MDC G4298, Ph. I

N73 20536 cy 1

DETECTION OF LACK OF FUSION USING OPAQUE ADDITIVES PHASE I

by

J. L. Cook

November 1972

Prepared under Contract NAS8-28708
For the period
2 June to 31 October 1972
by
McDonnell Douglas Astronautics Company
Huntington Beach, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Alabama 35812

MDC G4298

DETECTION OF LACK OF FUSION USING OPAQUE ADDITIVES PHASE I

by

J. L. Cook

November 1972

Prepared under Contract NAS8-28708
For the period
2 June to 31 October 1972
by
McDonnell Douglas Astronautics Company
Huntington Beach, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Alabama 35812

PRECEDING PAGE BLANK NOT FILMED

ABSTRACT

There are currently two major problems in welded aluminum spacecraft structure. These are reliable nondestructive inspection for incomplete weldment penetration and the rapid oxidation of aluminum surfaces left exposed to the atmosphere. Incomplete-penetration defects are extremely hard to detect and can lead to catastrophic failure of the structure. The moisture absorbed by aluminum oxide on the surface can cause weldment porosity if the surface is not cleaned carefully immediately before welding.

The approach employed in this program to solve both problems was to employ copper as a coating to prevent oxidation of the aluminum and as an opaque additive in the weldment to enhance x-ray detection in the event of incomplete penetration.

Both plasma spray and vacuum vapor deposition techniques were evaluated for depositing the copper. A series of welded panels was made using three thicknesses of vacuum-vapor-deposited copper. All weldments were nondestructively inspected by x-ray, then excised into tensile and bend specimens. Mechanical tests were conducted and all data evaluated.

It was determined that the vacuum-vapor-deposited coating was superior to a plasma sprayed coating of the same thickness. The vacuum-vapor-deposited coating was more uniform in thickness, provided complete coverage of the aluminum, and was free of cracks and porosity. X-rays of weldments with intentional incomplete penetration showed the remaining copper very clearly. The mechanical tests indicated that there was very little change in properties because of the added copper.

Preceding page blank

The concept of the opaque additive was proved very effective. Promise of long-term protection of aluminum surfaces was indicated by successful storage of coated test panels for over two weeks. Additional effort is necessary to develop a practical and economical means of applying the copper in a manufacturing environment.

ACKNOWLEDGMENTS

The author wishes to express his appreciation for the very able assistance of Mr. G. R. Stoeckinger, who planned and conducted all the welding effort in Phase I of this program.

CONTENTS

PRECEDING PAGE BLANK NOT FILMED

FIGURES

Preceding page blank

PRECEDING PAGE BLANK NOT FILMED

TABLES

Preceding page blank

Section 1
INTRODUCTION

Welded aluminum alloy structure has been used extensively in current-generation spacecraft and is expected to be used for future space shuttle vehicles and propellant tankage. Weldment porosity is a major problem in production of aluminum weldments. This porosity is caused by moisture absorbed by the aluminum oxide which forms on the surface before welding. This problem occurs because of the spontaneous formation of the moisture-absorbing oxide in storage. This oxidation process is very rapid, and extensive cleaning procedures immediately prior to welding are mandatory for production of porosity-free weldments.

Another problem of serious concern, particularly in welding thick-section butt joints from both surfaces, is incomplete penetration of the weldment. When this condition occurs, a knife-edge crack or separation is left unfused in the weld joint. Such a stress concentrator in a weldment can produce catastrophic failure during proof testing or service of large cryogenic propellant tankage. Previous MDAC-West experience on the S-IVB program demonstrated that incomplete penetration of a weldment could result in failure of a vessel. One such defect led to failure during a hydrostatic pressure test. Considering the cost of such vehicles as the S-IVB, and particularly of the larger tankage anticipated for the Space Shuttle program, any reasonable means of averting such failure must be explored.

It has been shown that a lack-of-penetration defect is perhaps one of the most difficult to detect by conventional nondestructive inspection techniques. Because of the high residual compressive stresses present in weldments containing this type of defect, it is possible for x-ray and ultrasonic inspection techniques to miss such defects (Reference 1). Even if the defect is open to the surface of the aluminum structure, it is possible for the joint to be so tightly closed that even very sensitive penetrant inspection techniques will not reveal its presence.

The objective of this program is to develop means of solving the problems of surface oxidation and detection of lack-of-penetration defects. The means to this solution lies in coating the aluminum surfaces to be protected with an x-ray-opaque metal such as silver or copper. In this way, the formation of moisture-absorbing aluminum oxide may be stopped. Furthermore, any protective coating remaining in an area of incomplete weld penetration would be clearly evident on the x-ray of the weldment.

To meet the objective, the effort was divided into two phases. The objective of the Phase I was to select a technique that would provide a thin but impervious coating of copper. The required minimum thickness was to be ascertained and the effect on x-ray inspection evaluated. Mechanical properties tests were to be conducted to assess the effect of the copper on weldment properties. This report presents the technical approach, technical efforts, and results for Phase I, together with a detailed plan for completion of Phase II.

Section 2
TECHNICAL APPROACH

The approach taken in this program was to develop a suitable thin, moisture-free, continuous copper coating for application to 2219 aluminum. The alloy 2219 was selected because of its current and anticipated future use in major spacecraft structures.

There were several factors which had to be considered in this approach.

A. Covering and protective capability of the coating.

B. Effect of coating on the composition of the weldment.

C. Minimum thickness of coating necessary to provide x-ray indication of lack of weld penetration.

Copper was selected for several reasons. It has an x-ray absorption coefficient (Reference 2) very much greater than that of aluminum, and therefore is easily detectable in x-rays of aluminum. Copper is also contained in many aluminum alloys—approximately 6 percent in 2219. Therefore, minor additions of copper would not be detrimental to alloy composition.

In the Phase I effort, an attempt was made to understand the factors listed above and to select a specific deposition technique for further effort. Two copper deposition techniques were employed: plasma spray and vacuum vapor deposition. Both techniques were felt to be potentially capable of depositing a thin layer of copper of sufficient density to protect the aluminum surface.

Section 3
PROCEDURES AND RESULTS

3.1 MATERIAL

Nine plates of 2219-T87 aluminum alloy were procured from stock for the various panels and specimens. These plates were 0.127 m (0.5 in.) thick. Seven of these plates were 0.610 m (24 in.) wide and 1.829 m (72 in.) long, and two plates were 1.219 m (48 in.) wide and 3.048 m (120 in.) long. A cutting plan (Figure 1) was developed to provide the necessary samples for both phases of the program. The samples for the Phase I effort were machined as follows:

25 samples 0.0254 by 0.0508 by 0.00127 m thick
(1 by 2 by 0.0505 in. thick)
16 panels 0.152 by 0.610 by 0.127 m thick
(6 by 24 by 0.5 in. thick)
14 panels 0.152 by 0.452 by 0.0127 m thick
(6 by 18 by 0.5 in. thick)

The 25 small samples were used for evaluation of the copper coating techniques. The larger panels were used to make welded panels. The welded panels included those for baseline mechanical properties tests (no copper coating) and those for determining the effects of various thicknesses of copper.

3.2 MATERIAL CODING PLAN

In order to provide complete material traceability, a coding plan was established to identify every specimen and welded panel. The seven plates were designated L1 through L7, and the two larger plates were designated B1 and B2.

The cutting plan for these two sizes of plates is shown in Figure 1. All panels are numbered, and the resulting welded panels are designated by starting panel numbers. For example, if panels 13 and 14 are welded together, the

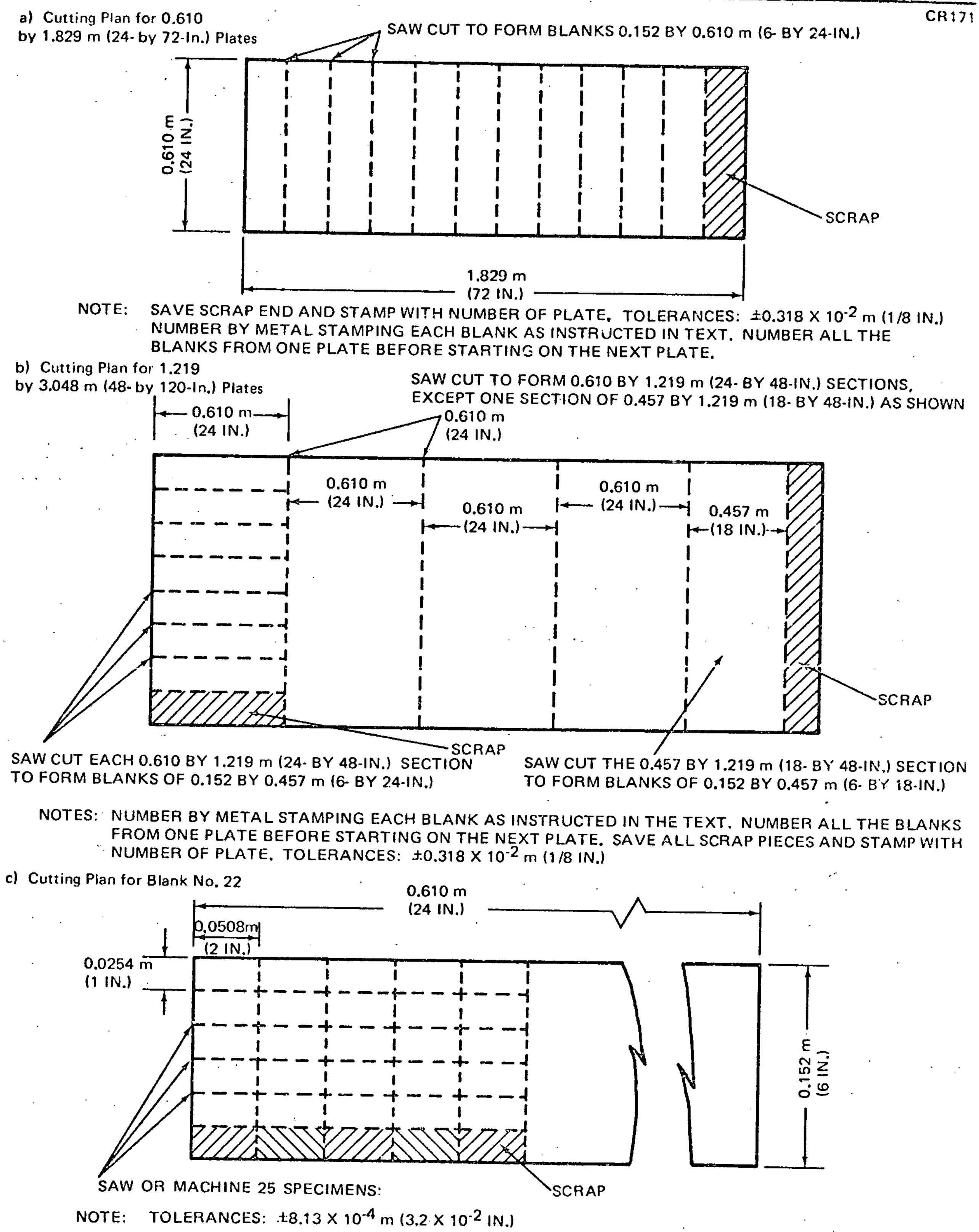


Figure 1. Cutting Plans for Aluminum Plates

code number of the resulting welded panel is 1314. Subsequent mechanical test specimens each carry the code of the welded panel from which they were cut. Therefore, complete traceability of every test specimen is assured.

The twenty-five 1.27×10^{-3} m (5×10^{-2} in.) thick samples were numbered 01 through 25. They were cut from panel No. 22, which was sacrificed to provide the smaller samples.

The material is 2219-T87 aluminum plate 0.0127 m (1/2 inch) thick. Nine plates were involved:

A. Seven 0.610-m by 1.829-m (2- by 6-ft) plates were numbered L1, L2, L3, L4, L5, L6, and L7 by metal stamping.
B. Two 1.219-m by 3.048m (4- by 10-ft) plates were numbered B1 and and B2 by metal stamping.

All nine of these plates were sawed into blanks as described below.

The seven plates designated L1 through L7 were sawed into blanks, 0.152 m (6 in.) wide by 0.610 m (24 in.) long as shown in Figure 1. Each 0.152-by 0.610-m (6- by 24-in.) blank was numbered by metal stamping as follows:

Plate No. L1 - blanks numbered 01 through 11
Plate No. L2 - blanks numbered 12 through 22
Plate No. L3 - blanks numbered 37 through 47
Plate No. L4 - blanks numbered 48 through 58
Plate No. L5 - blanks numbered 59 through 69
Plate No. L6 - blanks numbered 70 through 80
Plate No. L7 - blanks numbered 81 through 91

The two plates designated B1 and B2 were sawed into blanks 0.152-m (6-in.) wide by 0.610-m (24-in.) long as shown in Figure 1.

Each 0.152 by 0.610-m (6- by 24-in.) blank was numbered by metal stamping as follows:

Plate No. B1 - blanks numbered 92 through 119
Plate No. B2 - blanks numbered 120 through 147

In addition to the above-described blanks, seven additional blanks 6-in. wide by 18-in. long were cut from Plates B1 and B2, as shown in Figure 1. These 18-in. -long blanks were numbered by metal stamping as follows:

Plate No. B1 - blanks numbered 23 through 29

Plate No. B2 - blanks numbered 30 through 36

When all blanks were excised from the original plate and metal-stamp-numbered as previously described, they were further machined as described below:

Several small samples were machined from blank No. 22, as shown in Figure 1. These 25 samples were metal stamped 01 through 25 in sequence.

3.3 COPPER DEPOSITION

3.3.1 Vacuum Vapor Deposition Procedure

Twelve panels designated 05 through 16 were shipped to MDAC-East for vacuum vapor deposition of copper. In addition, fifteen 1.27×10^{-3} m (5×10^{-2} in.) thick samples were included to be coated at the same time. These were numbered 11 through 25; not all were copper coated. The panels designated 05 through 16 were coated on one 0.610-m (24-in.) by 0.0127-m (0.5-in.) edge only. The smaller 1.27×10^{-3} m (5×10^{-2} in.) thick specimens wer coated on only one 0.0254-m (1-in.) by 0.0508-m (2-in.) surface. Table 1 lists the panels and specimens and the resulting thickness of the copper coatin

Table 1

SUMMARY OF VACUUM VAPOR DEPOSITION RESULTS

Specimen No.	Required Coating Thickness	Coating Passes	Actual Coating* Thickness
11. 12, and 13	5.08×10^{-6} m (2×10^{-4} in.)	6	5.00×10^{-6} m (1.97×10^{-4} in.)
16, 17, 18, and 19	12.7×10^{-6} m (5×10^{-4} in.)	15	14.2×10^{-6} m (5.61×10^{-4} in.)

*Average of 6 measurements.

Table 1

SUMMARY OF VACUUM VAPOR DEPOSITION RESULTS (Continued)

Specimen No.	Required Coating Thickness	Coating Passes	Actual Coating* Thickness
21, 22, and 23	19.32×10^{-6} m (8×10^{-4} in.)	24	20.5×10^{-6} m (8.07×10^{-4} in.)
Panel No.			
05, 06, 07, and 08	5.08×10^{-6} m (2×10^{-4} in.)	6	5.00×10^{-6} m (1.97×10^{-4} in.)
09, 10, 11, and 12	12.7×10^{-6} m (5×10^{-4} in.)	15	14.2×10^{-6} m (5.61×10^{-4} in.)
13, 14, 15, and 16	19.32×10^{-6} m (8×10^{-4} in.)	24	20.5×10^{-6} m (8.07×10^{-4} in.)

*Average of 6 measurements.

Prior to coating, the aluminum pieces were chemically cleaned. This cleaning consisted of degreasing followed by alkaline cleaning to remove soil and acid pickling to remove smut and oxide films. The cleaning solutions used were:

	Chemical	Concentration	Temperature	Immersion Time (minutes)
Alkaline Cleaner	Turco 4215S chromated non-silicated cleaner	16.3×10^{-5} m^3 to 20.7×10^{-5} m^3 per 3.78×10^{-3} m^3 (5.5 to 7.0 oz/gal)	150 °F	15
	Turco 4215 additive	2.96×10^{-5} m^3 per 3.78×10^{-3} m^3 (1 fl oz/gal) cleaner		
Acid Pickling	Nitric acid	35.2×10^{-3} m^3 to 39.7×10^{-3} m^3 (9.3 to 10.5 gal)*		
	Chromic acid	17.3 to 19.1 kg (38 to 42 lb)*	70 to 100 °F	1 to 2
	Hydrochloric acid	3.21×10^{-3} m^3 to 3.78×10^{-3} m^3 (0.85 to 1 gal)*		

*Based on 0.378 m^3 (100-gal) water solution.

After chemical cleaning, the plates were positioned in a vacuum chamber with the surfaces to be coated facing downward. The plate-holding fixture was electrically insulated from the rest of the chamber so that the plates could be glow-discharge-cleaned. This cleaning method was used to remove the adsorbed gases and moisture from the metal surfaces. The glow discharge was accomplished by applying a high-voltage discharge between the plate and the chamber wall. The sequence after initial pumpdown to 1.33×10^{-2} N/m^2 (10^{-4} torr) was to: (1) bleed argon gas into the chamber to maintain a chamber pressure of 3.33 to 6.66 N/m^2 (0.025 to 0.050 torr), (2) glow discharge at 3,000 v and 450 ma in the partial pressure of argon for 30 minutes, and (3) pump down to 1.33×10^{-2} N/m^2 (10^{-4} torr) for the coating operation.

Copper deposition was started immediately after pumpdown following the glow discharge cleaning. The copper was deposited from a single self-resistance-heated molybdenum boat. The aluminum plates were held stationary 0.30 m (12 in.) above the boat, and during coating the boat was traversed horizontally at 0.089 mpm (3.5 ipm). Copper coatings 7.62×10^{-7} to 8.89×10^{-7} m (30 to 35 μin.) thick were deposited on aluminum substrates on each pass. During coating, the boat was about three-fourths filled with copper, and this level was maintained throughout the coating operation by continuous additions of 99.9 percent pure copper (ASTM B170 Grade I). The wire feed rate was adjusted throughout the run to maintain a constant boat temperature, which in turn controlled the rate of copper deposition.

Coating thickness was measured using the weight method, in which preweighed, 0.05- by 0.08-m (2- by 3-in.) aluminum sheet specimens are weighed after plating. The amount and thickness of copper are then calculated. Six weight specimens were used for each coating run. These specimens were equally spaced adjacent to the aluminum plate specimens.

Adhesion of the copper coating was measured by tape peel testing 0.03 by 0.08 m (1- by 3-in.) specimens placed along side the subject aluminum panels. This test was made by placing a 0.08-m (3-in.) long strip of No. 250 Scotch tape on the copper surface and hand-pressing firmly in place. The loose end of the tape was then quickly withdrawn. The adhesive test conducted on six specimens in each coating run revealed no evidence of peeling.

3.3.2 Plasma-Spray Procedure

Ten panels designated 23 through 32 were shipped to General Plasma Associates in Venice, California, for plasma-spray deposition of copper. In addition, ten 1.27×10^{-3} m (5×10^{-2} in.) thick samples were included to be plasma-sprayed with the larger panels. Panels 23 through 32 were only 0.452 m (18 in.) long to permit them to fit within the controlled-atmosphere chamber used by General Plasma. Panels 23 through 32 were coated on one 0.452-m (18-in.) by 0.0127-m (0.5-in.) edge only. The 1.27×10^{-3} m (5×10^{-2} in.) thick specimens were coated on only one 0.0254-m (1-in.) by 0.0508-m (2-in.) surface.

The objective of the copper deposition procedure was to place a thin, dense layer of copper on the aluminum surface. The target thickness was approximately 1.27×10^{-5} m (5×10^{-4} in.). This was well within the capability of the vacuum vapor-deposition process, but was a potential problem for plasma spray.

First attempts in the plasma-spray effort indicated that plasma-spray coatings in the range of 1.27×10^{-5} to 2.54×10^{-5} m (5×10^{-4} to 10×10^{-4} in.) could not provide any reasonable density or coverage of the aluminum surface. Incomplete coverage was evident in the cross sections of the test samples. It was considered necessary to increase the coating thickness to about 7.62×10^{-5} m (3×10^{-3} in.) in order to achieve the desired coverage.

Since it was not certain exactly how much copper was necessary to protect the aluminum surface, the plasma-spray effort was modified to provide two different coatings. Four each of the small samples and larger panels were plasma-sprayed to produce coatings no more than 2.54×10^{-5} m (1×10^{-3} in.) thick. The remaining six samples and panels were to be plasma-sprayed to produce a copper coating approximately 7.62×10^{-5} m (3×10^{-3} in.) thick. At the time, that thickness was considered adequate to produce suitable coverage and protection of the aluminum.

The first objective of this approach was to assess the suitability of the thin plasma-spray coating even though the coverage was minimal. The four panels were coated by General Plasma as described and will be held in storage until the welding sequences are begun during Phase II of the program. The resulting weldments will then be carefully reviewed for porosity. The anticipated storage delay for these four panels is five months.

The second objective was to determine the effect of copper approximately 7.62×10^{-5} m (3×10^{-3} in.) thick on each faying surface. It was anticipated that such thicknesses would be much more than is necessary to properly tag the lack-of-penetration areas for x-ray inspection. The effect of such thicknesses on the welding parameters was not known, since earlier efforts by MDAC West had been limited to strip implants 3.81×10^{-5} m (1.5×10^{-3} in.) thick.

Even though an inert gas drive was used, it was considered desirable to conduct the coating as originally planned in an inert-atmosphere chamber, as well. However, it was found extremely difficult to deposit a controlled thickness in the chamber. The length of the panels, even though reduced to 0.452 m (18 in.) to allow the panels to fit in the chamber, prevented sweeping the plasma gun along the length of the panel uniformly and repeatably. Therefore, all the panels were coated in the open atmosphere. Table 2 lists the specimens and panels which were coated by plasma spray along with the coating thicknesses reported by General Plasma.

3.4 COPPER COATING ANALYSIS

The 0.00127 m (0.050-in.) thick samples were used to assess the nature of the copper coating and to determine thickness uniformity. Several from each process were submitted for sectioning, mounting, and photomicrographs.

The sections of the plasma-sprayed samples (Figure 2) reveal a very uneven and nonuniform coating. Many areas of the aluminum surface appeared to be open to the atmosphere. The thickness varied from no copper at all to about 5.08×10^{-5} m (2×10^{-3} in.) on specimen 03. Specimen 03 had been sprayed with the intention of applying approximately 7.62×10^{-5} m (3×10^{-3} in.) of copper. Apparently the estimate of coating thickness provided by General Plasma was in error, as the sectioned sample revealed a maximum thickness

Table 2

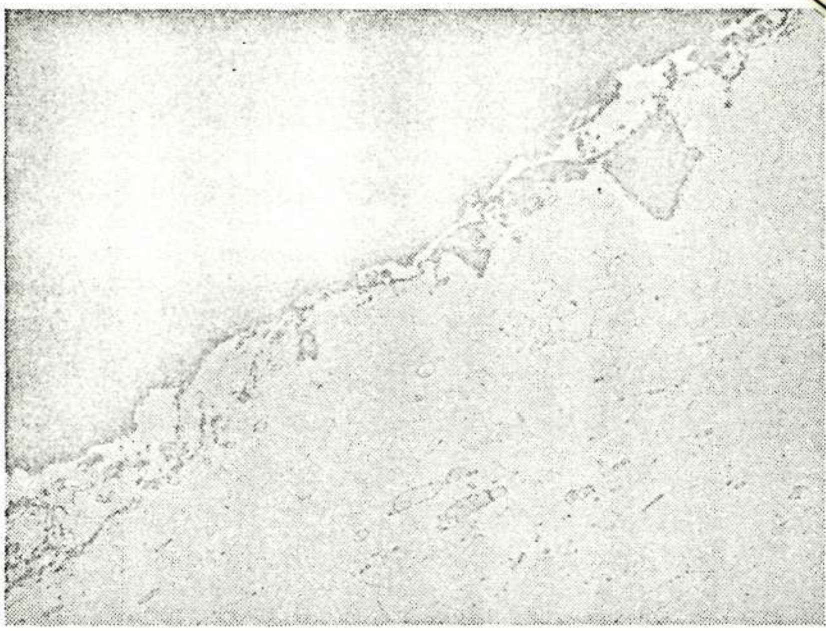
SUMMARY OF PLASMA SPRAY DEPOSITION RESULTS

Items	SN	Original Thickness	Plasma Process	Coating Nominal Thickness	Remarks
10 pieces 0.0254 by 0.0508 m (1 by 2 in.)	1	1.29×10^{-3} m (5.07×10^{-2} in.)	Air	7.6×10^{-5} m (3×10^{-3} in.)	
	2	1.28×10^{-3} m (5.04×10^{-2} in.)	Argon Atmosphere	7.6×10^{-5} m (3×10^{-3} in.)	
	3	1.29×10^{-3} m (5.07×10^{-2} in.)	Argon Atmosphere	7.6×10^{-5} m (3×10^{-3} in.)	
	4	1.28×10^{-3} m (5.04×10^{-2} in.)	Argon Atmosphere	7.6×10^{-5} m (3×10^{-3} in.)	Parts 1 through 6 sprayed for good coverage disregarding thickness
	5	1.28×10^{-3} m (5.04×10^{-2} in.)	Argon Atmosphere	7.6×10^{-5} m (3×10^{-3} in.)	
	6	1.29×10^{-3} m (5.07×10^{-2} in.)	Argon Atmosphere	7.6×10^{-5} m (3×10^{-3} in.)	
	7	1.28×10^{-3} m (5.04×10^{-2} in.)	Argon Atmosphere	2.54×10^{-5} m (1×10^{-3} in.)	
	8	1.29×10^{-3} m (5.07×10^{-2} in.)	Argon Atmosphere	2.54×10^{-5} m (1×10^{-3} in.)	Plasma sprayed to 2.54×10^{-5} m (1×10^{-3} in.) nominal thickness
	9	1.29×10^{-3} m (5.07×10^{-2} in.)	Argon Atmosphere	2.54×10^{-5} m (1×10^{-3} in.)	
	10	1.29×10^{-3} m (5.07×10^{-2} in.)	Argon Atmosphere	2.54×10^{-5} m (1×10^{-3} in.)	

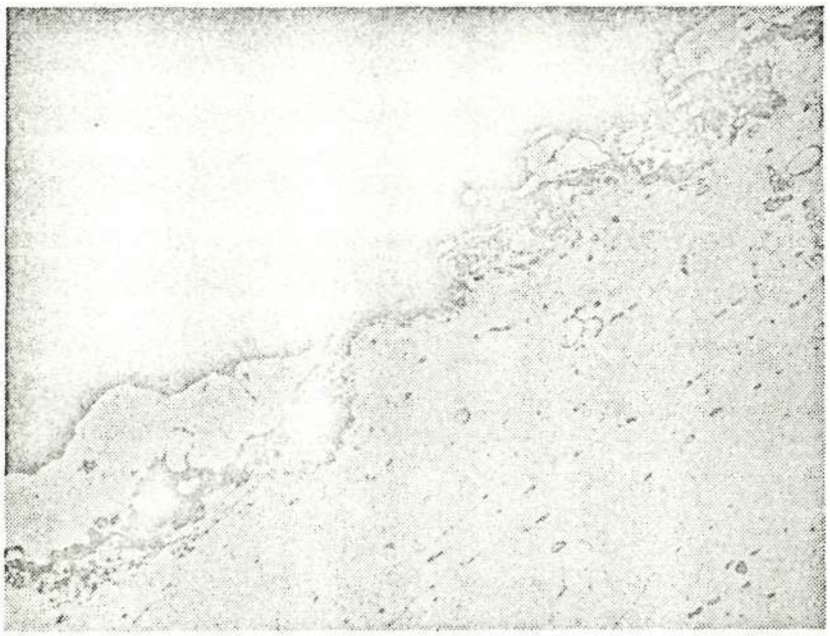
Table 2

SUMMARY OF PLASMA SPRAY DEPOSITION RESULTS (Continued)

Items	SN	Original Thickness	Plasma Process	Coating Nominal Thickness	Remarks
10 pieces 0.152 by 0.458 m (6 by 18 in.)	23	0.152 m (6.002 in.)	Air	2.54×10^{-5} m (1×10^{-3} in.)	Plasma sprayed to 2.54×10^{-5} m (1×10^{-3} in.)
	24	0.152 m (6.002 in.)	Air	2.54×10^{-5} m (1×10^{-3} in.)	
	25	0.152 m (6.002 in.)	Air	2.54×10^{-5} m (1×10^{-3} in.)	
	26	0.152 m (6.002 in.)	Air	2.54×10^{-5} m (1×10^{-3} in.)	
	27	0.152 m (6.002 in.)	Air	7.6×10^{-5} m (3×10^{-3} in.)	Parts 27 to 32 sprayed for good coverage disregarding thickness
	28	0.152 m (6.002 in.)	Air	7.6×10^{-5} m (3×10^{-3} in.)	
	29	0.152 m (6.002 in.)	Air	7.6×10^{-5} m (3×10^{-3} in.)	
	30	0.152 m (6.002 in.)	Air	7.6×10^{-5} m (3×10^{-3} in.)	
	31	0.152 m (6.002 in.)	Air	7.6×10^{-5} m (3×10^{-3} in.)	
	32	0.152 m (6.002 in.)	Air	7.6×10^{-5} m (3×10^{-3} in.)	



a) Plasma Spray Copper Coating 2.54×10^{-5}m (0.001 in.) Thick



b) Plasma Spray Copper Coating 5.08×10^{-5}m (0.002 in.) Thick

Figure 2. Sections of Plasma Sprayed Aluminum at 500X

of 5.08×10^{-5} m (2×10^{-3} in.) with many areas substantially less than that. It should be recognized, however, that measurement of such thin coatings is very difficult without actually sectioning a test sample. Specimen 11, which was sprayed to provide about 2.54×10^{-5} m (1×10^{-3} in.) of copper showed even larger areas of aluminum surface unprotected. In addition, nowhere did the coating on the sectioned sample approach the 2.54×10^{-5} m (1×10^{-3} in.) thickness reported by General Plasma.

The specimens which were coated by vacuum vapor deposition showed a much more uniform layer of copper (Figure 3). In all cases, the copper appeared to be without porosity and of a constant thickness. Optical thickness measurements revealed virtually no variations in thickness. Table 3 documents the optically measured thickness as compared to the thicknesses reported by MDAC-East, where the vacuum vapor deposition had been performed.

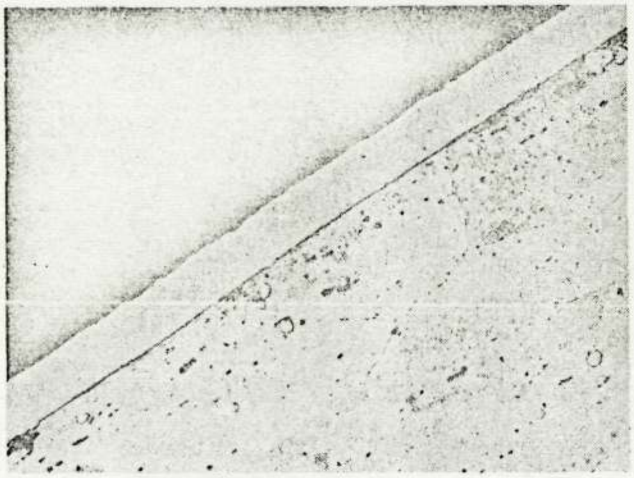
Samples 03 and 07 were examined using the MDAC electron microprobe. Two series of tests were conducted, the first to assess the extent of the aluminum not covered by the copper coating. The second was to determine the presence of oxygen and the manner in which the oxygen was combined.

Sample 03, as previously described, was sprayed with the intention of producing a coating 7.62×10^{-5} m (3×10^{-3} in.) thick. In the same manner, Sample 07 was sprayed to produce 2.54×10^{-5} m (1×10^{-3} in.) thick coating. However, in each case the actual copper coating thickness was less than anticipated. Sections of each sample indicated that there were substantial areas of the aluminum which were uncoated and therefore unprotected.

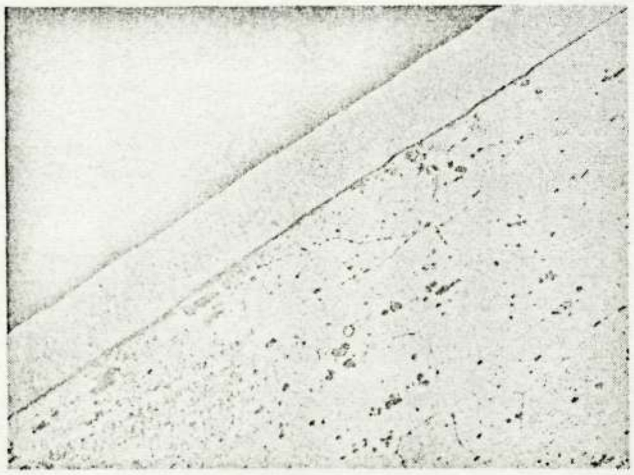
The electron microprobe verified that the copper-coated surfaces of both samples had large areas in which the aluminum was unprotected. Sample 07 had a greater unprotected area than Sample 03. The oxygen detected on the surface of both samples was combined with the aluminum as aluminum oxide. There was no indication of copper oxide on either sample.

The above information leads to the conclusion that plasma-sprayed coatings up to 5.08×10^{-5} m (2×10^{-3} in.) thick do not adequately cover the aluminum

a) Vacuum Vapor Deposited Copper Coating 5.08×10^{-6} (0.0002 in.) Thick



b) Vacuum Vapor Deposited Copper Coating 12.7×10^{-6}m (0.0005 in.) Thick



c) Vacuum Vapor Deposited Copper Coating 20.32×10^{-6}m (0.0008 in.) Thick

Figure 3. Sections of Vacuum Vapor Deposited Copper on Aluminum at 500X

Table 3

COMPARISON OF OPTICALLY MEASURED COATING THICKNESS VACUUM-VAPOR-DEPOSITED COPPER ON ALUMINUM

Specimen No.	Thickness Reported by MDAC-East	Optically Measured on Microsection
11	5.00×10^{-6} m (1.97×10^{-4} in.)	5.64×10^{-6} m (2.22×10^{-4} in.)
18	14.2×10^{-6} m (5.61×10^{-4} in.)	16.9×10^{-6} m (6.66×10^{-4} in.)
21	20.5×10^{-6} m (8.07×10^{-4} in.)	22.6×10^{-6} m (8.88×10^{-4} in.)

surface and cannot prevent the formation of aluminum oxide on the unprotected surface. Despite the fact that the samples were plasma-sprayed in open atmosphere, there does not seem to be any noticeable formation of copper oxide. Comparison of the photomicrographs in Figures 2 and 3 clearly indicates the superiority of the vacuum-vapor-deposited copper coating. Copper coating as thin as 5.08×10^{-6} m (2×10^{-4} in.) was deposited with excellent uniformity and no cracks or porosity. Such a thin coating would be expected to have little or no effect on welding parameters or on mechanical properties.

3.5 WELDING

3.5.1 Approach

The GMA (gas metal arc) welding process operating in the spray mode of metal transfer was used for this program. This process capability is provided by the eight-axis N/C (numerically controlled) GMA welding machine partially shown in Figure 4. This machine enables accurate programming on punched tape of torch movements within 5.08×10^{-6}m (2×10^{-4} in.) and primary welding parameters such as welding current, arc voltage, and wire feed speed in increments of 0.6 amp, 0.04 v, and 0.024 m/minute (1.0 ipm), respectively. In addition, it is possible to preprogram in-process changes to these parameters anywhere within the weld cycle as frequently as every 1.5 sec. This feature was used extensively for producing the tapered 0.152-m

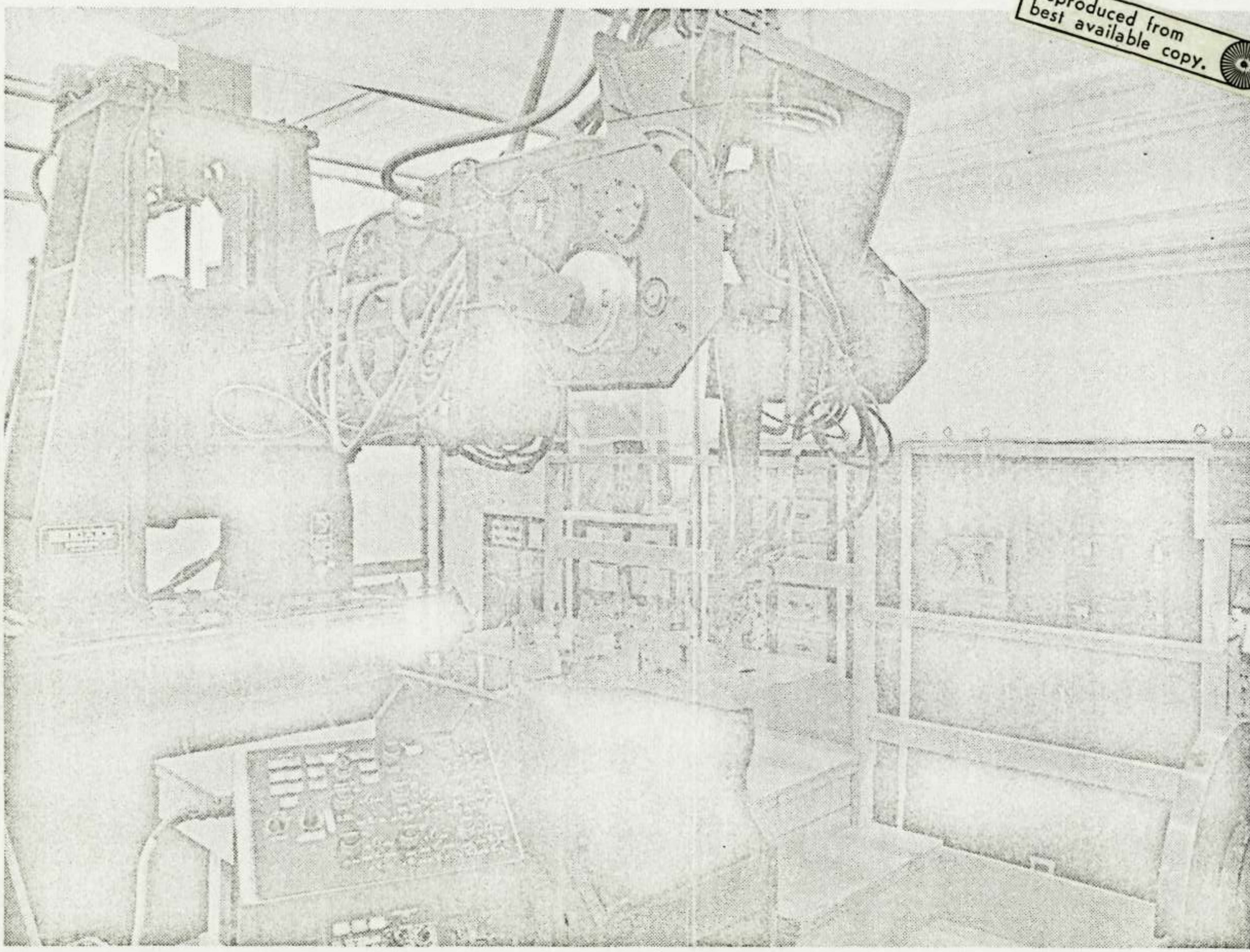


Figure 4. Eight-Axis Numerically Controlled Welding Machine

(6-in.) lack-of-fusion condition required for the panels in this program. With the procedure developed, there is the assurance that every subsequent panel will be welded in precisely the same manner due to the accurate repeatability of an N/C welding system. This eliminates any variation in the test data that might otherwise be attributable to welding inconsistencies.

The filler wire used in this program was 16.0×10^{-4} m (6.3×10^{-2} in.) diameter 2319 procured to Federal Specification QQ-R-566 (Reference 4). It was previously analyzed spectrographically and found to have the following chemical composition:

Element	Weight (percent)
Si	0.08
Cu	6.00
Ti	0.14
Zr	0.13
V	0.09
Fe	0.23
Zn	0.07
Al	Balance

Shielding gas was a mixture of 75 percent He, 24.99 percent Ar, and 0.01 percent O_2. This gas is preferred over a mixture of 99.99 percent Ar and 0.01 percent O_2 for its greater thermal conductivity and ionization potential and, thus, better penetration capability.

Immediately before welding the control panels, the individual surfaces were cleaned as required by MSFC-SPEC-504 (Reference 3) as follows. All three surfaces on the joint edge were wiped with a clean, lint-free cloth dampened with acetone. They were then etched with a tri-etch (chromic, nitric, and hydrofluoric acids) for a minimum of 5 minutes and agitated frequently. After water rinsing, the edges were neutralized with a solution of sulfuric acid and sodium dichromate and rinsed with de-ionized water until a pH value of 5.0 to 8.0 was reached. After drying with clean, lint-free cloths, the top and bottom surfaces were mechanically cleaned with a clean, power-driven, small-bristle, stainless steel brush. Precautions were taken to not apply excessive pressure, because some of the remaining contaminants or surface oxides could be driven into the surface instead of being removed. Then the faying surface was draw-filed with a Vixen file, at the same time removing any burrs from the corners. The chips and dust remaining from this operation were vacuumed or blown clean with filtered dry nitrogen. The assembled joint was inspected with a black light for any remaining organic contaminants just prior to welding. If found, they were removed with a clean, dry, lint-free cloth.

The faying surfaces of the coated specimens were not brushed or chemically etched in any way. Only the corners were broken with a Vixen file and the coating wiped with a clean, lint-free cloth dampened with acetone. The top and bottom surfaces of the assembled panel were power-wire-brushed in the weld fixture, blown clean with dry nitrogen, and inspected with a black light before welding.

3.5.2 Experimental Procedure

3.5.2.1 Preliminary Setup

The eight-axis N/C welder was converted from the GTA (gas tungsten arc) to the GMA mode of operation for performance of Phase I welding. An aluminum base weld fixture containing a 6.35×10^{-3} by 5.72×10^{-2} m (0.250 by 2.250 in.) rectangular groove with six lever-type toggle clamps for securing the specimens was mounted to the positioner baseplate, as shown in Figure 5. Employing bead-on-plate welds, attempts were made to develop arc consistency using a constant-current, demand-wire-feed GMA welding approach. It was found, however, that consistent arc operation could not be obtained for more than 0.20 to 0.25 m (8 to 10 in.) of weld. Therefore, the more conventional constant-potential, constant-wire-feed mode was employed. Parameters were then developed that produced penetration to a depth of 8.13×10^{-2}m (0.320 in.) as verified by measurement on transverse weld sections.

3.5.2.2 Welding of Control Panels

The developed welding parameters were verified by welding in an automatic mode (no tape) from opposite sides a 1.27×10^{-2}m (0.500 in.) thick by

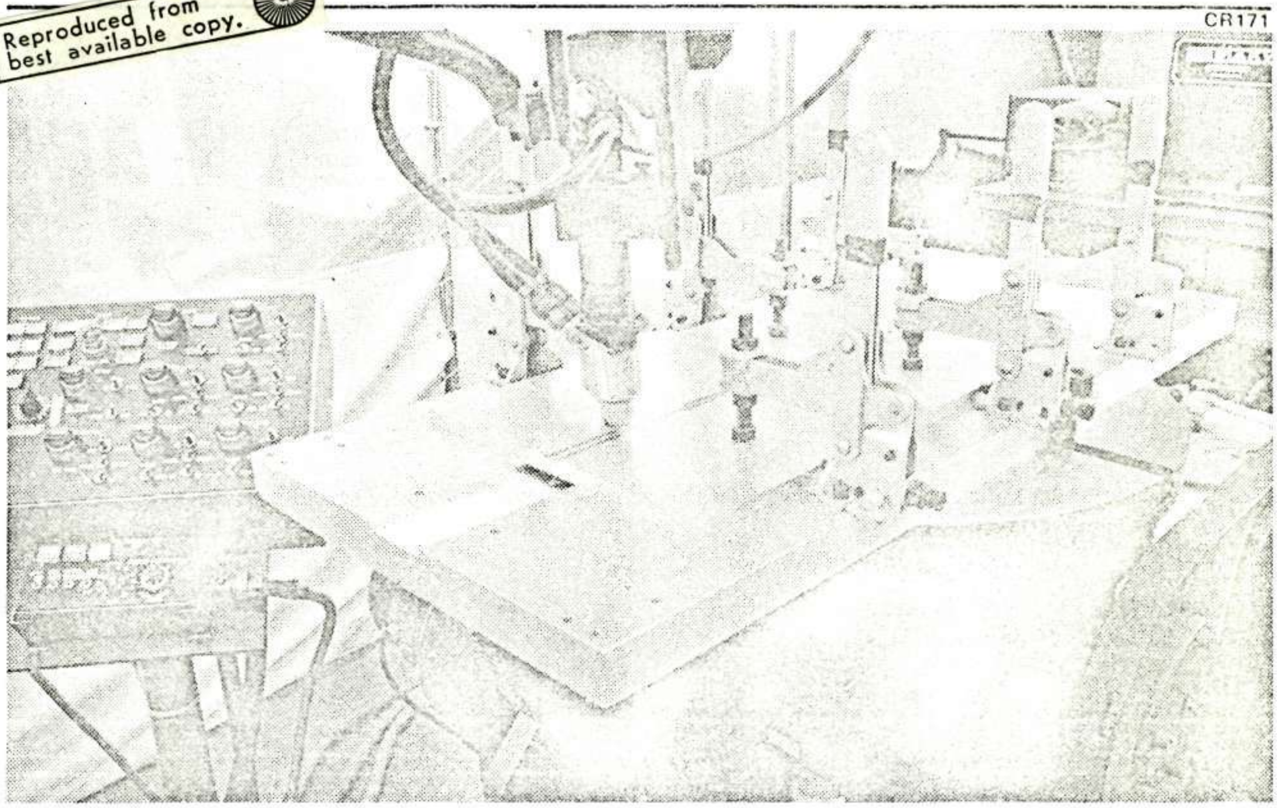


Figure 5. Welding Arrangement for Test Panels with Tapered Lack of Penetration

0.30 by 0.61 m (12 by 24 in.) 2219-T87 aluminum panel with a square-edge butt joint. Transverse sectioning revealed 1.27×10^{-3} m (5.0×10^{-2} in.) overlap of the root nodes of the two welds and a mistracking between the two of 1.02×10^{-3} m (4×10^{-2} in.).

Both sets of control panels, 0102 and 0304, were tack-welded 0.038m (1.5 in.) from the far end and then satisfactorily welded up to the tack weld on both sides. Parameters used for these panels are shown on the N/C welder parameter sheet, Table 4. These panels were then mechanically shaved on both sides.

3.5.2.3 Development of Tapered Lack-of-Penetration Welds

The program requirement to produce a tapered lack-of-penetration condition in the first 0.152 m (6 in.) of the weld before overlap of the two opposing welds was met as follows. An N/C tape was prepared, in which a decreasing travel speed ramp was programmed. The bead-on-plate weld was initiated at 0.86 m/minute (34.0 ipm) and decreased in 0.038 m/minute (1.5 ipm) increments to a nominal run speed of 0.52 m/minute (20.5 ipm). A total of 10

Table 4

WELDING PARAMETERS—N/C WELDER

CURRENT SOURCE	TAPE	DIAL
INITIAL ~~CURRENT IN AMPS~~ VOLTAGE		265
INITIAL SLOPE IN SEC'S		0
FINAL ~~CURRENT IN AMPS~~ VOLTAGE		240
FINAL SLOPE IN SEC'S		100
CURRENT STOP DELAY IN SEC'S		0
SURGE SUPPRESSION SETTING		333
VOLT AMPERE CONTROL SETTING		175
BACKGROUND CURRENT PERCENT		---
GMA PULSED ARC SWITCH	ON	OFF
VOLT/AMPERE SWITCH	ON	OFF
CONSTANT CUR./CONST. POTEN./ SWITCH	CC	CP
OPEN CIRCUIT VOLTAGE SWITCH	85	150
POLARITY SWITCH	STR	REV
INDUCTANCE TAP SWITCH (FRONT)	1 2	3 4
INDUCTANCE JUMPER TAP (REAR)	PULSE	NO PULSE

PULSED ARC DRAWER	SEC'S	DIAL
PULSE START DELAY		--
PULSE STOP DELAY		-
PEAK CYCLES LEVEL #1 SETTING		-
BASE CYCLES LEVEL #2 SETTING		-
BASE CURRENT PERCENT SETTING		-
PULSE SWITCH	ON	OFF

ARC HEAD DRAWER & HIGH FREQ.	SEC'S	DIAL
HEAD LOCK DIAL		0
HEAD UNLOCK DIAL		0
RATE OF RESPONSE DIAL SETTING		-
POLARITY SWITCH	STR.	REV.
HIGH FREQUENCY INTENSITY SETTING		Hi
HIGH FREQUENCY SWITCH	ON	OFF

AUTOMATIC SEQUENCE DRAWER	SEC'S	DIAL
WIRE FEED START DELAY		0
WIRE FEED STOP DELAY		0
TRAVEL START DELAY	0.5	1.0
TRAVEL STOP DELAY		0
TORCH GAS PREFLOW	5	
TORCH GAS POSTFLOW	5	
TORCH GAS SWITCHOVER DELAY		-
TORCH GAS SWITCHOVER SWITCH	ON	OFF
GAS MIXTURE SWITCH	ON	OFF
TORCH GAS SWITCH	AUTO	OFF
BACK UP GAS SWITCH	AUTO	OFF
GAS TYPE SWITCH	He	A

PART OR TAPE NO.	CRAD 3
PROJECT NAME	Opaque Aid
WELDING ENGINEER	GRS
DEPT. NO. & GROUP	253, AFB1
DATE:	8/8/72

AXIS TRANSFER		
Z AXIS TO C AXIS	Z	C
A AXIS TO D AXIS	A	D
B AXIS TO E AXIS	B	E

WIRE FEED DRAWER		DIAL
GTA RETRACT DIAL SETTING		-
GMA APPROACH DIAL SETTING		8.5
SENSITIVITY DIAL SETTING		500
DAMPING DIAL SETTING		500
GTA/GMA SWITCH	GTA	GMA
CONSTANT/DEMAND SWITCH	CONST	DEM

PENDANT CONTROL	TAPE	DIAL
RUNNING CURRENT IN AMPS		
WIRE FEED SPEED IN IPM		330
VOLTAGE IN VOLTS		29.0
WELDING TRAVEL SPEED IPM		20.5
WELD OR SET UP SEQUENCE	OPER	SETUP
TRAVEL FEEDRATE OVERRIDE PERCENT		
WIRE FEED FEEDRATE OVERRIDE SETTING		
MANUAL OR TAPE DATA SWITCH	MAN	TAPE
TAPE MODE SWITCH & MCU SWITCH	ON	OFF
ARC HEAD SWITCH SETTING	LOCK	UNLOCK

TRAVEL SEQUENCE	DIAL	DIRECT	SEQ MAN	OFF ON
X AXIS			SEQ MAN	OFF ON
Y AXIS			SEQ MAN	OFF ON
Z OR C AXIS			SEQ MAN	OFF ON
A OR D AXIS			SEQ MAN	OFF ON
B OR E AXIS			SEQ MAN	OFF ON
WIRE FEED SPEED SWITCH			SEQ MAN	OFF ON

PURGE GAS	TYPE	CFH
TORCH PURGE GAS	He	80
BACKUP PURGE GAS	--	--
MIXTURE GAS	--	--
TRAIL SHIELD GAS	--	--

MISC. DATA	
FILLER WIRE TYPE	2319
FILLER WIRE DIA.	1/16
ELECTRODE TYPE	--
ELECTRODE DIA.	--
ELECTRODE EXTENSION	--
CONTACT TUBE SIZE	.081
CONTACT TUBE SETTING (INCHES)	5/16 drill
TYPE OF JOINT	Sq. Butt
TYPE OF MATERIAL	2219-T87
MATERIAL THICKNESS	0.5"

NOTES:

7.5° Torch Lead Angle

#10 Cup

blocks of tape data were required to produce this condition. The wire feed speed and arc voltage were held constant. Subsequent examination of a longitudinal section through the center of the weld showed virtually no tapering in the weld bead penetration.

Therefore, another tape was prepared in which the arc voltage and commensurate wire feed speed were successively increased to accompany the decreasing travel of the torch as in the previous tape program. Examination of a longitudinal section of this weld again failed to reveal much taper in the weld bead penetration. In addition, it showed that for every incremental increase in wire feed speed, a surge on spiking in the weld bead occurred. This phenomenon was believed due to a loss in the reference signal as the electromechanical relays in the N/C machine control unit received new data. The changes in arc voltage which occurred on alternate blocks of tape data were smooth and free of any disturbances.

As a result of this finding, a further tape was prepared wherein the wire feed changes were eliminated and only the arc voltage and travel speed were varied. In addition, the overall travel speed was increased in the tapered region starting at 1.27 m/minute (50 ipm) and decreased in seven successive blocks of tape data to 0.51 m/minute (20 ipm). A longitudinal section again revealed very little taper in weld penetration over the first 0.15 m (6 in.) of the weld. This finding demonstrated that the reduction in arc power (arc voltage times welding current) only tended to neutralize the increased heating effect of the decreasing travel speed in the tapered region.

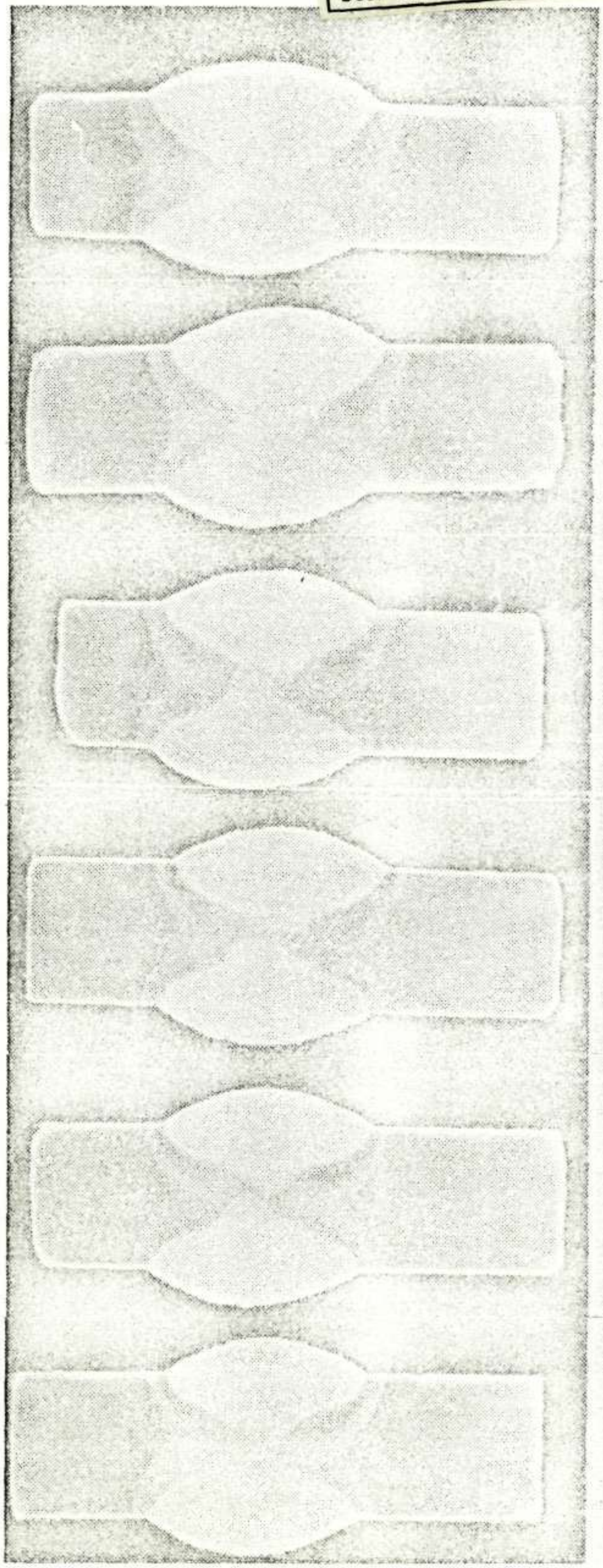
Therefore, to obtain more tapering in the weld penetration, it was decided to increase arc power and reduce travel speed in the tapered region for maximum effect. This was accomplished by starting the arc at a very low arc voltage and then increasing it sequentially up to the run voltage in five steps. Having such a short arc voltage while maintaining a constant high rate of filler wire feed speed results in an extremely short arc condition accompanied by fine weld spatter. This arc behavior is typical when welding in the transition region between short-circuiting and spray-arc conditions. Thus, the revised N/C tape was used to make a bead-on-plate weld on opposite sides of the plate. Longitudinal sectioning of these welds revealed a smooth taper in weld bead penetration with marginal overlap of the two beads occurring 0.15 m (6 in.) from the weld start.

Several successive tapes with slight modifications to arc voltage and travel speed were made to ensure a more positive weld overlap condition at the 0.15 m (6 in.) point and to maintain this condition for the remainder of the weld. It was also found that by programming a wire-feed speed increase in the proximity of the weld overlap point, the spiking condition associated with it could be used to advantage, as discussed previously.

3.5.2.4 Welding of Plasma Sprayed Copper Coated Panels

The developed N/C tape was expanded to include a tack weld sequence and a movement back to the weld start point to weld the 0.457 m (18 in.) long panels, which had been plasma-sprayed with copper to a thickness of approximately 5.08×10^{-5} m (2×10^{-3} in.). Before welding, the panels were wiped clean with acetone, the edges broken by draw filing, and the top and bottom surfaces power-wire-brushed as an assembly to avoid removal of the copper coating. Panels 27 and 28 were then welded together. During the weld, the arc behavior was highly irregular in that it gouged in a cutting fashion in the tapered region and then pumped periodically during the remainder of the weld. The weld on the opposite side of this panel did not pump as severely, possibly as a result of less unalloyed copper present in the joint.

The presence of approximately 10.16×10^{-5} m (4×10^{-3} in.) of copper in the weld interface had such an adverse effect on arc stability that it was decided to investigate its effect on separate weld specimens. Thus, some 12.7×10^{-5} m (5×10^{-3} in.) thick copper foil was placed in the joint interface between two 0.0127 m (0.5 in.) thick by 0.152 m (6 in.) wide by 0.457 m (18 in.) long 2219-T87 aluminum weld specimens. New N/C tapes were prepared, in which six values of wire feed speed were programmed with a constant arc voltage. The first side of the panel was welded with, from an arc stability standpoint, an optimal wire feed speed of 8.64 m/minute (340 ipm). Thus, the second side of the panel was welded with this wire feed speed held constant while the arc voltage was programmed in six equal steps from 26.7 to 29 v. Optimum arc stability was obtained when the voltage was 27.9. Transverse sections through each condition are shown in Figure 6 along with the values of arc voltage and wire feed speed employed. The upper



WF	VOLTAGE
360	29.7
340	26.7
350	29.7
340	27.3
340	29.7
340	27.9
330	29.7
340	28.5
320	29.7
340	29.1
310	29.7
340	29.7

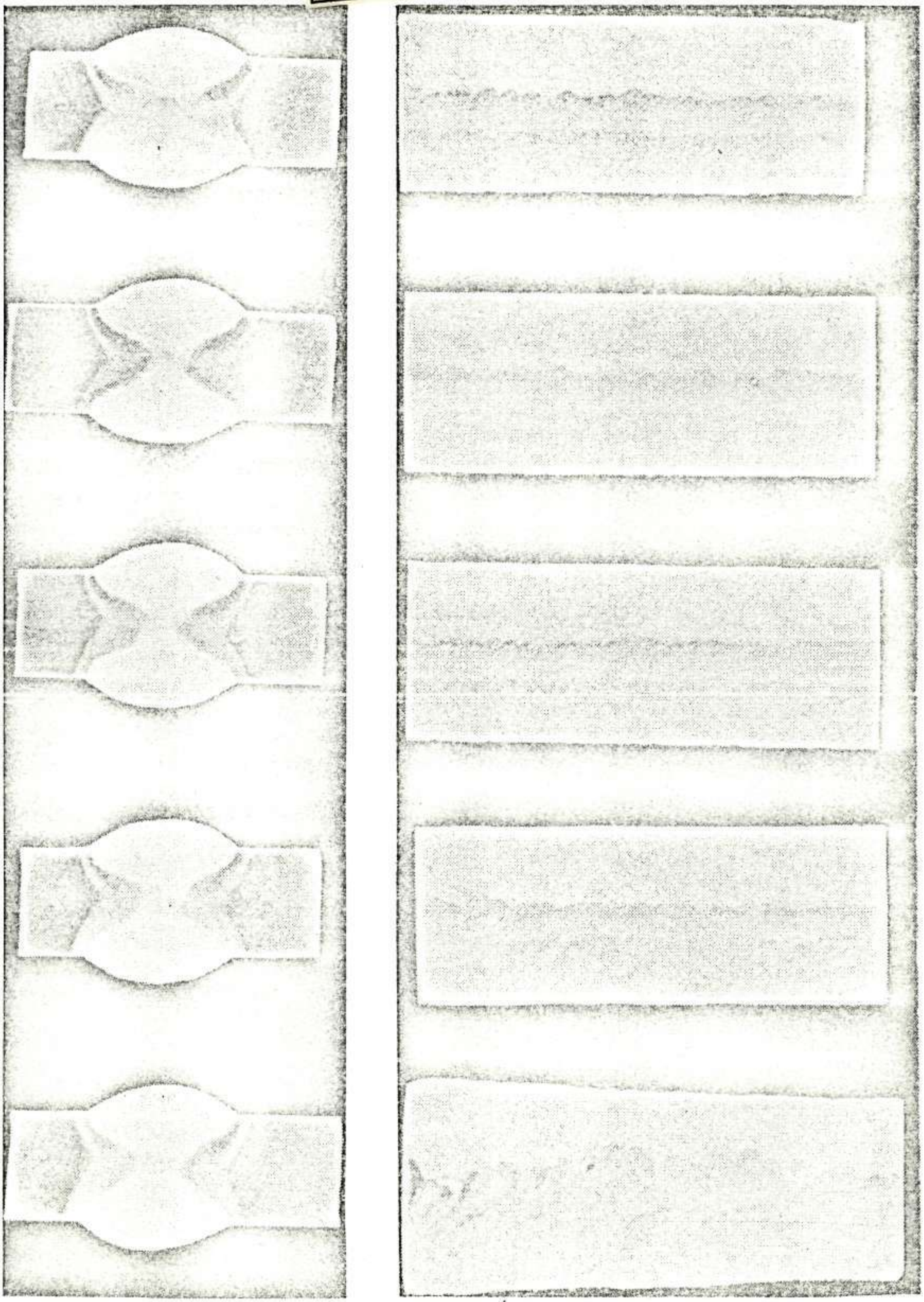
Figure 6. Variable Wire Feed and Arc Voltage Test with 5-Mil Copper Implant

welds on the first side revealed an expected reduction in penetration as wire feed speed was reduced. The lower second side welds were slightly mistracked and revealed a characteristic spiking in the root bead node as the arc voltage was reduced below 27.9. This phenomenon is contrary to what usually occurs when the voltage of a GMA spray arc weld is reduced. The presence of copper in this case produced the greatest penetration at the lowest arc power. The only explanation that can be offered is that copper ions in the arc plasma tended to collimate the arc in the center region and in effect increase the current density.

To obtain optimal values of wire feed speed and arc voltage, another N/C test tape was prepared in which the arc voltage was varied in five steps over a narrower range. Another panel containing a 12.7×10^{-5} m (5×10^{-3} in.) thick copper foil implant was welded with a wire feed speed on the first side of 8.89 m/minute (350 imp) and 8.75 m/minute (345 imp) on the second. These weld segments were sectioned both transversely and longitudinally as shown in Figure 7. It again shows that penetration increases as voltage is reduced. The longitudinal sections portray the degree of spiking or surging in the arc. At 27.2 v (start of the weld), spiking was excessive; otherwise it was relatively uniform, especially at the 27.8-v level. (Spiking can only be examined on the second side weld because of overlap.) Therefore, a new N/C tape was prepared, incorporating these lower values of arc voltage and wire feed speed for the primary weld, and reducing these values in the tapered regions accordingly. The tape was checked by making a bead-on-plate weld on bare plate, and it operated smoothly. Then the second set of plasma-sprayed, copper-coated specimens, 29 and 30, was prepared as before and welded with this revised tape. Arc instability was so severe that the arc penetrated the plate at the end of the tapered lack-of-fusion region. At this juncture, further efforts were abandoned for the 5.08×10^{-5} m (2×10^{-3} in.) thick plasma-coated specimens.

3.5.2.5 Welding of Vacuum-Vapor-Deposited, Copper-Coated Panels

Before proceeding directly to the welding of the vacuum-vapor-deposited copper-coated panels, preliminary tests were run with a 2.54×10^{-5} m (1×10^{-3} in.) thick copper foil implant in the joint. The final N/C tape prepared for the 5.08×10^{-5} m (2×10^{-3} in.) thick plasma copper-coated



Voltage
28.4
28.1
27.8
27.5
27.2

Note: Wire Feed Speed | 350 ipm for first side weld
| 345 ipm for second side weld

Figure 7. Variable Voltage Test (Constant Wire Feed) with 5-Mil Copper Implant

specimens was used and ran quite well. A longitudinal section revealed weld overlap occurred 0.163 m (6.4 in.) after weld start with a spike-type closure just ahead of it at 0.155 m (6.1 in.). Thus, some minor changes were made to travel speed and arc voltage in the block of tape data affecting that region. This new tape was used to weld another panel with a 2.54×10^{-5} m (1×10^{-3} in.) copper foil implant. Arc operation was stable, as were the oscillograph traces of arc voltage, weld current, and wire feed speed. A longitudinal and transverse section of this weld is depicted in Figure 8. The transverse section shows adequate weld overlap (0.009 m (0.35 in.) total penetration on the second side weld), and a tapered lack-of-fusion condition in the longitudinal specimen with bead overlap occurring 0.156 m (6.15 in.) from weld start.

The N/C printout for this weld is shown in Table 5, with some of the key welding parameters listed in the right column. The other welding conditions are detailed in the N/C welding parameter data sheet shown in Table 6.

Having verified penetration and taper, the vacuum-vapor-deposited specimens were prepared for welding. Each specimen was wiped clean with clean, lint-free cloths dampened with acetone. The edges were broken with a draw file and then assembled in the weld fixture where both the top and bottom surfaces of the joint were power-wire-brushed.

This procedure was employed for all the panels copper-coated by vacuum vapor deposition. Panels 05, 06, 07, and 08, which were coated to a thickness of 5.08×10^{-6} m (2×10^{-4} in.), were welded with the tape and data of Tables 5 and 6. Panels 09, 10, 11, and 12, which were coated to a thickness of 12.7×10^{-6} m (5×10^{-4} in.), were welded in the same manner except for an increase in torch distance of 0.84×10^{-2} m (3.28×10^{-1} in.) to 0.86×10^{-2} m (3.4×10^{-1} in.).

This additional wire length creates more resistance heating in the filler wire and reduces the current density of the arc, which was found necessary to stabilize the arc for the heavier copper concentration. In like manner, the torch distance was increased from 0.86×10^{-2} m (3.44×10^{-1} in.) to 0.95×10^{-2} m

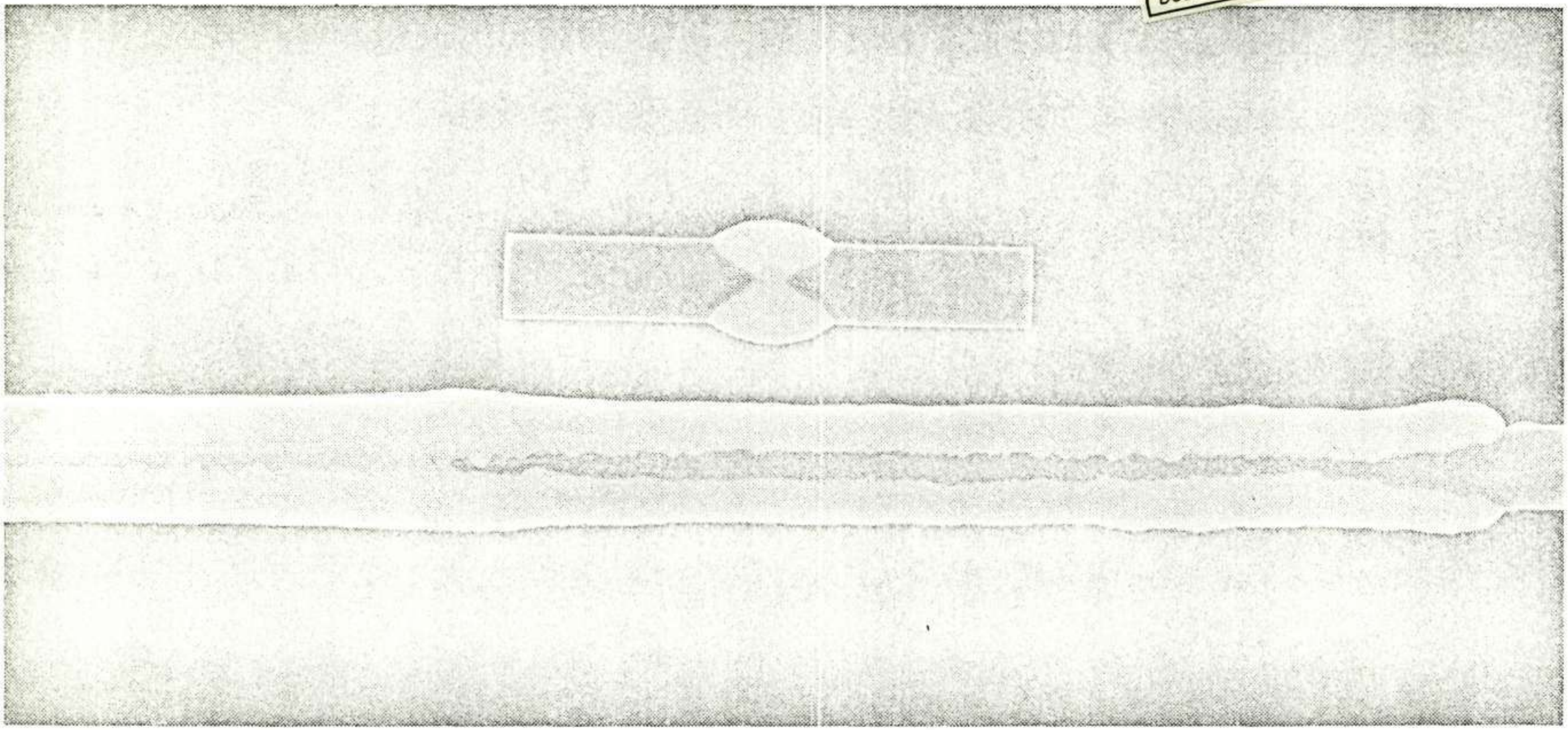


Figure 8. Longitudinal and Transverse Sections of Tapered Lack-of-Fusion with a 1-Mil Copper Implant

Table 5

N/C TAPE PRINTOUT FOR GMA WELDING 0.6/m (24 IN.) VACUUM-VAPOR-DEPOSITED, COPPER-COATED 2219-T87 ALUMINUM TAPE NO. 929

n01						
t10440						Tack Weld Parameters
t20300						
t30000						
t40043						
t50038						
t60077						
t70001						
t80001						
m00						
m81						
g08x20000f637						Tack Weld Movement
m82						
m00						
n02						
g08x-230000f935						Torch Return Movement
m00						
n03						
t10375						Primary Weld Parameters
t20327						
t30000						
t40043						
t50038						
t60077						
t70001						
t80001						
m00		Wire Speed		Travel Speed		
m81	Arc-Volts	(m/minute)	(ipm)	(m/minute)	(ipm)	
g08x20000f1470		9.14	360	1.12	44	*
x11000f1140				0.97	38	*
x11000f1060t10408	24.5			0.89	35	*
x11000f970t10423	25.4			0.81	32	*
x7000f600t10438	26.3			0.64	25	*
x8500f630t20360				0.41	16	*
x141500f720t10494	29.6			0.48	19	*
m82						
m00						

*Tapered Lack-of-Fusion Weld Movement

Table 6

WELDING PARAMETERS—N/C WELDER

CURRENT SOURCE	TAPE	DIAL
INITIAL CURRENT IN AMPS	X	
INITIAL SLOPE IN SEC'S	X	
FINAL CURRENT IN AMPS	X	
FINAL SLOPE IN SEC'S	X	
CURRENT STOP DELAY IN SEC'S	X	
SURGE SUPPRESSION SETTING	400	
VOLT AMPERE CONTROL SETTING	175	
BACKGROUND CURRENT PERCENT	X	
GMA PULSED ARC SWITCH	ON	OFF
VOLT/AMPERE SWITCH	ON	OFF
CONSTANT CUR./CONST. POTEN./ SWITCH	CC	CP
OPEN CIRCUIT VOLTAGE SWITCH	85	150
POLARITY SWITCH	STR	REV
INDUCTANCE TAP SWITCH (FRONT)	1 2	3 4
INDUCTANCE JUMPER TAP (REAR)	PULSE	NO PULSE

PULSED ARC DRAWER	SEC'S	DIAL
PULSE START DELAY	--	--
PULSE STOP DELAY	--	--
PEAK CYCLES LEVEL #1 SETTING		--
BASE CYCLES LEVEL #2 SETTING		--
BASE CURRENT PERCENT SETTING		--
PULSE SWITCH	ON	OFF

ARC HEAD DRAWER & HIGH FREQ.	SEC'S	DIAL
HEAD LOCK DIAL	0	0
HEAD UNLOCK DIAL	0	0
RATE OF RESPONSE DIAL SETTING		400
POLARITY SWITCH	STR.	REV
HIGH FREQUENCY INTENSITY SETTING		High
HIGH FREQUENCY SWITCH	ON	OFF

AUTOMATIC SEQUENCE DRAWER	SEC'S	DIAL
WIRE FEED START DELAY	0	0
WIRE FEED STOP DELAY	0	0
TRAVEL START DELAY	0	0
TRAVEL STOP DELAY	0	0
TORCH GAS PREFLOW	4	8
TORCH GAS POSTFLOW	3	6
TORCH GAS SWITCHOVER DELAY	-	-
TORCH GAS SWITCHOVER SWITCH	ON	OFF
GAS MIXTURE SWITCH	ON	OFF
TORCH GAS SWITCH	AUTO	OFF
BACK UP GAS SWITCH	AUTO	OFF
GAS TYPE SWITCH	He	A

PART OR TAPE NO.	9/29/72
PROJECT NAME	GMA CRAD
WELDING ENGINEER	GRS
DEPT. NO. & GROUP	AFB1
DATE:	10/2/72

AXIS TRANSFER		
Z AXIS TO C AXIS	Z	C
A AXIS TO D AXIS	A	D
B AXIS TO E AXIS	B	E

WIRE FEED DRAWER		DIAL
GTA RETRACT DIAL SETTING		0
GMA APPROACH DIAL SETTING		1.25
SENSITIVITY DIAL SETTING		500
DAMPING DIAL SETTING		500
GTA/GMA SWITCH	GTA	GMA
CONSTANT/DEMAND SWITCH	CONST	DEM

PENDANT CONTROL	TAPE	DIAL
RUNNING CURRENT IN AMPS	X	
WIRE FEED SPEED IN IPM	X	
VOLTAGE IN VOLTS	X	
WELDING TRAVEL SPEED IPM	X	
WELD OR SET UP SEQUENCE	OPER	SETUP
TRAVEL FEEDRATE OVERRIDE PERCENT	100	
WIRE FEED FEEDRATE OVERRIDE SETTING	0	
MANUAL OR TAPE DATA SWITCH	MAN	TAPE
TAPE MODE SWITCH & MCU SWITCH	ON	OFF
ARC HEAD SWITCH SETTING	LOCK	UNLOCK

TRAVEL SEQUENCE	DIAL	DIRECT	SEQ MAN	OFF ON
X AXIS			SEQ MAN	OFF ON
Y AXIS			SEQ MAN	OFF ON
Z OR C AXIS			SEQ MAN	OFF ON
A OR D AXIS			SEQ MAN	OFF ON
B OR E AXIS			SEQ MAN	OFF ON
WIRE FEED SPEED SWITCH			SEQ MAN	OFF ON

PURGE GAS		TYPE	CFH
TORCH PURGE GAS	Tri Mix		40
BACKUP PURGE GAS		--	--
MIXTURE GAS		--	--
TRAIL SHIELD GAS		--	--

MISC. DATA	
FILLER WIRE TYPE	2319
FILLER WIRE DIA.	.063
ELECTRODE TYPE	----
ELECTRODE DIA.	----
ELECTRODE EXTENSION	----
CONTACT TUBE SIZE	.081
CONTACT TUBE SETTING (INCHES)	21/64-3/8
TYPE OF JOINT	Butt
TYPE OF MATERIAL	2219
MATERIAL THICKNESS	0.500"

NOTES:

Cup-to-work distance varied with amount of Cu

2 mil - 21/64
5 mil - 11/32
8 mil - 3/8

5° Torch Lead Angle

(3.75×10^{-1} in.) for welding panels 13, 14, 15, and 16. These panels had been coated to a thickness of 20.32×10^{-6} m (8×10^{-4} in.).

Each panel welded was cooled to ambient temperature between welds, and an oscillograph recording was made of travel speed, arc voltage, wire feed speed, and welding current. All completed panels including panel 2728 (plasma-spray copper coated) were mechanically shaved on both sides to 2.54×10^{-4} m (1×10^{-2} in.) reinforcement and submitted for x-ray inspection.

3.5.3 Summary

The welding development portion of this phase of work demonstrated that the N/C GMA welding process was effective in producing a tapered lack-of-fusion condition in an 0.0127 m (0.5 in.) thick 2219-T87 aluminum butt joint. It was further shown that as the copper-coating concentration in the joint increases, the arc dynamics are affected. For the same level of arc power, penetration and arc instability are greater in a joint containing copper than in one devoid of it. It was also found that weld penetration increases as arc voltage decreases in an aluminum joint containing a copper-foil implant. This behavior is anomalous, in that a reduction in arc voltage is usually accompanied by a penetration reduction in spray arc welding of aluminum.

3.6 NONDESTRUCTIVE TESTING

After the panel welding had been completed and the weld bead mechanically shaved on each surface, all weldments were inspected using film radiography (x-ray). The work was done using a Norelco constant-potential unit of 300-kv maximum voltage. The exposures were made using 70-mm M film (Kodak) with a lead screen. The panels were arranged with a distance of 1.52 m (60 in.) between source and film. The exposures were made for 2 minutes at 100 kv and 15 ma. Exposed film was processed automatically by a Kodak X-omat unit.

The two test panels welded to produce a satisfactory full-penetration weldment contained only a few scattered indications of porosity. None of these indications was cause for rejection. There were no indications of cracks in either test panel and both were considered suitable for baseline mechanical properties testing. These two panels were designated 0102 and 0304.

The results of inspecting the copper-coated panel weldments are summarized in Table 7. In all cases, the remaining copper was clearly shown in the areas of weldment lack of penetration. Examples of this are shown in Figure 9, which includes x-ray positive prints of weldments made with all three thicknesses of vacuum-vapor-deposited copper. These prints clearly show that even the thinnest copper coating, 5.08×10^{-6} m (2×10^{-4} in.), was sufficient to indicate those areas where full penetration was not accomplished. Furthermore, it should be noted that the porosity in the weldments was within acceptable limits. This indicates that the aluminum surface was indeed protected by the copper, and that formation of aluminum oxide had been stopped or severely inhibited.

The protective quality of the vacuum-vapor-deposited copper coating can be anticipated if a review is made of the delay between actual copper coating and the welding of the test panels. The vacuum vapor deposition was completed at MDAC-East on 13 September 1972. The welding was not performed until 29 September 1972, a period of over two weeks. During that time, no special care was taken to protect the copper-coated surfaces. The panels were wrapped in paper to keep out dust and fingerprints. The two-week period is several times that permitted by specification after cleaning in preparation for welding aluminum.

The resulting weldments showed no rejectable porosity. The panels which had the thinnest copper coating, 5.08×10^{-6} m (2×10^{-4} in.), had the least porosity of any of the welded panels. Therefore, it must be assumed that the vacuum-vapor-deposited copper coating provides adequate protection for at least a two-week storage period. Sections of the coated samples showed the copper coating to be uniform and without porosity or cracks. Based on this it might be expected that the coating would provide good protection for much longer times, perhaps several months. Phase II of this program will assess the protective quality of the coating over a 60-day period.

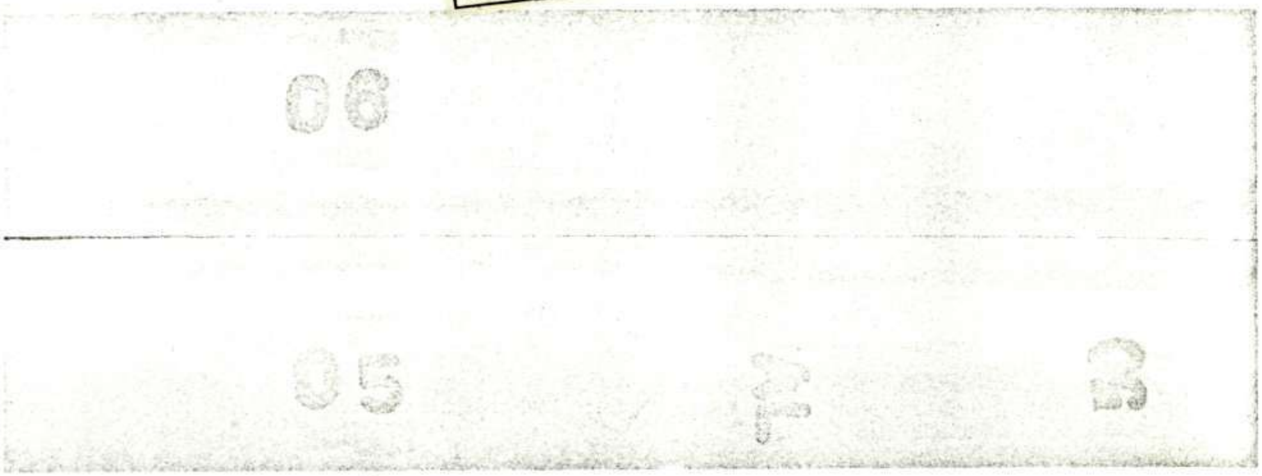
Thus far we have established empirically that copper coating as thin as 5.08×10^{-6}m (2×10^{-4} in.) on each of two abutting surfaces can be easily detected in x-rays of weldments containing intentional incomplete penetration. Since this was the thinnest copper coating evaluated, it seems the most logical selection for the work to be performed in Phase II.

Table 7

SUMMARY OF X-RAYS OF WELDED PANELS CONTAINING COPPER

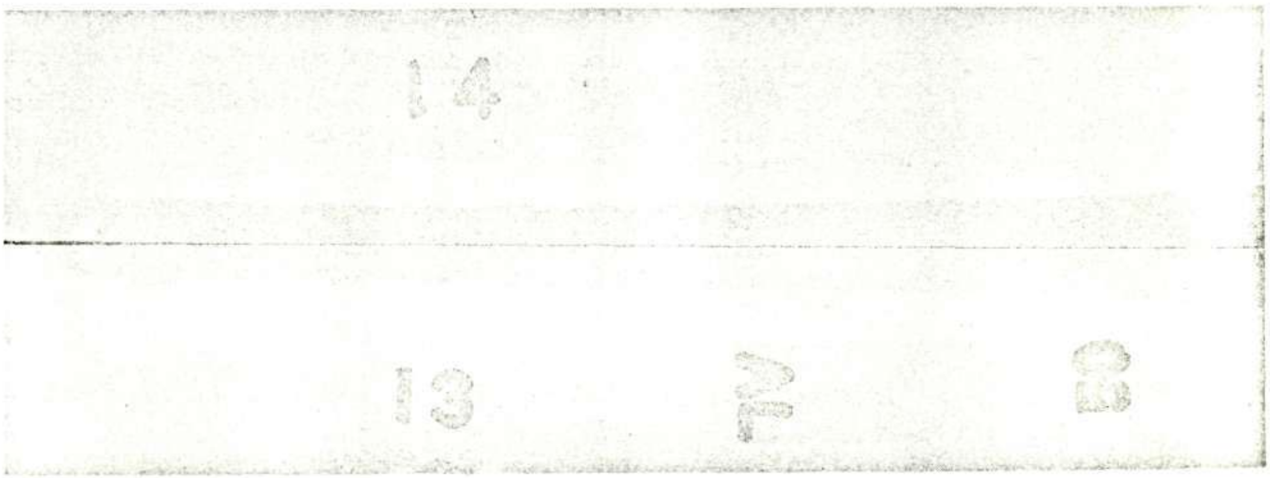
Panel No.	Comments	
0506 5.08×10^{-6} m Cu (2×10^{-4} in.)	Clear indication of remaining copper	One small pore in remainder of weldment
0708 5.08×10^{-6} m Cu (2×10^{-4} in.)	Clear indication of remaining copper	Three small pores in remainder of weldment
0910 12.7×10^{-6} m Cu (5×10^{-4} in.)	Very clear indication of remaining copper	Ten scattered pores in remainder of weldment
1112 12.7×10^{-6} m Cu (5×10^{-4} in.)	Very clear indication of remaining copper	Seven pores within 5 in. of end of copper. Three more scattered pores
1314 19.3×10^{-6} m Cu (8×10^{-4} in.)	Very clear indication of remaining copper	Nine pores within 6 in. of end of copper. One more pore in remainder of weldment
1516 19.3×10^{-6} m Cu (8×10^{-4} in.)	Very clear indication of remaining copper	Ten pores within 6 in. of end of copper. Four more scattered pores
Note: All of above panels had copper deposited by vacuum vapor deposition.		
2728 5.08×10^{-5} m Cu (2×10^{-3} in.) by plasma spray	Copper clearly indicated although lack of penetration area very confused	There were several scattered pores

There are, however, several factors affecting the x-ray inspection of weldments containing copper as an opaque additive. There will be some thickness of copper in the direction of the aluminum panel thickness that cannot be detected because of the x-ray sensitivity limitations. Further, the copper at the abutting surfaces is very thin, and an x-ray taken at some angle other than normal to the aluminum surface will not detect copper remaining in a zone of incomplete penetration. These two questions can be addressed



a) Weldment of Panels with 5.08×10^{-6}m (0.0002 in.) Copper on the Abutting Surfaces (0506)

b) Weldment of Panels with 12.70×10^{-6}m (0.0005 in.) Copper on the Abutting Surfaces (0910)



c) Weldment of Panels with 20.32×10^{-6}m (0.0008 in.) Copper on the Abutting Surfaces (1314)

Figure 9. X-Ray Positive Prints of Lack of Penetration Weldments

both empirically and by analysis, and should be settled before the opaque additive concept is put to practical use.

3.7 MECHANICAL PROPERTIES TESTING

The welded panels were all coded with four-digit numbers derived from the original panel numbers. All tensile and bend test specimens were numbered using the welded panel code plus the letters T for tensile and B for bend.

The tensile specimens were constant-section and were cut approximately 0.0508 m (2 in.) wide. The bend specimens were cut approximately 0.019 m (0.75 in.) wide. The length of all specimens was 0.305 m (12 in.), which was the width of all the welded panels.

Both series of tests (tensile and bend) were conducted on a Baldwin Universal Testing Machine of 266,880 N (60,000 lb) maximum capacity. The tensile tests were conducted measuring load and strain, both of which were recorded autographically as the test was conducted. A 0.0508 m (2 in.) gage length breakaway extensometer was employed. The extensometer is a multiple-magnification instrument; the elastic portion of the recording can be made at a high magnification and the remainder at a lower magnification. This permitted recording of the complete load-versus-strain curve from start to failure.

The results of the tensile tests of the control specimens from panel 0102 are presented in Table 8. The results of the tensile tests of the weldments made with copper deposited on the faying surfaces are presented in Table 9.

The statistical evaluation was based on tensile yield (0.2-percent offset) values from Tables 8 and 9. It was determined that all seven populations had equal variances at the 5-percent level of significance. The populations consisted of the control group from panel 0102 and the six groups (0506, 0708, 0910, 1112, 1314, and 1516) which were welded from panels coated with various thicknesses of copper. The calculations were made as outlined in Reference 5 to test the hypothesis that the variances of the populations were equal. This indeed proved to be the case and indicates that the effect of the additive copper is very slight.

Table 8

TENSILE DATA FOR WELDMENTS WITHOUT COPPER

Specimen Code	Yield Strength (0.2 Percent Offset) N/m^2	Yield Strength (0.2 Percent Offset) psi	Ultimate Tensile Strength N/m^2	Ultimate Tensile Strength psi	Percent Elongation 0.0508 m (2 in.) Gage
0102T1	141.3×10^6	20.5×10^3	265.9×10^6	38.6×10^3	6.0
0102T2	154.3×10^6	22.4×10^3	276.1×10^6	40.0×10^3	5.5
0102T3	160.9×10^6	23.3×10^3	273.5×10^6	39.7×10^3	5.5
0102T4	158.1×10^6	22.9×10^3	271.5×10^6	39.4×10^3	5.0
0102T5	156.6×10^6	22.7×10^3	273.4×10^6	39.7×10^3	5.0
0102T6	152.2×10^6	22.1×10^3	273.0×10^6	39.6×10^3	5.0
0102T7	160.3×10^6	23.3×10^3	259.0×10^6	37.6×10^3	5.0
Average	154.8×10^6	22.5×10^3	270.3×10^6	39.3×10^3	5.3

Table 9

TENSILE DATA FOR WELDMENTS WITH VARIOUS THICKNESSES OF COPPER ADDED

Specimen Code	Yield Strength (0.2 Percent Offset) (N/m^2)	Yield Strength (0.2 Percent Offset) (psi)	Ultimate Tensile Strength (N/m^2)	Ultimate Tensile Strength (psi)	Percent Elongation 0.0508 m (2 in.) Gage
0506 T1	142.7×10^6	20.7×10^3	260.0×10^6	37.7×10^3	6.0
0506 T2	144.3×10^6	20.9×10^3	267.5×10^6	38.8×10^3	7.0
0506 T3	143.7×10^6	20.8×10^3	266.5×10^6	38.7×10^3	6.0
0506 T4	148.1×10^6	21.5×10^3	258.8×10^6	37.5×10^3	6.0
Average	144.7×10^6	21.0×10^3	263.2×10^6	38.2×10^3	6.3
0708 T1	145.1×10^6	21.0×10^3	256.1×10^6	37.2×10^3	6.0
0708 T2	140.7×10^6	20.4×10^3	258.0×10^6	37.4×10^3	5.5
0708 T3	145.7×10^6	21.1×10^3	267.6×10^6	38.8×10^3	6.5
0708 T4	147.3×10^6	21.4×10^3	252.6×10^6	36.6×10^3	5.0
0708 T5	150.7×10^6	21.9×10^3	268.1×10^6	38.9×10^3	6.0
Average	145.9×10^6	21.2×10^3	260.5×10^6	37.8×10^3	5.8

Table 9

TENSILE DATA FOR WELDMENTS WITH VARIOUS THICKNESSES OF COPPER ADDED (Continued)

Specimen Code	Yield Strength (0.2 Percent Offset)		Ultimate Tensile Strength		Percent Elongation 0.0508 m (2 in.) Gage
	(N/m^2)	(psi)	(N/m^2)	(psi)	
0910T1	151.2×10^6	21.9×10^3	259.9×10^6	37.7×10^3	6.0
0910T2	152.6×10^6	22.1×10^3	265.6×10^6	38.5×10^3	6.0
0910T3	149.8×10^6	21.7×10^3	264.6×10^6	38.4×10^3	6.0
0910T4	137.6×10^6	20.0×10^3	259.0×10^6	37.6×10^3	5.5
Average	147.8×10^6	21.4×10^3	262.3×10^6	38.1×10^3	5.9
1112T1	151.3×10^6	21.6×10^3	265.1×10^6	38.5×10^3	5.0
1112T2	143.2×10^6	20.8×10^3	262.7×10^6	38.1×10^3	5.0
1112T3	149.4×10^6	21.7×10^3	265.5×10^6	38.5×10^3	6.0
1112T4	148.2×10^6	21.5×10^3	261.3×10^6	37.9×10^3	5.5
Average	148.0×10^6	21.4×10^3	263.7×10^6	38.3×10^3	5.4

Table 9

TENSILE DATA FOR WELDMENTS WITH VARIOUS THICKNESSES OF COPPER ADDED (Continued)

Specimen Code	Yield Strength (0.2 Percent Offset) (N/m^2)	(psi)	Ultimate Tensile Strength (N/m^2)	(psi)	Percent Elongation 0.0508 m (2 in.) Gage
1314T1	144.1×10^6	20.9×10^3	260.9×10^6	37.8×10^3	5.0
1314T2	145.8×10^6	21.1×10^3	259.5×10^6	37.6×10^3	6.0
1314T3	149.9×10^6	21.7×10^3	261.9×10^6	38.0×10^3	5.0
1314T4	148.4×10^6	21.5×10^3	263.1×10^6	38.2×10^3	5.0
1314T5	148.6×10^6	21.5×10^3	260.6×10^6	37.8×10^3	5.0
Average	147.4×10^6	21.3×10^3	261.2×10^6	37.9×10^3	5.2
1516T1	155.2×10^6	22.5×10^3	256.5×10^6	37.2×10^3	5.5
1516T2	152.4×10^6	22.1×10^3	258.0×10^6	37.4×10^3	5.5
1516T3	153.8×10^6	22.3×10^3	265.3×10^6	38.5×10^3	4.0
1516T4	151.4×10^6	22.0×10^3	264.5×10^6	38.4×10^3	5.0
1516T5	153.3×10^6	22.2×10^3	263.2×10^6	38.2×10^3	5.5
Average	153.2×10^6	22.2×10^3	261.5×10^6	37.9×10^3	5.1

Table 9

TENSILE DATA FOR WELDMENTS WITH VARIOUS THICKNESSES OF COPPER ADDED (Continued)

Specimen Code	Yield Strength (0.2 Percent Offset) (N/m^2)	(psi)	Ultimate Tensile Strength (N/m^2)	(psi)	Percent Elongation 0.0508 m (2 in.) Gage
2728T1	148.2×10^6	21.5×10^3	258.6×10^6	37.5×10^3	5.5
2728T2	146.1×10^6	21.2×10^3	249.6×10^6	36.2×10^3	5.0
2728T3	146.4×10^6	21.2×10^3	251.8×10^6	36.5×10^3	5.0
Average	146.9×10^6	21.3×10^3	253.3×10^6	36.7×10^3	5.2

The bend tests were conducted in a 266, 880 N (60, 000 lb) maximum capacity universal testing machine, in accordance with ASTM E16-64, Standard Method of Free Bend Test for Ductility of Welds. However, all specimens failed, developing cracks in the weldment and sharp load reductions during the initial "prebending" procedure. This occurred on both groups of specimens, the control group which was taken from panel 0102 (no copper added) and the remainder of samples which were taken from the panels having various thicknesses of copper on the abutting welded surfaces.

The data from the control group are presented in Table 10; the data from the group having a copper additive are presented in Table 11. In all cases, the failure loads were slightly higher for those specimens containing the copper additive. However, the percent elongations were slightly less and the included angles somewhat greater. This indicates a slight decrease in ductility for the weldments containing added copper. Based on measurement of the included angle of the bent specimen after springback, the change was less than 3 percent on the average. The increase in load at failure was between 1 and 2 percent on the average.

Table 10

BEND TEST DATA FOR CONTROL SPECIMENS, PANEL 0102

Specimen Code	Load at Failure		Percent Elong 0.0127 in. (1/2 in.) Gage	Included Angle	
	N	lb		Rad	Deg
0102B1	--	--	28	2.443	140
0102B2	--	--	32	2.269	130
0102B3	12,610	2,835	30	2.443	140
0102B4	12,588	2,830	28	2.530	145
0102B5	12,944	2,910	30	2.443	140
0102B6	13,722	3,085	28	2.530	145
0102B7	13,678	3,075	26	2.530	145
Average	13,108	2,947	29	2.455	141

Table 11

BEND TEST DATA FOR SPECIMENS WELDED WITH COPPER ADDITIVE

Specimen Code	Load at Failure		Percent Elong 0.0127 m (1/2 in.) Gage	Included Angle	
	N	lb		Rad	Deg
0506B1	13,010	2,925	22	2.618	150
0506B2	14,189	3,190	26	2.530	145
0506B3	14,056	3,160	26	2.356	135
0506B4	15,501	3,485	30	2.443	140
Average	14,189	3,190	26	2.487	143
0708B1	15,479	3,480	22	2.618	150
0708B2	14,100	3,170	22	2.443	140
0708B3	15,501	3,485	26	2.530	145
0708B4	16,769	3,770	24	2.443	140
Average	15,462	3,476	24	2.509	144
0910B1	15,701	3,530	28	2.530	145
0910B2	14,678	3,300	20	2.705	155
0910B3	15,879	3,570	24	2.618	150
0910B4	15,212	3,420	24	2.618	150
Average	15,368	3,455	24	2.618	150
1112B1	16,858	3,790	26	2.443	140
1112B2	15,879	3,570	28	2.530	145
1112B3	16,124	3,625	28	2.530	145
1112B4	16,769	3,770	26	2.443	140
Average	16,408	3,689	27	2.487	143
1314B1	15,056	3,385	24	2.618	150
1314B2	14,367	3,230	22	2,530	145
1314B3	16,613	3,735	26	2.530	145
1314B4	16,102	3,620	32	2.303	132
Average	15,535	3,493	26	2.495	143
1516B1	14,412	3,240	22	2.618	150
1516B2	12,188	2,740	22	2.670	153
1516B3	15,190	3,415	22	2.530	145
1516B4	14,056	3,160	22	2.618	150
Average	13,962	3,139	22	2.609	150

3.8 METALLOGRAPHIC ANALYSIS

Based on mechanical testing data, addition of the copper caused little effect on the alloy properties. However, there were two questions that needed answers. These were (1) the effect of copper on alloy composition, and (2) possible segregation of copper in the weldment.

In order to assess the effect on alloy composition, all the 2219-T87 plates were analyzed prior to any coating or welding operations. After welding had been completed, a second analysis was made on a sample of the weldment from panel 1314. This panel was welded from two panels which had been copper coated to a thickness of 19.3×10^{-6} m (8×10^{-4} in.). Comparison of the alloy composition in each case indicated that the copper increased from 6.2 percent to 6.5 percent by weight. The allowable maximum for copper in 2219 alloy is 6.8 percent. Table 12 presents the complete analysis, including that of plate L2, from which panels 13 and 14 were cut.

No analysis has yet been made of a weldment on panels copper-coated to only 5.08×10^{-6} m (2×10^{-4} in.). This will be completed during the Phase II effort, but thinner coatings of copper as compared with those on panels 13 and 14 should result in proportionately lower copper in the alloy analysis.

In order to determine the location of the added copper in the weldment microstructure, metallographic mounts were made and the scanning electron microscope used for their evaluation. It was found that there was no significant difference between weldments made with and without the copper addition.

Samples were taken from welded panels 0304 and 1516. Panel 0304 was welded without the addition of copper and was to be used for mechanical property test control specimens. Panel 1516 was welded from panels which had abutting surfaces coated with 20.32×10^{-6}m (8×10^{-4} in.) of copper. As can be seen in Table 12, this increased the weight percent of copper in the weldment, and it was considered possible that the added copper would segregate in the microstructure in a detrimental manner. As shown in Figure 10, however, the microstructures of the two weldments are very similar.

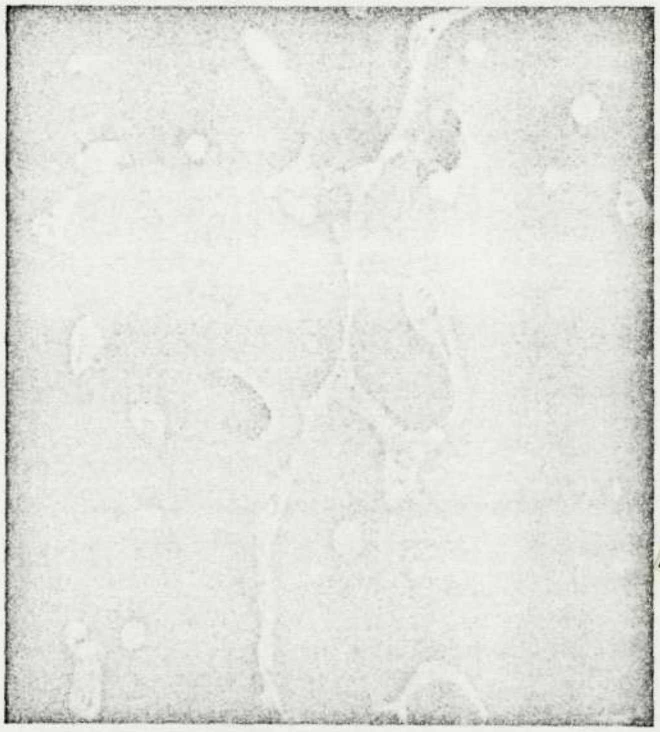
Table 12

EFFECT OF ADDED COPPER ON ALLOY COMPOSITION

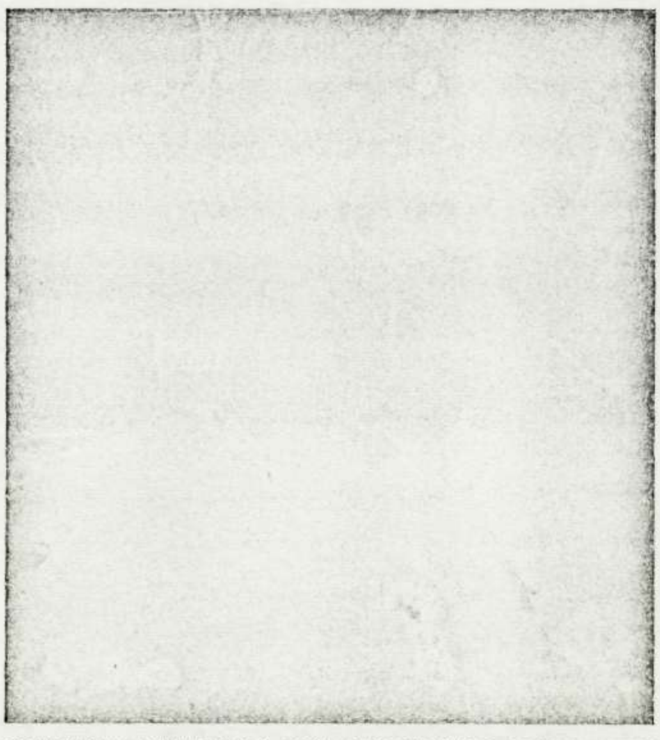
Element	Alloy Content by Weight Percent Plate L2	Panel 1314 Weldment	2219 Alloy Specification
Si	0.08	0.10	0.20 maximum
Fe	0.16	0.17	0.30 maximum
Cu	6.2	6.5	5.8 to 6.8
Mn	0.24	0.27	0.20 to 0.40
V	0.10	0.09	0.05 to 0.15
Zr	0.14	0.13	0.15 maximum
Ti	0.06	0.08	0.02 to 0.10
Mg	<0.013	<0.013	0.020 maximum

To further verify the similarity, the scanning electron microscope was used to determine the relative copper content of the matrix and precipitate in both microstructures. Figure 11 shows charts representing x-ray wavelength versus counts per unit time. The very high aluminum peaks are evident in all cases, and the smaller copper peaks are shown for the precipitate only. However, the copper peaks are approximately the same height for the precipitate of both microstructures, indicating that the copper is combined in the same way in both microstructures.

CR171
POLAROIDS



A) MICROSTRUCTURE OF WELDMENT IN PANEL 1516 AT 2,000 X (20.32×10^{-6}m OR 5.16×10^{-7} IN. COPPER ON EACH ABUTTING SURFACE)



B) MICROSTRUCTURE OF WELDMENT IN PANEL 0304 AT 2,000 X (NO COPPER ADDED)

Figure 10. Comparison of Weldment Microstructure With and Without Copper Additive

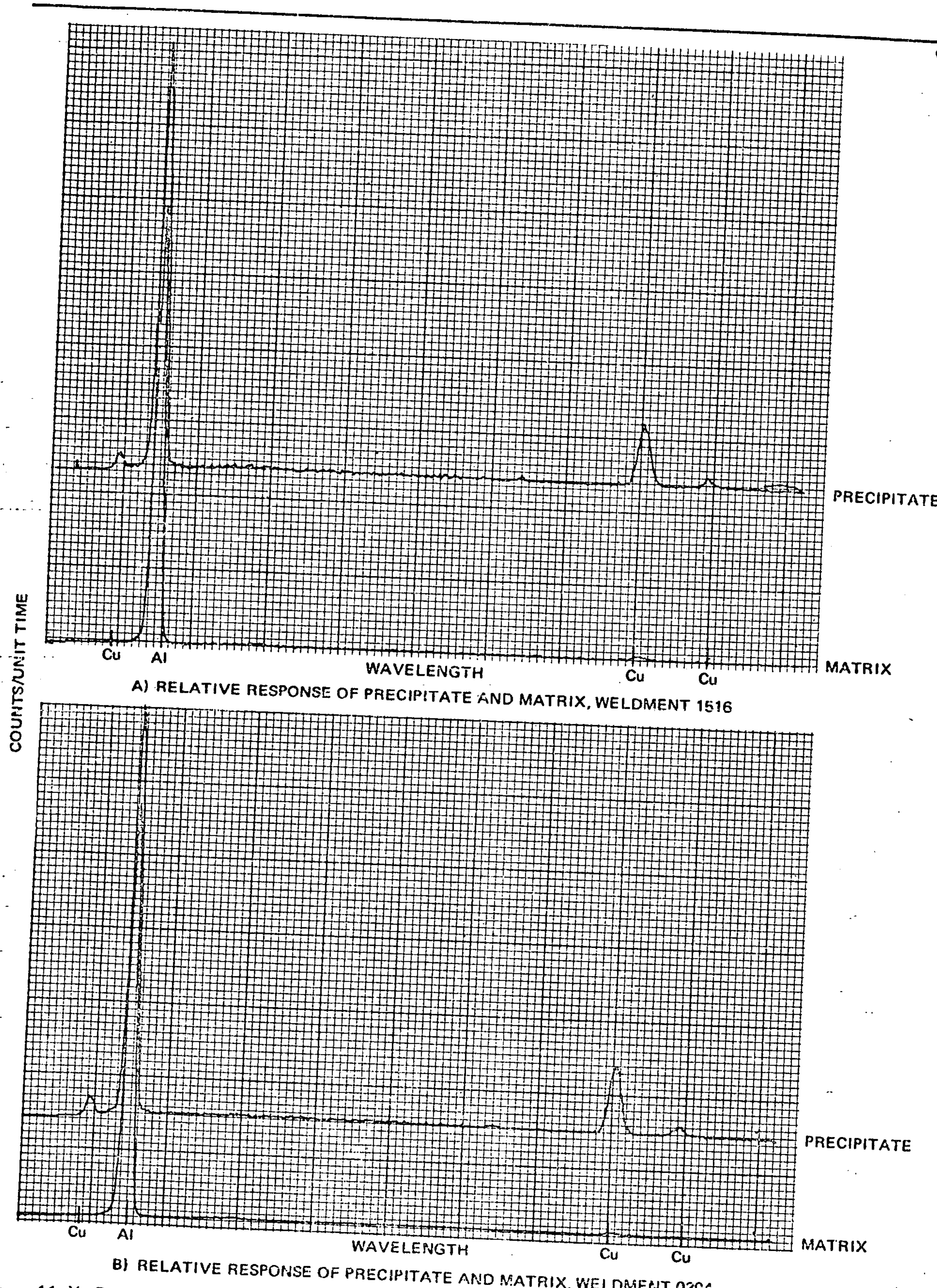


Figure 11. X-Ray Response of Aluminum and Copper in Precipitate and Matrix of Microstructure of Weldments 0304 and 1516

Section 4
DISCUSSION AND CONCLUSIONS

The results of this effort are thus far very positive and encouraging. Copper addition to weldments in the form of vacuum-vapor-deposited coatings on the abutting surfaces has met the two primary objectives of the Phase I effort. These objectives were to enhance x-ray detection of incomplete weldment penetration and to protect the abutting surfaces against oxidation of the aluminum.

The vacuum vapor deposition process proved far superior to plasma spray for the purposes of this program. It provides a smooth, dense coating of uniform thickness down to 5.08×10^{-6} m (2×10^{-4} in.) of copper. The plasma spray technique could not provide such uniformity with a thickness of 5.08×10^{-5} m (2×10^{-3} in.), and even then there were many areas of the aluminum surface left exposed to the atmosphere for further oxidation.

Welding test panels coated by vacuum vapor deposition was much easier than welding those coated with a plasma spray coating. The weldment chemistry was not seriously affected by the addition of the copper. The 19.32×10^{-6} m (8×10^{-4} in.) copper coating resulted in an increase of copper in the weldment of 0.3 percent by weight from 6.2 to 6.5 percent. The maximum allowable copper in 2219 alloy is 6.8 percent.

The mechanical properties of the weldments were changed only slightly by the addition of the copper. The weldment 0.2-percent offset yield strength decreased approximately 4.5 percent, and the ultimate tensile decreased approximately 3.0 percent. The effect of varied thickness of copper on the abutting surfaces was not detectable at all in the mechanical properties.

From a nondestructive inspection viewpoint, the copper additive works exceptionally well. All intentional incomplete penetration was clearly indicated on the x-ray film of the test panels. Even when only 5.08×10^{-6} m (2×10^{-4} in.) of copper was employed on each abutting surface, incomplete penetration was clearly evident.

The protective quality of the vacuum-vapor-deposited copper coating is very promising. Even in the relatively short time between coating and welding (two weeks) in the Phase I effort, unprotected aluminum might have been oxidized to the point of causing unacceptable weldment porosity. Very little porosity was observed in the x-rays of the weldments. The weldment of the panels which had the 5.08×10^{-6} m (2×10^{-4} in.) thick copper were almost completely free of porosity. In all probability, a period of several months could elapse without serious degradation of the abutting surfaces.

The most pressing need for successful application of the copper coating approach is the development of an inexpensive, practical means of copper application in a manufacturing environment. Vacuum vapor deposition is, of course, a prime candidate for such application. In the case of parts and structure of limited size, a large vacuum chamber can be used, such as the system employed for this program at MSFC-East. Very large aluminum structures and components, however, preclude the use of such a chamber. Portable "clamp-on" chambers are a possibility, but there is a need for additional development in that area.

Attention should be addressed to other means of laying down a thin, uniform, and continuous layer of copper that are similar to the vacuum vapor depositing process. There are at least two possible approaches which should be studied and if possible verified on a laboratory basis. These are "peen plating" and chemical reduction of a copper compound applied to the aluminum surface. Of these two, the peen plating may be the simplest and most easily verified. In this approach copper powder is mixed with glass beads which are impinged upon the aluminum surface to be coated, and the copper is "hammered" into place on the surface. Using this method should make it possible to deposit a thin, uniform coating of copper.

Of primary importance is the need to firmly establish through laboratory development effort a practical and economical means of depositing copper on aluminum. Once this has been accomplished, the copper implant concept can be widely employed with resulting increased inspection reliability and savings in aluminum cleaning procedures.

Based upon the factors previously discussed, several significant conclusions can be made.

1. Film radiography of weldments can be significantly enhanced by addition of very thin copper coating, 5.08×10^{-6} m (2×10^{-4} in.), on each abutting surface. The appearance of the copper on the x-ray film is so distinct that in-motion radiography could very easily be employed, and the sensitivity requirements relaxed to implement rapid inspection of large tankage structure.
2. There are no significant effects in alloy chemistry or mechanical properties as a result of the addition of copper to the weldment.
3. Copper coatings offord excellent protection against oxidation of aluminum, for periods up to two weeks at least, and probably much longer.

Section 5
PHASE II WORK PLAN

The successful completion of Phase I demonstrated the superiority of vacuum vapor deposition of copper over the plasma spray method. All three thicknesses of copper evaluated were adequate to indicate the intentional incomplete penetration weldment. Furthermore, microscopic examination revealed the vacuum-vapor-deposited coatings to be very uniform and without any indications of porosity or cracking. Such characteristics should provide excellent protection of the aluminum surface against oxidation, even with the thinnest coating used. Therefore, the thinnest vacuum-vapor-deposited coating of 5.08×10^{-6} m (2×10^{-4} in.) will be employed for all work during Phase II of the program.

Sufficient 2219-T87 aluminum plate is available for this effort and has been reserved pending start of this work. The cutting plan for the various panels has already been presented (Figure 1). The work statement for Phase II is outlined below.

5.1 PHASE II EVALUATION OF DEVELOPED COATING

5.1.1 Preparation and Test of Control Specimens

A. Machine 20 blanks (0.152 by 0.610 by 0.0127 m or 6 by 24 by 1/2 in.) from 2219-T87 plate, 10 each with long dimension parallel and transverse to rolling direction of plate.

B. Weld 10 panels with lack of penetration in approximately 0.152 m (6 in.) and 0.467 m (18 in.) of full-penetration "good" weldment.

C. X-ray and Delta-scan welded panels.

D. Machine from each control panel three tensile and four bend specimens, for a total of 30 tensile and 40 bend specimens.

E. Conduct mechanical properties tests on the 30 tensile and 40 bend specimens.

5.1.2 Preparation and Welding of Copper-Coated Material

A. Machine 80 blanks (0.152 by 0.610 by 0.0127 m or 6 by 24 by 1/2 in.) from 2219-T87 plate, 40 each with long dimension parallel and transverse to rolling direction of plate.

B. Apply copper coating to the 80 blanks on one 0.0127 by 0.610 m (1/2 by 24 in.) edge.

C. Hold 40 coated blanks (20 longitudinal and 20 transverse) for 10 days before welding.

D. Weld 20 panels after holding in storage for 10 days.

E. Hold 40 coated blanks (20 longitudinal and 20 transverse) for 60 days before welding.

F. Weld 20 panels after holding in storage for 60 days.

5.1.3 Testing Welded Panels

A. Conduct nondestructive testing of 40 panels to assess location and extent of lack of penetration and quality of full-penetration weldment. Use x-ray and ultrasonic Delta Scan.

B. Machine from each panel three tensile and four bend test specimens, for a total of 120 tensile and 160 bend test specimens.

C. Conduct quantitative analysis of weldments (two samples) to assess effect of copper implant in alloy composition of weldment.

D. Perform metallographic evaluation of one weldment of each group, welded after 10 days and after 60 days.

E. Conduct metallographic examinations (macrographs) to determine location of beginning of full penetration weldments.

F. Conduct mechanical properties tests of the 120 tensile and 160 bend test specimens.

G. Analyze data and assess effectiveness of copper implant for detection of lack of penetration. Evaluate effect of 10- and 60-day delays in making weldments.

5.1.4 Reporting

A. Prepare Phase II report.

B. Prepare final program report including all data and findings from Phases I and II.

Section 6
RECOMMENDATIONS

The implementation of Phase II of this effort is, of course, mandatory. The Phase I effort was very successful and pointed the way for the work originally planned for Phase II. In addition, several areas of investigation were found which are beyond the scope of the planned Phase II program.

The vacuum vapor deposition of copper on aluminum was very successful. However, this approach to coating aluminum becomes more difficult as the size of the aluminum structure increases, as in the case of large spacecraft cryogenic tankage. In order to most efficiently apply the copper implant concept, means must be developed to apply the copper coating economically and rapidly in a manufacturing environment. There are several potential approaches to this problem, including portable vacuum chambers for the vacuum-vapor-deposition process, "peen plating," and chemical reduction of a copper compound. The latter two approaches have been previously discussed.

It is extremely important to initiate exploratory and development efforts on these techniques concurrently with the Phase II effort. Such efforts on a relatively small scale at this time can most probably result in early implementation of the implant concept for practical manufacturing use.

PRECEDING PAGE BLANK NOT FILMED

Section 7
REFERENCES

1. Martin, B. G., and Adams, C. J., Detection of Lack-of-Fusion in Aluminum Alloy Weldments by Ultrasonic Shear Waves, Douglas Aircraft Company Technical Paper 3499, 1965.

2. Berger, Harold, Neutron Radiography, Methods, Capabilities, and Applications, American Elsevier Publishing Company, New York, 1965.

3. Specification, Welding, Aluminum and Aluminum Alloys, George C. Marshall Space Flight Center, MSFC-SPEC-504, 25 March 1970.

4. Federal Specification, Rods, Welding, Aluminum and Aluminum Alloys, Federal Specification QQ-R-566a, 8 March 1964.

5. Davies, O. L., The Design and Analysis of Industrial Experiments, Hofner Publishing Company, New York, 1956.

Preceding page blank