	COPPER PLATE	ABRASIVE 150 GRIT	ARGON	900	20,000	5	60	.000	~	~	NO WELD CU CONTAMINATED	
	321	.083								.000				
534	INCONEL 718	.062	NICKEL PLATE			900		5	60	.000	PASSED	MEDIUM STR. LOW DUCT.	FAILED AT Ni-Ni INTERFACE	
	321	.082								.000				
535	INCONEL 718	.062	COPPER PLATE			1100		5	60	.000	PASSED	LOW STRENGTH	COPPER CONTAMINATED	
	321	.082								.000				
536	INCONEL 718	.063	NICKEL PLATE			1100		5	60	.000	PASSED	HIGH STRGN. MED DUCT.	Ni-Ni INTERFACE FAILED	
	321	.083								.000				
537	INCONEL 718	.063	COPPER PLATE			1100		5	10	.000	~	~	COPPER CONTAMINATED	
	321	.082								.000				
538	INCONEL 718	.063	NICKEL PLATE			1100		5	10	.000	PASSED	HIGH STRGN LOW DUCT.	NOT COMPLETELY WELDED	
	321	.082								.000				
539	INCONEL 718	.063	COPPER PLATE			1300		10	10	.000	~	~	NO WELD CU CONTAMINATED	
	321	.082								.001				
540	INCONEL 718	.062	NICKEL PLATE			1300		10	10	.000	PASSED	HIGH STRGN & DUCT.	FAILED AT Ni-Ni INTERFACE	
	321	.082								.000				
541	INCONEL 718	.063	COPPER PLATE			1500		7	10	.002	~	~	NO WELD Cu CONTAMINATED	
	321	.082								.003				
542	INCONEL 718	.063	NICKEL PLATE	ABRASIVE 150 GRIT	ARGON	1500	20,000	7	10	.001	PASSED	~	COULD NOT PEEL	
	321	.082								.002				
543	INCONEL 718	.061	NONE	ABRASIVE 80 GRIT	VACUUM	1600	12,500	15	10	.001	PASSED	HIGH STRGN & DUCT.	DIFFICULT TO PEEL	
	321	.080								.002				
544	INCONEL 718	.060	NONE	ABRASIVE 80 GRIT	VACUUM	1600	12,500	15	30	.004	PASSED	—	IMPOSSIBLE TO PEEL	
	321	.079												

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					SINGLE LAP SHEAR SPECIMENS				NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320°F	SHEAR FAILURE LOAD	TYPE OF FAILURE	
	ALLOY	GAGE						HEATUP	AT TEMP.					
545	2219	.056	NONE	CHEMICAL CLEAN	VACUUM	950	5,500	10	30	.005	OK	.10" OVERLAP 1650#	TENSILE - IN ALUMINUM	
	321	.081								.000				
546	2219	.056								.005		.10" OVERLAP 1550#	SHEARED AT INTERFACE	
	321	.081								.000				
547	2219	.056								.004		.20 OVERLAP 1720#	TENSILE - IN ALUMINUM	
	321	.081								.000				
548	2219	.056								.005		.20" OVERLAP 1700#	TENSILE IN ALUMINUM	
	321	.081								.000				
549	2219	.056								.006		.30" OVERLAP 1750#	TENSILE - IN ALUMINUM	
	321	.081								.000				
550	2219	.056								.005		.30 OVERLAP 1675#	TENSILE IN ALUMINUM	
	321	.081								.000				
551	7106	.060								.007		.12" OVERLAP 1400#	SHEAR	
	321	.081								.000				
552	7106	.060								.007		.12" OVERLAP 1525#	SHEAR	
	321	.081								.000				
553	7106	.060								.006		.20" OVERLAP 1420#	SHEAR	
	321	.081								.000				
554	7106	.060								.008		.20" OVERLAP 2140#	SHEAR	
	321	.081								.000				
555	7106	.060								.007		.29" OVERLAP 1620#	SHEAR	
	321	.081								.000				
556	7106	.060		CHEMICAL CLEAN						.009		.35" OVERLAP 1900#	SHEAR	
	321	.081								.000				
557	2219	.056		ABRASIVE 320 GRIT						.003		.10" OVERLAP 1400#	SHEAR	
	Ti-5Al-2.5Sn	.053								.000				
558	2219	.056								.004		.12" OVERLAP 1640#	SHEAR AND TENSILE IN ALUM.	
	Ti-5Al-2.5Sn	.053								.000				
559	2219	.056								.004		.15" OVERLAP 1775#	TENSILE IN ALUMINUM	
	Ti-5Al-2.5Sn	.053								.000				
560	2219	.056								.003		.20" OVERLAP 1850#	TENSILE IN ALUMINUM	
	Ti-5Al-2.5Sn	.053								.000				
561	2219	.056								.003		.30" OVERLAP 1820#	TENSILE IN ALUMINUM	
	Ti-5Al-2.5Sn	.053								.000				
562	2219	.056		ABRASIVE 320 GRIT		950	5,500	10	30	.005		.30" OVERLAP 1940#	TENSILE IN ALUMINUM	
	Ti-5Al-2.5Sn	.053								.000				
563	INCONEL 600	.061		ABRASIVE 80 GRIT		1350	20,000	8	10	.005		.12" OVERLAP 1900#	SHEAR	
	Ti-8Al-1Mo-1V	.061								.000				
564	INCONEL 600	.061	NONE	ABRASIVE 80 GRIT	VACUUM	1350	20,000	8	10	.006	NONE	.11" OVERLAP 1790#	SHEAR	
	Ti-8Al-1Mo-1V	.060								.000				

SUMMARY OF DIFFUSION WELDII IG DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					SINGLE LAP SHEAR SPECIMENS				NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320° F	SHEAR FAILURE LOAD	TYPE OF FAILURE	
	ALLOY	GAGE						HEATUP	AT TEM					
565	INCONEL 600	.062	NONE	ABRASIVE BO GRIT	VACUUM	1350	20,000	12	10	.005	NONE	.32" OVERLAP 3970#	SHEAR	
	Ti-8Al-1Mo-1V	.058												
566	INCONEL 600	.061				1350	20,000	12	10	.004		.35" OVERLAP 5430#		
	Ti-8Al-1Mo-1V	.060												
567	INCONEL 600	.061				1350	20,000	10	10	.004		.50" OVERLAP 4350#		
	Ti-8Al-1Mo-1V	.059												
568	INCONEL 600	.060				1350	20,000	10	10	.003		.50" OVERLAP 4950#		
	Ti-8Al-1Mo-1V	.058												
569	321	.081				1450	20,000	15	10	.008		.10" OVERLAP 1420#		
	Ti-8Al-1Mo-1V	.060												
570	321	.081				1450	20,000	15	10	.006		.09" OVERLAP 1300#		
	Ti-8Al-1Mo-1V	.059												
571	321	.081				1450	20,000	12	10	.005		.33" OVERLAP 2950#		
	Ti-8Al-1Mo-1V	.059												
572	321	.081				1450	20,000	12	10	.005		.30" OVERLAP 2775#		
	Ti-8Al-1Mo-1V	.059												
573	321	.081				1450	20,000	10	10	.005		.53" OVERLAP 3250#		
	Ti-8Al-1Mo-1V	.058												
574	321	.081				1450	20,000	10	10	.007		.51" OVERLAP 3260#		
	Ti-8Al-1Mo-1V	.059												
575	INCONEL 718	.060				1600	15,000	15	30	.005		.10" OVERLAP 5250#		
	321	.081												
576	INCONEL 718	.060				1600	15,000	15	30	.006		.10" OVERLAP 4950#		
	321	.081												
577	INCONEL 718	.060				1600	15,000	15	30	.006		.22" OVERLAP 6260#		
	321	.081												
578	INCONEL 718	.060				1600	15,000	15	30	.008		.21" OVERLAP 6430#		
	321	.081												
579	INCONEL 718	.060				1600	15,000	12	30	.006		.31" OVERLAP 7075#		
	321	.081												
580	INCONEL 718	.060	NONE	ABRASIVE BO GRIT	VACUUM	1600	15,000	12	30	.007	NONE	.30" OVERLAP 6910#	SHEAR	
	321	.081												

D31

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP.					
S81	2219	.125	NONE	CHEMICAL CLEAN	ARGON	850	ROLL WELD	15	~	.031	OK	COULD NOT PEEL	~	
	321	.080								.000				
S82	2219	.125				750		15	~	.029	OK	COULD NOT PEEL	~	
	321	.080								.000				
S83	2219	.125				650		15	~	.030	OK	MEDIUM - LOW STR.	STEEL APPEARED ALUMINIZED	
	321	.080								.000				
S84	7106	.121				850		15	~	.028	OK	COULD NOT PEEL	~	
	321	.080								.000				
S85	7106	.121				750		15	~	.026	OK	DIFFICULT TO PEEL	STEEL APPEARED ALUMINIZED	
	321	.080								.000				
S86	7106	.121				650		15	~	.025	OK	LOW-MED. PEEL STR.	STEEL APPEARED ALUMINIZED	
	321	.080								.000				
S87	2219	.125				850		20	~	.026	~	~	~	DID NOT WELD
	Ti-5Al-2.5Sn	.052								.002				
S88	2219	.125		CHEMICAL CLEAN		950		20	~	.040	~	~	~	DID NOT WELD
	Ti-5Al-2.5Sn	.052								.000				
S89	2219	.125		ABRASIVE BO GRIT		950		20	~	.030	OK	HIGH STRENGTH & DUCTILITY	SURFACES APPEARED CRAZED	
	Ti-5Al-2.5Sn	.051								.000				
S90	INCONEL 600	.061		CHEMICAL CLEAN		1400		20	~	.005	OK	LOW STR. BRITTLE	SMOOTH GREY SAME AS PRESS WELD	
	Ti-8Al-1Mo-1V	.061								005				
S91	INCONEL 600	.061				1300		20	~	.004	~	~	~	DID NOT WELD
	Ti-8Al-1Mo-1V	.060								.000				
S92	INCONEL 600	.061				1500		20	~	.005	~	~	~	DID NOT WELD
	Ti-8Al-1Mo-1V	.060								.003				
S93	321	.081				1400		20	~	.010	OK	LOW-MED STRENGTH BRITTLE	DULL GREY	ROLL WELD EXHIBITED MORE DUCTILITY THAN PRESS WELD
	Ti-8Al-1Mo-1V	.060								.005				
S94	Ti-8Al-1Mo-1V	.081				1500		30	~	.009	~	~	~	PARTIAL WELD SHEETS SEPARATED IN REMOVING FROM RETORT
	321	.060								.004				
S95	321	.081				1600		30	~	.008	OK	LOW-MED STRENGTH BRITTLE	DULL GREY	
	Ti-8Al-1Mo-1V	.060								.004				
S96	INCONEL 718	.060				1400		30	~	.007	OK	MEDIUM - LOW STR. & DUCTILITY	100% WELD	
	321	.081								.015				
S97	INCONEL 718	.060				1600		30	~	.005	OK	MEDIUM STR. & DUCTILITY	100% WELD	PRESS WELDED SPECIMENS AT THESE TEMPERATURES EXHIBIT HIGHER PEEL STRENGTH
	321	.081								.008				
S98	INCONEL 718	.060	NONE	CHEMICAL CLEAN	ARGON	1800	ROLL WELD	30	~	.008	OK	HIGH STR. & DUCTILITY	100% WELD	
	321	.081								.013				
S99	2219	.056	NONE	CHEMICAL CLEAN	ARGON	950	5,500	10	60	.008	TUNGSTEN WIRE MARKERS USED FOR DIFFUSION STUDIES			
	321	.081								000				
600	7106	.060	NONE	CHEMICAL CLEAN	ARGON	950	5,500	10	60	.010				
	321	081								000				

D 32

SUMMARY OF DIFFUSION WELDIN 3 DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					GUALITY OF WELDED JOINTS				NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP					
601	2219	.056	NONE	ABRASIVE 320 GRIT	ARGON	950	5,500	5	60	.008	TUNGSTEN WIRE MARKERS USED FOR DIFFUSION STUDIES			
	Ti-5Al-2.5Sn	.054								.000				
602	INCONEL 718	.060	NONE	ABRASIVE 80 GRIT	ARGON	1600	17,500	10	60	.010				
	321	.081												
603	2219	.058	SILVER PLATE	ABRASIVE 320 GRIT	AIR	500	30,000	5	60	.005	OK	MEDIUM STRENGTH & DUCTILITY	Ag-Ag, AND Ag to Al INTERFACE	
	321	.083								.000				
604	2219	.058	↑	↑	↑	500	30,000	↑	120	.006	↑	MEDIUM STRENGTH & DUCTILITY	Ag to Ag and Ag to Al. INTERFACE	
	321	.053								.000				
605	2219	.058				500	30,000		240	.008		MEDIUM STRENGTH & DUCTILITY	Ag TO Al INTERFACE SOME Ag to Ag	
	321	.083								.000				
606	2219	.058				600	25,000		30	.008		MEDIUM STRENGTH & DUCTILITY	Ag TO Al INTERFACE SOME Ag TO Ag	
	321	.083								.000				
607	2219	.058				600	25,000		60	.010		MEDIUM STRENGTH & DUCTILITY	Ag TO Al INTERFACE SOME Ag TO Ag	
	321	.083								.000				
608	2219	.058				600	25,000		120	.018		LOW-MEDIUM STRENGTH & DUCTILITY	Ag TO Al INTERFACE	
	321	.083								.000				
609	2219	.058				700	20,000		10	.003		LOW-MEDIUM STRENGTH & DUCTILITY	Ag TO Al INTERFACE	
	321	.053								.000				
610	2219	.058				700	20,000		30	.006		LOW-MEDIUM STRENGTH & DUCTILITY	Ag TO Al INTERFACE	
	321	.053								.000				
611	2219	.058				700	20,000		60	.015		LOW-MEDIUM STRENGTH & DUCTILITY	Ag TO Al INTERFACE	
	321	.083								.000				
612	7106	.062				500	30,000		60	.004		MEDIUM STRENGTH & DUCTILITY	PRIMARILY FAILED AT Ag TO Al INTERFACE	ALL 7106 ALUM SPECIMENS APPEARED TO HAVE GREATER DUCTILITY THAN 2219 ALUM. SPECIMENS
	321	.083								.000				
613	7106	.062				500	30,000		120	.008		↑	↑	
	321	.083								.000				
614	7106	.062				500	30,000		240	.015				
	321	.083								.000				
615	7106	.062				600	25,000		30	.010				
	321	.083								.000				
616	7106	.062				600	25,000		60	.000				
	321	.083								.015				
617	7106	.062				600	25,000		120	.000				
	321	.083								.020				
618	7106	.062				700	20,000		10	.011				
	321	.083								.000				
619	7106	.062				700	20,000		30	.025				
	321	.083								.000				
620	7106	.062	SILVER PLATE	ABRASIVE 320 GRIT	AIR	700	20,000	5	60	.032	OK	MEDIUM STRENGTH & DUCTILITY	PRIMARILY FAILED AT Ag-Al INTERFACE	
	321	.083								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
621	2219	.058	COPPER PLATE	ABRASIVE 320 GRIT	AIR	500	30,000	5	60	.002	OK	LOW STRENGTH & DUCTILITY	FAILED AT Cu TO Al INTERFACE	
	321	.083								.000				
622	2219	.058				500	30,000		120	.005				
	321	.083								.000				
623	2219	.059				500	30,000		240	.010				LESS STRENGTH & DUCTILITY THAN Ag PLATE
	321	.083								.000				
624	2219	.058				600	30,000		30	.002				
	321	.082								.000				
625	2219	.058				600	30,000		60	.005				
	321	.083								.000				
626	2219	.058				600	30,000		120	.008				
	321	.083								.000				
627	2219	.058				700	20,000		10	.004				
	321	.083								.000				
628	2219	.058				700	20,000		30	.006				
	321	.083								.000				
629	2219	.057				700	20,000		60	.008		LOW STRENGTH & DUCTILITY	FAILED AT Cu TO Al INTERFACE	
	321	.083								.000				
630	7106	.062				500	30,000		60	.005		MEDIUM STRENGTH & DUCTILITY	PRIMARILY AT Cu TO Al INTERFACE	BETTER THAN 2219 WITH Cu PLATE
	321	.082								.000				
631	7106	.062				500	30,000		120	.010		MEDIUM STRENGTH & DUCTILITY		
	321	.083								.000				
632	7106	.062				500	30,000		240	.020		MEDIUM STRENGTH & DUCTILITY		
	321	.083								.000				
633	7106	.062				600	30,000		30	.006		MEDIUM STRENGTH & DUCTILITY		
	321	.083								.000				
634	7106	.062				600	30,000		60	.009		MEDIUM STRENGTH & DUCTILITY		
	321	.083								.000				
635	7106	.062				600	30,000		120	.015		MEDIUM STRENGTH & DUCTILITY		
	321	.083								.000				
636	7106	.062				700	20,000		10	.020		LOW STREN. SOME DUCTILITY	PRIMARILY AT Cu TO Al INTERFACE	
	321	.083								.000				
637	7106	.062				700	20,000		30	.025		LOW STRENGTH BRITTLE	FAILED AT Cu TO Al INTER.	
	321	.083								.000				
638	7106	.062	COPPER PLATE	ABRASIVE 320 GRIT	AIR	700	20,000	5	60	.030	OK	LOW STRENGTH- BRITTLE	FAILED AT Cu TO Al INTER.	
	321	.083								.000				
639	2219	.057	SILVER PLATE	ABRASIVE 320 GRIT	AIR	600	30,000	5	30	.003	OK	LOW STRENGTH	FAILED AT Ag TO Ti INTERFACE	LOW ADHERENCE OF SILVER TO TITANIUM
	Ti-5Al-2.5Sn	.055								.000				
640	2219	.057	SILVER PLATE	ABRASIVE 320 GRIT	AIR	500	30,000	5	120	.002	OK	LOW STRENGTH	FAILED AT Ag TO Ti	
	Ti-5Al-2.5Sn	.055								.000				

SUMMARY OF DIFFUSION WELDING D :VELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
641	2219	.057	SILVER PLATE	ABRASIVE 320 GRIT	AIR	600	30,000	5	30	.003	OK	MEDIUM STRENGTH	Ag to Ag INTERFACE	Ti PREDIFFUSED AT 1100°F- 10 MIN.
	Ti-5Al-2.5Sn	.055								.000				
642	2219	.058			AIR	600	30,000	5	30	.004	OK	MEDIUM STRENGTH	Ag to Al INTERFACE	Ti PREDIFFUSED AT 1300°F- 10 MIN.
	Ti-5Al-2.5Sn	.055								.000				
643	2219	.057			AIR	600	30,000	5	30	.003	OK	MEDIUM STRENGTH	Ag to Ag (25%) Ag to Al (75%)	Ti PREDIFFUSED AT 1500°F- 10MIN
	Ti-5Al-2.5Sn	.055								.000				
644	2219	.057			AIR	600	30,000	5	30	.004	~	~	DID NOT WELD PREDIFFUSION TEMP TOO HIGH	Ti PREDIFFUSED AT 1700°F-10 MIN.
	Ti-5Al-2.5Sn	.055								.000				
645	INCONEL 600	.062			AIR	600	30,000	5	240	.000	~	~	SPECIMEN PEELED SILVER LIFTED FROM Ti	No - PRE DIFFUSION OF TITANIUM ON 645 - 648
	Ti-8Al-1Mo-1V	.058								.000				
646	INCONEL 600	.062			ARGON	1300	20,000	10	10	.000	OK	LOW STRENGTH	NOW COMPLETELY WELDED. Ag To Ag INTERFACE	
	Ti-8Al-1Mo-1V	.057								.000				
647	INCONEL 600	.062			ARGON	1300	20,000	10	60	.000	OK	LOW - MED STRENGTH	FAILED AT Ag to Ag INTERFACE	
	Ti-8Al-1Mo-1V	.060								.002				
648	INCONEL 600	.063			ARGON	1300	20,000	10	120	.000	OK	MEDIUM STRENGTH	FAILED AT Ag - Ag INTERFACE	
	Ti-8Al-1Mo-1V	.059								.002				
649	INCONEL 600	.062			AIR	600	30,000	5	30	.000	OK	POOR STRENGTH		Ti PREDIFFUSED AT 1100°F-10 MIN
	Ti-8Al-1Mo-1V	.060								.001				
650	INCONEL 600	.063			AIR	600	30,000	5	30	.000	OK	SILVER PLATING DID NOT ADHERE - SPECIMEN		Ti - PREDIFFUSED AT 1300°F- 10 MIN
	Ti-8Al-1Mo-1V	.059								.000				
651	INCONEL 600	.062			AIR	600	30,000	5	30	.000	OK	RERUN # 767 - 771 WITH ACCEPTABLE PLATING		Ti - PREDIFFUSED AT 1500°F- 10 MIN
	Ti-8Al-1Mo-1V	.060								.000				
652	INCONEL 600	.062	SILVER PLATE		AIR	600	30,000	5	30	.000	~	~	DID NOT WELD	Ti - PREDIFFUSED AT 1700°F-10 MIN
	Ti-8Al-1Mo-1V	.060								.000				
653	INCONEL 600	.061	VANADIUM FOIL .001"		ARGON	1400	20,000	10	10	.002	OK	LOW STRENGTH	FOIL PEELED FROM Ti SIDE.	
	Ti-8Al-1Mo-1V	.059								.000				
654	INCONEL 600	.061			ARGON	1400	20,000	10	30	.003	OK	LOW STRENGTH	FOIL PEELED FROM Ti SIDE	
	Ti-8Al-1Mo-1V	.059								.000				
655	INCONEL 600	.061			ARGON	1400	20,000	10	60	.003	OK	LOW-MED. STRENGTH	FOIL PEELED 80% FROM Ti. 20% FROM 600.	
	Ti-8Al-1Mo-1V	.059								.002				
656	INCONEL 600	.061			ARGON	1500	15,000	10	10	.001	OK	LOW-MED. STRENGTH	FOIL PEELED FROM Ti SIDE.	
	Ti-8Al-1Mo-1V	.059								.003				
657	INCONEL 600	.061			ARGON	1500	15,000	10	30	.003	OK	LOW-MED. STRENGTH	FOIL PEELED PRIMARILY FROM Ti	
	Ti-8Al-1Mo-1V	.059								.001				
658	INCONEL 600	.061			ARGON	1500	15,000	10	60	.004	OK	LOW-MED STRENGTH	FOIL PEELED PRIMARILY FROM INCO 600 SIDE.	
	Ti-8Al-1Mo-1V	.059								.005				
659	INCONEL 600	.061			ARGON	1600	10,000	10	10	.004	OK	LOW STRENGTH	FOIL PEELED PRIMARILY FROM Ti SIDE	
	Ti-8Al-1Mo-1V	.059								.003				
660	INCONEL 600	.061	VANADIUM FOIL .001	ABRASIVE 320 GRIT	ARGON	1600	10,000	10	30	.002	OK	LOW STRENGTH BRITTLE	RANDOM PEELING FROM EACH INTERFACE	
	Ti-8Al-1Mo-1V	.059								.008				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP.					
661	INCONEL 600	.061	VANADIUM FOIL .001"	ABRASIVE 320 GRIT	ARGON	1600	10,000	10	60	.000	OK	LOW STRENGTH - BRITTLE	PEELED FROM INCONEL 600	
	Ti-8Al-1Mo-1V	.051								.002				
662	321	.083	SILVER PLATE		AIR	600	30,000	5	240	.001		LOW STRENGTH	SILVER STRIPPED FROM Ti	No PREDIFFUSION
	Ti-8Al-1Mo-1V	.059								.000				
663	321	.083			ARGON	1300	30,000	15	10	.000		MEDIUM STRENGTH	FAILED AT Ag TO Ag INTERFACE	
	Ti-8Al-1Mo-1V	.059								.000				
664	321	.083			ARGON	1300	20,000	15	60	.001		MEDIUM STRENGTH	FAILED AT Ag TO Ag INTERFACE	
	Ti-8Al-1Mo-1V	.059								.000				
665	321	.083			ARGON	1300	20,000	15	120	.002		MEDIUM STRENGTH	FAILED AT Ag TO Ag INTERFACE	
	Ti-8Al-1Mo-1V	.060								.002				
666	321	.083			AIR	600	30,000	5	30	.000		LOW STRENGTH	FAILED AT Ag TO Ag INTERFACE	PREDIFFUSED Ti 1100°F - 10 MIN.
	Ti-8Al-1Mo-1V	.062								.000				
667	321	.083			AIR	600	30,000	5	30	.001		LOW STRENGTH	SILVER APPEARED CONTAMINATED.	PREDIFFUSED Ti 1300°F - 10 MIN.
	Ti-8Al-1Mo-1V	.060								.000				
668	321	.083			AIR	600	30,000	5	30	.000		LOW STRENGTH	SPECIMENS RERUN #764 TO 773	PREDIFFUSED Ti 1500°F - 10 MIN.
	Ti-8Al-1Mo-1V	.060								.000				
669	321	.083	SILVER PLATE		AIR	600	30,000	5	30	.000		LOW STRENGTH		PREDIFFUSED Ti 1700°F - 10 MIN.
	Ti-8Al-1Mo-1V	.059								.000				
670	321	.083	VANADIUM FOIL .001"		ARGON	1400	30,000	10	10	.002		LOW STRENGTH	FOIL PEELED FROM Ti SIDE	
	Ti-8Al-1Mo-1V	.060								.000				
671	321	.083			ARGON	1400	30,000	10	30	.003		LOW STRENGTH	FOIL PEELED FROM Ti SIDE	
	Ti-8Al-1Mo-1V	.060								.000				
672	321	.083			ARGON	1400	30,000	10	60	.006		LOW STRENGTH	FOIL PEELED PRIMARILY FROM Ti	
	Ti-8Al-1Mo-1V	.059								.002				
673	321	.083			ARGON	1500	15,000	10	10	.002		LOW-MEDIUM STREN.	FOIL PEELED PRIMARILY FROM Ti	
	Ti-8Al-1Mo-1V	.059								.002				
674	321	.083			ARGON	1500	15,000	10	30	.007		LOW-MEDIUM STREN.	FOIL PEELED RANDOMLY FROM Ti	
	Ti-8Al-1Mo-1V	.060								.002				
675	321	.083			ARGON	1500	15,000	10	60	.010		MEDIUM STRENGTH	FOIL PEELED 321 PRIMARILY FROM [redacted]	
	Ti-8Al-1Mo-1V	.060								.006				
676	321	.083			ARGON	1600	10,000	15	10	.002		MEDIUM STRENGTH	FOIL PEELED PRIMARILY FROM Ti	
	Ti-8Al-1Mo-1V	.060								.006				
677	321	.083			ARGON	1600	10,000	15	30	.006		LOW-MEDIUM STRENGTH	ROUGH SURFACE RANDOM PEEL	
	Ti-8Al-1Mo-1V	.060								.007				
678	321	.083	VANADIUM FOIL .001"		ARGON	1600	10,000	15	60	.011		LOW-MEDIUM-BRITTLE	ROUGH SURFACE PEELED PRIMARILY FROM 321	
	Ti-8Al-1Mo-1V	.060								.010				
679	INCONEL 718	.061	SILVER PLATE		AIR	500	30,000	5	30	.000		MEDIUM STRENGTH & DUCTILITY	Ag TO Ag FAILURE 15% Ag TO Cu FLASH ON 718 SIDE	
	321	.083								.000				
680	INCONEL 718	.062	SILVER PLATE	ABRASIVE 320 GRIT	AIR	600	30,000	5	30	.000	OK	MEDIUM STRENGTH & DUCTILITY	Ag TO Ag & SOME Ag TO Cu FLASH ON 718 SIDE	
	321	.083								.001				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	NOTES
681	INCONEL 718	.062	SILVER PLATE	ABRASIVE 320 GRIT	AIR	800	30,000	5	30	.000	OK	LOW-MEDIUM STRENGTH	Ag TO Ag INTERFACE	
	321	.083								.000				
682	INCONEL 718	.062			AIR	900	30,000	5	30	.000		LOW-MEDIUM STRENGTH	FAILED AT Ag TO Ag INTERFACE	
	321	.083								.001				
683	INCONEL 718	.061			ARGON	1100	30,000	10	30	.000		MEDIUM STRENGTH & DUCTILITY	FAILED AT Ag TO Ag INTERFACE	
	321	.083								.000				
684	INCONEL 718	.061				1100	30,000	10	240	.000		LOW STRENGTH	Ag TO Ag FAILURE	
	321	.083								.000				
685	INCONEL 718	.061				1300	20,000	10	10	.000		LOW STRENGTH	PALE GREY - FAILED IN Ag	
	321	.083								000				
686	INCONEL 718	.061	SILVER PLATE			1300	20,000	10	120	.000		LOW STRENGTH	CRACKED DURING SAWING Ag TO Ag INTERFACE	
	321	.083								.001				
687	INCONEL 718	061	NICKEL PLATE			1100	30,000	5	30	.000		MEDIUM STRENGTH & DUCTILITY	ROUGH SURFACE FAILED THROUGH Ni	
	321	.083								.000				
688	INCONEL 718	.061				1100	30,000	5	120	.000				
	321	.083								.001				
689	INCONEL 718	.062				1100	30,000	5	240	.000				
	321	.083								.001				
690	INCONEL 718	.062				1300	20,000	15	10	000				
	321	.083								.000				
691	INCONEL 718	.062				1300	20,000	15	60	.000				
	321	.083								.002				
692	INCONEL 718	.062				1300	20,000	15	120	.000				
	321	.083								.002				
693	INCONEL 718	.061				1500	10,000	10	10	.000				
	321	.083								.001				
694	INCONEL 718	.061				1500	10,000	10	30	.000				
	321	.083								.002				
695	INCONEL 718	.062	NICKEL PLATE			1500	10,000	10	60	.000		MEDIUM STRENGTH & DUCTILITY	ROUGH SURFACE FAILED THROUGH Ni	
	321	.083								.005				
696	321	.083	TANTALUM FOIL .005"			1600	10,000	15	10	.016		LOW STRENGTH	FOIL PEELED FROM 321	
	Ti-8Al-1Mo-1V	.060												
697	321	.083	TA FOIL Cu FOIL			1400	30,000	10	30	.002		HIGH STRENGTH & DUCTILITY	FAILED THROUGH Cu & Cu TO Ta INTERFACE	Ta ON TITANIUM SIDE Cu ON 321 SIDE
	Ti-8Al-1Mo-1V	.060												
698	321	.081	ALUM FOIL .005"			1000	ROLL WELD	15	—	.005		GOOD STRENGTH & DUCTILITY	FAILED THROUGH ALUMINUM	
	Ti-8Al-1Mo-1V	.060												
699	321	.081	Ag PLATE Ta FOIL	ABRASIVE 320 GRIT		1600	15,000	10	10	.008		GOOD STRENGTH & DUCTILITY	FAILED THROUGH Ag	
	Ti-8Al-1Mo-1V	.060												
700	321	.081	Ni FOIL .002"	CHEMICAL CLEAN	ARGON	1400	ROLL WELD	30	~		OK			
	Ti-8Al-1Mo-1V	.060												

D37

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME Min.		MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP.					
701	INCONEL 600	.080	NICKEL FOIL .002"	CHEMICAL CLEAN	ARGON	1700	ROLL WELD	30	1	.002	~	DID NOT WELD	NICKEL ADHERED TO INCO 600	
	Ti-8Al-1Mo-1V	.061								.004				
702	321	.081	SILVER FOIL .001"	CHEMICAL CLEAN	ARGON	1600	ROLL WELD	30	~	.003	~	DID NOT WELD	SILVER ADHERED TO INCO 321 SS	
	Ti-8Al-1Mo-1V	.060								.004				
703	321	081	ALUM. FOIL .005"	CHEMICAL CLEAN	ARGON	1000	ROLL WELD	15	~	.005	OK	USED FOR SHEAR SPECIMENS		
	Ti-8Al-1Mo-1V	.061												
704	7106	.060	COPPER PLATE	ABRASIVE CLEAN	AIR	700	20	5	10	.008	~			
	321	.083								.000				
705	7106	.062	COPPER PLATE	↓	↓	↓	〃	〃	60	〃	DIFFUSION TIME WELDING WITH		AFTER 704	USED FOR DIFFUSION STUDIES
	321	.083								〃				
706	7106	.062	COPPER PLATE				〃	〃	240	〃				
	321	.083								〃				
707	7106	.062	COPPER PLATE				〃	〃	480	〃				
	321	.083								〃				
708	7106	.062	COPPER PLATE				20	5	10	.005				
	321	.083								.000				
709	7106	.062	SILVER PLATE				〃	〃	60	〃				
	321	.083								〃				
710	7106	.062	SILVER PLATE				〃	〃	240	〃	DIFFUSION TIME WELDING WITH		AFTER 708	
	321	.083								〃				
711	7106	.062	SILVER PLATE				〃	〃	480	〃				
	321	.083								〃				
712	2219	.057	COPPER PLATE				20	5	10	.006				
	321	.083								.000				
713	2219	.057	COPPER PLATE				〃	〃	60	〃				
	321	.083								〃				
714	2219	.057	COPPER PLATE				〃	〃	240	〃	DIFFUSION TIME WELDING WITH		AFTER 712	
	321	.083								〃				
715	2219	.057	COPPER PLATE				〃	〃	480	〃				
	321	.083								〃				
716	2219	.057	SILVER PLATE				20	5	10	.005				
	321	.083								.000				
717	2219	.058	SILVER PLATE				〃	〃	60	〃				
	321	.083								〃				
718	2219	.058	SILVER PLATE				〃	〃	240	〃	DIFFUSION TIME WELDING WITH		AFTER 716	
	321	.083								〃				
719	2219	.057	SILVER PLATE		AIR	700	7〃	〃	480	〃				
	321	.083								〃				
720	321	.081	ANNEALED	ABRASIVE CLEAN	ARGON	1300	40,000	10	10	.002	OK	LOW-MED. STRENGTH & DUCTILITY	75% WELDED	
	INCONEL 718	.060	AGED							.001				

D38

SUMMARY OF DIFFUSION WELDIN ; DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP.					
721	321	.028	COLD WORKED	ABRASIVE	ARGON	1300	40,000	10	10	.000	OK	LOW-MED. STRENGTH	75% WELDED	
	INCONEL 718	.060	ANNEALED							.001				
722	321	.027	COLD WORKED			1300	40,000	10	10	000	OK	LOW-MED STRENGTH	75% WELDED	
	INCONEL 718	.023								.000				
723	321	.081	ANNEALED			1300	40,000	12	60	.002	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.060	AGED							.001				
724	321	.027	COLD WORKED			1300	40,000	12	60	.001	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.060	ANNEALED							.003				
725	321	.028	COLD WORKED			1300	40,000	12	60	.001	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.024												
726	321	.081	ANNEALED			1400	40,000	10	10	.003	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.060	AGED							.001				
728	321	.027	COLD WORKED			1400	40,000	10	10	.000	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.060	ANNEALED							.002				
729	321	.028	COLD WORKED			1400	40,000	10	10	.001	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.024												
730	321	.081	ANNEALED			1400	40,000	10	60	.003	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.060	AGED							.002				
731	321	.027	COLD WORK			1400	40,000	10	60	.007	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.060	ANNEALED											
732	321	.027	COLD WORKED			1400	40,000	10	60	.001	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.024								.003				
733	321	.081	ANNEALED			1500	30000	12	10	.001	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.060	AGED							.000				
734	321	.027	COLD WORK			1500	30000	12	10	.000	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.060	ANNEAL							.001				
735	321	.028	COLD WORKED			1500	30,000	12	10	.001	OK	MEDIUM STRENGTH	100% WELDED	
	INCONEL 718	.024												
736	321	.081	ANNEAL			1500	30,000	8	60	.003	OK	HIGH STRENGTH		
	INCONEL 718	.060	AGED							.001				
737	321	.027	COLD WORK			1500	30,000	8	60	.000	OK	HIGH STRENGTH	DIFFICULT TO PEEL	
	INCONEL 718	.060	ANNEAL							.002				
738	321	.028	COLD WORKED			1500	30,000	8	60	.002	OK	HIGH STRENGTH		
	INCONEL 718	.024												
739	321	.081	ANNEAL			1600	17,500	10	10	002	OK	MED-HIGH STRENGTH	COMPLETELY WELDED	
	INCONEL 718	.060	AGED							.000				
742	321	.027	COLD WORK			1600	17,500	10	10	.000	OK	MED-HIGH STRENGTH	DIFFICULT TO PEEL	
	INCONEL 718	.060	ANNEAL							.002				
743	321	.027	COLD WORKED	ABRASIVE	ARGON	1600	17,500	10	10	.002	OK	MED-HIGH STRENGTH		
	INCONEL 718	.024												

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORM-ATION -INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP.					
744	321	.081	ANNEAL	ABRASIVE	ARGON	1600	17,500	5	60	.008	OK	DIFFICULT TO PEEL		
	INCONEL 718	.060	AGED											
745	321	.027	COLD WORK			1600	17,500	5	60	.007	OK	DIFFICULT TO PEEL	COMPLETELY WELDED- LIGHT GREY COLOR	
	INCONEL 718	.060	ANNEAL											
746	321	.027	COLD WORK			1600	17,500	5	60	.002	OK	DIFFICULT TO PEEL		
	INCONEL 718	.024												
747	321	.081	ANNEAL			1700	12,500	5	10	.006	OK	COULD NOT PEEL		
	INCONEL 718	.060	AGED											
748	321	.027	COLD WORK			1700	12,500	5	10	.004	OK			
	INCONEL 718	.060	ANNEAL											
749	321	.028	COLD WORKED			1700	12,500	5	10	.001	OK			
	INCONEL 718	.024												
750	321	.081	ANNEAL			1700	12,500	5	60	.008	OK			
	INCONEL 718	.060	AGED											
751	321	.028	COLD WORK			1700	12,500	5	60	.004	OK			
	INCONEL 718	.060	ANNEAL											
752	321	.027	COLD WORKED			1700	12,500	5	60	.001	OK			
	INCONEL 718	.023												
753	321	.081	ANNEAL			1800	7,500	10	10	.020	OK			
	INCONEL 718	.060	AGED											
754	321	.028	COLD WORK			1800	7,500	10	10	.013	OK			
	INCONEL 718	.060	ANNEAL											
755	321	.027	COLD WORK			1800	7,500	10	10	.005	OK			
	INCONEL 718	.024												
756	~~INCONEL~~ 321	.081	ANNEAL			1800	7,500	8	60	.018	OK			
	INCONEL 718	.060	AGED											
757	321	.028	COLD WORK			1800	7,500	8	60	.010	OK			
	INCONEL 718	.060	ANNEAL											
758	321	.027	COLD WORK		ARGON	1800	7,500	8	60	.005	OK	COULD NOT PEEL		
	INCONEL 718	.024												
759	2219	.057	SILVER PLATE		AIR	700	20,000	5	10	.005				
	321	.083								.000				
760	2219	.057	SILVER PLATE		AIR	700	20,000		60			DIFFUSED FOR DIFFUSION STUDY USING TUNGSTEN WIRES		
	321	.083												
761	2219	.057	SILVER PLATE		AIR	700	20,000		240					
	321	.083												
762	2219	.057	SILVER PLATE		AIR	700	20,000		480					
	321	.083												
763	2219	.057	SILVER PLATE	ABRASIVE	AIR	700	20,000		960					
	321	.083												

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
					ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORMATION INCHES	THERMAL SHOCK -320°F	RESULTS OF PEEL TEST	APPEARANCE OF JOINT INTERFACE AFTER PEELING	
	ALLOY	GAGE						HEATUP	AT TEMP.					
764	321	.082	SILVER PLATE	ABRASIVE 320 GRIT	VACUUM	600	30,000	10	30	.001	OK	LOW STRENGTH	SILVER STRIPPED FROM TITANIUM	NO PREDIFFUSION
	Ti-8Al-1Mo-1V	.061								.000				
765	321	.082	↕	↕	↕	↕	↕	↕	↕	.002	OK	LOW STRENGTH	SILVER PEELED PRIMARILY FROM Ti	PREDIFFUSED (Ti) AT 1100°F - 10 MIN.
	Ti-8Al-1Mo-1V	.061								.000				
766	321	.083								.002	OK	MED. STREN & DUCTILITY	PEELED THROUGH SILVER. SOME AT 321 SURFACE	PREDIFFUSED (Ti) AT 1300°F. 10 MIN
	Ti-8Al-1Mo-1V	.061								.000				
767	INCONEL 600	.063								.000	OK	LOW STRENGTH	SILVER STRIPPED FROM TITANIUM	NO PREDIFFUSION
	Ti-8Al-1Mo-1V	.062								.000				
768	INCONEL 600	063								.000	OK	LOW STRENGTH	PRIMARILY AT SILVER-TITANIUM SURFACE	PREDIFFUSED (Ti) AT 1100°F - 10 MIN
	Ti-8Al-1Mo-1V	.061								.001				
769	INCONEL 600	.063								.001	OK	MED. STREN. & DUCTILITY	Ag-Ag SURFACE SOME Ag TO 600	PREDIFFUSED (Ti) AT 1300°F - 10 MIN
	Ti-8Al-1Mo-1V	.061								.000				
770	INCONEL 600	.063								.001	OK	MED. STREN. & DUCTILITY	PEELED AT Ag-Ag SOME AT Ag-600	Ti PREDIFFUSED AT 1500°F - 10 MIN
	Ti-8Al-1Mo-1V	.061								.000				
771	INCONEL 600	.063								.001	OK	LOW STREN	DID NOT COMPLETELY WELD (1700° TOO HIGH)	Ti PREDIFFUSED AT 1700°F - 10 MIN,
	Ti-8Al-1Mo-1V	.061								.000				
772	321	.083								.002	OK	MED. STREN & DUCTILITY	PEELED AT Ag-Ag SOME AT Ag-321	Ti PREDIFFUSED AT 1500°F - 10 MIN.
	Ti-8Al-1Mo-1V	.061								.000				
773	321	.083	SILVER PLATE	ABRASIVE 320 GRIT	VACUUM	600	30,000	10	30	.002	OK	LOW STRENGTH	POOR WELD LACK OF Ag ON Ti	Ti PREDIFFUSED AT 1700°F - 10 MIN
	Ti-8Al-1Mo-1V	.061								.000				

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	TEST TEMP., °F	RESULTS OF SHEAR TEST	Joint Overlap, in.	
774	2219 / 321	.068 / .081	None	Chemical Clean	Vacuum	940 ±10	Controlled Deformation	15 min.	30 min.		300	1150 lbs.	0.12	
775											300	1050 lbs.	0.10	
776											300	980 lbs.	0.12	
777											500	800 lbs.	0.15	
778											500	850 lbs.	0.12	
779											500	860 lbs.	0.12	
780											-320	900 lbs.	0.15	
781											-320	1020 lbs.	0.10	
782										800-1500	-320	1080 lbs.	0.12	
783											-423	1500 lbs.	0.10	
784											-423	1475 lbs.	0.10	
785											-423	1500 lbs.	0.10	
786			Silver	Abrasive	Air	500		5 min.	120 min.		Room	1125 lbs.	0.14	
787												1170 lbs.	0.12	
788												1950 lbs.	0.23	
789												1480 lbs	0.20	
790												2080 lbs.	0.28	
791												2300 lbs.	0.32	
792											300	1440 lbs.	0.22	
793											300	1600 lbs.	0.24	

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION INCHES	TEST TEMP., °F	RESULTS OF SHEAR TEST	JOINT OVERLAP, IN.	NOTES
794	2219 / 321	.058 / .081	Silver	Abrasive	Air	500	Controlled Deformation	15 min.	60 min.		300	1680 Lbs.	0.22	
795											500	900 Lbs.	0.22	
796											500	760 Lbs.	0.22	
797											500	1000 Lbs.	0.24	
798											-320	1460 Lbs.	0.21	
799											-320	1700 Lbs.	0.20	
800											-320	1760 Lbs.	0.20	
801											-423	4500 Lbs.	0.24	
802											-423	3750 Lbs.	0.23	
803										.005-.008	-423	2870 Lbs.	0.26	
804	7106 / 321	.061 / .081	None	Chemical Clean	Vacuum						300	1570 Lbs.	0.20	
805											300	1480 Lbs.	0.20	
806											300	1260 Lbs.	0.18	
807											500	1020 Lbs.	0.22	
808											500	800 Lbs.	0.18	
809											500	880 Lbs.	0.20	
810											-320	1010 Lbs.	0.22	
811											-320	1125 Lbs.	0.22	
812											-320	980 Lbs.	0.20	
813											-423	1675 Lbs.	0.20	

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	TEST TEMP., °F	RESULTS OF SHEAR TEST	JOINT OVERLAP, in.	
814	7106 / 321	.061 / .081	None	Chemical Clean	Vacuum	500	Controlled Deformation	15 min.	60 min.	.080 - .090	-423	1685 Lbs.	0.20	
815			None	Chemical Clean	Vacuum						-423	1750 Lbs.	0.20	
816			Silver	Abrasive	Air						Room	1760 Lbs.	0.12	
817												1320 Lbs.	0.10	
818												2250 Lbs.	0.22	
819												2530 Lbs.	0.23	
820												2800 Lbs.	0.32	
821											Room	2900 Lbs.	0.34	
822											300	1810 Lbs.	0.22	
823											300	1600 Lbs.	0.22	
824											300	1650 Lbs.	0.24	
825											500	770 Lbs.	0.24	
826											500	950 Lbs.	0.22	
827											500	830 Lbs.	0.24	
828											-320	3280 Lbs.	0.20	
829											-320	3110 Lbs.	0.25	
830											-320	3360 Lbs.	0.23	
831											-423	5760 Lbs.	0.27	
832											-423	6150 Lbs.	0.25	
833											-423	6250 Lbs.	0.24	

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION INCHES	TEST TEMP., °F	RESULTS OF SHEAR TEST	JOINT OVERLAP, in.	NOTES
834	2219 / Ti-5Al-2.5Sn	.058 / .054	None	Abrasive	Vacuum	950	Controlled Deformation	15 min.	30 min.		300	1210	0.10	
835											300	930	0.10	
836											300	910	0.08	
837											500	740	0.10	
838											500	700	0.09	
839											500	820	0.10	
840											-320	980	0.12	
841											-320	1200	0.10	
842											-320	1310	0.10	
843											-423	1300	0.14	
844											-423	750	0.10	
845											-423	600	0.10	
846			Silver		Air	500		15 min.	120 min.	800 — 500	Room	1300	0.12	
847											Room	1310	0.11	
848											Room	1520	0.22	
849											Room	1500	0.20	
850											Room	2240	0.32	
851											Room	2400	0.33	
852											300	780	0.23	
853											300	530	0.18	

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS			NOTES
					ATMOS-PHERE	TEMP °F	PRESSURE PSI	TIME		MATERIAL DEFORM-ATION -INCHES	TEST TEMP., °F	RESULTS OF SHEAR TEST	JOINT OVERLAP, in.	
	ALLOY	GAGE						HEATUP	AT TEMP.					
854	2219 / Ti-5Al-2.5Sn	.059 / .054	Silver	Abrasive	Air	500	Controlled Deformation	15 min.	120 min.		300	1250	.22	
855											500	280	.20	
856											500	380	.22	
857										0	500	100	.18	
858										0.0005	-320	1790	.24	
859										0.001	-320	1400	.22	
860										0.0005	-320	1280	.23	
861											-423	675	.21	
862											-423	690	.22	
863											-423	725	.23	
864	Inconel 600 / Ti-8Al-1Mo-1V	.062 / .058	Bare		Vacuum	1300		15 min.	10 min.		400	5350	.52	
865											400	4750	.52	
866											400	4650	.48	
867											800	2905	.20	
868											800	2315	.16	
869										0.0005	800	1320	.10	
870											-320	3450	.52	
871										0.0003	-320	3150	.45	
872											-320	3600	.52	
873											-423	1625	.53	

D 46

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION INCHES	TEST TEMP., °F	RESULTS OF SHEAR TEST	JOINT OVERLAP, in.	
874	Inconel 600 / Ti-8Al-1Mo-1V	.062 / .058	Bare	Abrasive	Vacuum	1300	Controlled Deformation	15 min.	10 min.		-423	2925	.53	
875			Bare		Vacuum	1300			10 min.		-423	2650	.50	
876			Silver		Air	700			30 min.		Room	980	.09	
877											Room	1210	.12	
878											Room	2150	.18	
879											Room	2510	.24	
880											Room	2700	.30	
881											Room	2900	.28	
882											400	200	.22	
883										.005	400	170	.24	
884										.010	400	440	.25	
885										.015	800	Failed	.20	
886										.015	800	with no	.25	
887										.020	800	load.	.24	
888											-320	2910	.24	
889											-320	3110	.24	
890											-320	2850	.22	
891											-423	1625	.22	
892											-423	1625	.20	
893											-423	1700	.24	

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	TEST TEMP., °F	RESULTS OF SHEAR TEST	JOINT OVERLAP, in.	
894	321 / Ti-8Al-1Mo-1V	.081 / .058	Bare	Abrasive	Vacuum	1450	Controlled Deformation	15 min.	10 min.		400	3875	.54	
895											400	2940	.50	
896											400	2780	.50	
897											800	1670	.18	
898											800	3320	.20	
899											800	3240	.20	
900											-320	1590	.54	Cracked at 600# load.
901											-320	2710	.52	
902										5	-320	2050	.56	
903										0	-423	3200	.53	
904										0	-423	2100	.58	
905										1	-423	1625	.52	
906			Silver		Air	600			30 min.	3	Room	740	.07	
907										0	Room	1840	.15	
908											Room	2010	.22	
909											Room	2150	.20	
910											Room	2740	.26	
911											Room	3190	.29	
912											400	150	.20	
913											400	770	.20	

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					QUALITY OF WELDED JOINTS				NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	MATERIAL DEFORMATION -INCHES	TEST TEMP, °F	RESULTS OF SHEAR TEST	JOINT OVERLAP, in.	
914	321 / Ti-8Al-1Mo-1V	.081 / .058	Silver	Abrasive	Air	600	Controlled Deformation	15 min.	30 min.		400	150	.20	
915											800	Failed	.16	
916											800	with no	.20	
917											800	load.	.20	
918											-320	2960	.25	
919											-320	3160	.25	
920											-320	3140	.22	
921											-423	3300	.25	
922										.006	-423	3750	.21	
923										.003	-423	3050	.25	
924	Inconel 718 / 321	.060 / .081	Bare		Vacuum	1600					400	6280	.24	
925											400	5570	.23	
926											400	7540	.20	
927											800	7210	.22	
928											800	5260	.25	
929											800	6410	.20	
930											-320	5830	.20	
931											-320	6020	.32	
932											-320	7070	.20	
933											-423	6375	.20	

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION		INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS					MATERIAL DEFORMATION -INCHES	QUALITY OF WELDED JOINTS			NOTES
	ALLOY	GAGE			ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.		TEST TEMP., °F	RESULTS OF SHEAR TEST	JOINT OVERLAP, in.	
934	Inconel 718 / 321	.060 / .081	Bare	Abrasive	Vacuum	1600	Controlled Deformation	15 min.	30 min.		-423	6750	.20	
935			Bare		Vacuum	1600					-423	7550	.20	
936			Silver		Air	600					Room	2400	.16	
937											Room	2210	.14	
938											Room	3610	.32	
939											Room	2850	.30	
940											400	520	.22	
941											400	900	.22	
942											400	990	.20	
943										.005	800	200	.24	
944											800	20	.18	
945											800	80	.20	
946										.003	-320	2580	.25	
947											-320	1850	.23	
948											-320	2040	.22	
949											-423	3300	.20	
950											-423	3475	.22	
951											-423	3100	.18	
952			Nickel			1300					Room	3860	.16	
953			Nickel			1300					Room	4630	.18	

050

SUMMARY OF DIFFUSION WELDING DEVELOPMENT TESTS

TEST NO.	MATERIAL COMBINATION ALLOY	MATERIAL COMBINATION GAGE	INTERLEAF MATERIAL	SURFACE PREP	DIFFUSION WELDING CONDITIONS ATMOSPHERE	TEMP °F	PRESSURE PSI	TIME HEATUP	TIME AT TEMP.	QUALITY OF WELDED JOINTS MATERIAL DEFORMATION INCHES	TEST TEMP, °F	RESULTS OF SHEAR TEST	JOINT OVERLAP, in.	NOTES
954	Inconel 718 / 321	.060 / .081	Nickel	Abrasive	Air	1300	Controlled Deformation	15 min.	30 min.		Room	6570	.32	
955											Room	6950	.35	Failed in grip
956											400	3800	.21	
957											400	3320	.15	
958											400	3780	.18	
959											800	2210	.20	
960										.005	800	2850	.20	
961											800	2600	.20	
962											-320	5425	.22	
963										.003	-320	5080	.22	
964											-320	4690	.24	
965											-423	5250	.20	
966											-423	5975	.20	
967											-423	6825	.20	
968	2219 / 321	.125 / .080	Bare	Chemical	Argon	850	Roll			.025 / none	See	Table XXIV		
969	7106 / 321	.121 / .080	Bare	Chemical		850	welded			.026 / none				
970	2219 / Ti-5Al-2.5Sn	.125 / .054	Bare	Abrasive		950	in			.025 / none				
971	321 / Ti-8Al-1Mo-1V	.080 / .058	Aluminum	Chemical		1050	stainless			none / none				
972	Inconel 600 / Ti-8Al-1Mo-1V	.062 / .058	Aluminum	Chemical		1050	steel			.002 / none				
973	321 / Inconel 718	.080 / .060	Bare	Chemical		1650	retort.			.003 / .003				

151

APPENDIX E

PROCEDURES FOR PREPARATION OF METALLOGRAPHIC SPECIMENS

PROCEDURES USED FOR PREPARATION OF METALLOGRAPHIC SPECIMENS

BASE METAL SPECIMENS

Specimens were sectioned with an abrasive cutoff wheel using water as a coolant. Specimens were rough ground on water-flooded disc wheels using progressively 80, 320, 400 and 600-grit abrasive discs.

Final polish for all alloys except Ti-8Al-1Mo-1V was performed in the following steps:

1. 6M diamond paste as an abrasive on a wheel of Met Cloth (Buehler) with kerosene as a lubricant.

2. 3M diamond paste as an abrasive on Micro Cloth (Buehler) with kerosene as a lubricant.

3. .25M diamond paste as an abrasive on Rayvel Cloth (Buehler) with ethyl alcohol as a lubricant.

4. .05M gamma alumina on Gamal Cloth (Fisher Scientific) with distilled water as a lubricant.

The final polish procedure for Ti-8Al-1Mo-1V was as follows:

Polish on a wax wheel with 15M levigated alumina with water as lubricant, then to a final polish on a wheel made up of Micro Cloth with Linde C 1M alumina as an abrasive and Krolls etch (1% HF-4% HNO_3 in water) as the lubricant. The etch polish is used to remove the smeared material produced during polishing.

Procedures for etching the base metal were as follows:

1. 2219 Aluminum Alloy

   Dilute Kroll's Etch: 2% HNO_3-0.5% HF in water.
   Immersion etch for 10 to 15 seconds.

2. 7106 Aluminum Alloy

   Keller's Etch: 1% HF-1.5% HCl-2.5% HNO_3 in water.
   Immersion etch for 10 to 15 seconds.

3. 321 Stainless Steel

   Etch: 10% oxalic acid in water.
   Electrolytic etch for 30 seconds at 2 volts.

4. Ti-5Al-2.5Sn Titanium Alloy

   Etch: 1% HF-8% H_3PO_4 in water.
   Immersion etch for 20 seconds.

5. Ti-8Al-1Mo-1V Titanium Alloy

   Kroll's Etch: 1% HF-4% HNO_3 in water.
   Immersion etch for 20 seconds.

6. Inconel 600 Alloy

   Etch: 10% oxalic acid in water.
   Electrolytic etch for 30 seconds at 2 volts.

7. Inconel 718 Alloy

   Etch: 98% HCl-2% H_2O_2.
   Immersion etch for 5 seconds.

DIFFUSION WELDED SPECIMENS

Sectioning, rough grinding, and final polishing procedures were the same as used for base materials except for the 321 stainless steel to Ti-8Al-1Mo-1V and Inconel 600 to Ti-8Al-1Mo-1V combinations. These specimens were polished on diamond wheels as for the 321 and Inconel 600 base metal, then were polished on a Micro Cloth wheel with Linde C 1M alumina as an abrasive and Kroll's etch as a lubricant. The final polish was performed using a Gamal Cloth wheel with gamma alumina and distilled water.

The etching procedures for the diffusion welded specimens were as follows:

1. 2219 Al/321 SS

   Etch for Aluminum: Dilute Kroll's Etch: 2% HNO_3-0.5% HF in water.
   Immersion etch for 10 seconds.

2. 7106 Al/321 SS

   Etch for Aluminum: Keller's Etch: 1% HF-1.5% HCl-2.5% HNO_3 in water.
   Immersion etch for 10-15 seconds.

3. 2219 Al/Ti-5Al-2.5Sn

Etch for Aluminum:	Same as used for 2219 Al/321 SS
Etch for Titanium:	1% HF-8% H_3PO_4 in water. Immersion etch for 15 seconds.

4. 321 SS/Ti-8Al-1Mo-1V

Etch for 321 SS:	Dilute Kaln's etch: 60 ml HCl, 15 ml HNO_3, 15 ml acetic acid, 85 ml H_2O. Immersion etch 10 to 30 seconds.
Etch for Titanium:	Dilute Kroll's etch: 2% HNO_3-0.5% HF in water. Immersion etch for 15 seconds.

5. 321 SS/Inconel 718

Etch for 321SS:	Same as used for 321 SS/Ti-8Al-1Mo-1V
Etch for Inconel 718:	10% Chromic acid in H_2O with 1 drop HCl. Electrolytic etch for 2 seconds at 20 volts.

6. Inconel 600/Ti-8Al-1Mo-1V

Etch for Inconel 600:	Dilute Marbles' Etch: 200 ml HCl, 40 gms $CuCl_2$, 600 ml H_2O. Immersion etch for 10 to 20 seconds.
Etch for Titanium:	Same as used for 321 SS/Ti-8Al-1Mo-1V

7. Ag, Au, Cu Diffusion Aid Etch:

50 ml NH_4OH, 20 ml H_2O_2.
Immersion etch for 10 seconds.

8. 321 SS/Cu, Au or Ag/Ti-8Al-1Mo-1V

Etch for Titanium:	Same as used for 321 SS/Ti-8Al-1Mo-1V
Etch Cu, Au, Ag:	Ag-Au-Cu Etch

9. 321 SS/Cu/Inconel 718

Etch for Cu only:	Ag-Au-Cu Etch

10. 321 SS/Ni/Inconel 718

Etch for Ni:	Same as for Inconel 600
Etch for Inconel 718:	Same as for 321 SS/Inconel 718.

11. 7106 Al/Ni/321 SS

Etch for Aluminum:	Same as used for 2219 Al/321 SS.

12. 2219 Al/Ag, Cu/321 SS
    7106 Al/Ag, Cu/321 SS

    Etch for Aluminum: Same as used for 2219/321 SS.
    Etch for Ag, Cu: Ag-Au-Cu Etch

13. 2219 Al/Ag/Ti-5Al-2.5Sn

    Etch for Al & Ti: Same as used for 2219 Al/Ti-5Al-2.5Sn.
    Etch for Ag: Ag-Au-Cu Etch

14. 321 SS/Ag/Ti-8Al-1Mo-1V

    Etch for 321 SS & Ti: Same as used for 321 SS/Ti-8Al-1Mo-1V.
    Etch for Ag: Ag-Au-Cu Etch

15. Vanadium Diffusion Aid Etch:

    85% HNO_3, 15% HF.
    Immersion etch for 5 seconds.