DETECTION OF LACK OF FUSION USING OPAQUE ADDITIVES FINAL REPORT

by

J. L. Cook

May 1973

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for the period
2 June 1972 to 30 April 1973
by
McDonnell Douglas Astronautics Company
Huntington Beach, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Alabama 35812

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ABSTRACT

Reliable nondestructive inspection for incomplete weldment penetration and rapid oxidation of aluminum surfaces when exposed to the atmosphere are currently two major problems in welded aluminum spacecraft structure. Incomplete-penetration defects are extremely difficult 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 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. Also, copper was used as an opaque additive in the weldment to enhance x-ray detection in the event of incomplete penetration.

In the Phase I effort, both plasma spray and vacuum vapor deposition techniques were evaluated for depositing the copper. A series of welded panels was fabricated 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.

In the Phase II effort, the objectives were to determine if the vacuum vapor deposited copper coatings could protect the aluminum surface for a period of 60 days, correlate the actual location of transition between incomplete penetration and full penetration weldment with that shown on the x-ray film, assess the capability of ultrasonic Delta-scan for detecting incomplete weldment penetration, and further substantiate the retention of acceptable mechanical properties after the addition of the copper in the weldment. In addition, the feasibility of peen plating for applying copper to an aluminum surface was evaluated.

The 60-day storage of the copper-coated specimens had no effect upon the weldments. The x-ray film provided a very accurate indication of the transition from incomplete penetration to full penetration weldment. Ultrasonic Delta-scan was not suitable for detection of tight incomplete penetration defects, whether or not copper was present as an additive. Peen plating was only marginally successful in depositing copper on aluminum, and additional work is needed for practical application. The mechanical tests indicated that there was little or no change in properties because of the added copper.

The concept of the opaque additive proved very effective. Promise of long-term protection of aluminum surfaces was indicated by successful storage of coated samples for 60 days. Effort in the area of copper application indicated that peen plating may be a viable method. Continued effort is necessary to further develop this potentially 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 this program.

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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. A problem of serious concern, particularly in welding thick-section butt joings 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). Such defects are so tight that they cannot entrap a sensitive fluorescent penetrant, even when they are exposed to the surface and visually apparent.

At one time, weldment porosity was a major problem in production of aluminum weldments. This porosity was attributed to moisture absorbed by the aluminum oxide which forms on the surface before welding. This problem occurs because of the formation of the moisture-absorbing oxide in storage. This oxidation process is very rapid, and cleaning procedures as shortly before welding as is practical are necessary to improve the probability of making a porosity-free weld.

The objective of this program was to develop means of solving the problems of detection of lack-of-penetration defects and surface protection after cleaning. The means to this solution lay in coating the aluminum surfaces to be protected with an x-ray-opaque metal such as silver or copper. In this way, the coated surface was protected against moisture absorption. 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.

The objectives of Phase II of this program were:

A. Determine if a vacuum-vapor-deposited coating of copper 0.0002-in. thick could adequately protect the aluminum surface for a minimum of 60 days.

B. Determine how accurately the x-ray film can indicate the location of transition between incomplete penetration and full penetration aluminum weldment.

C. Assess the capability of ultrasonic Delta-scan techniques to detect tight incomplete penetration defects.

D. Substantiate the Phase I results indicating that the added copper does not significantly effect on the weldment mechanical properties.

E. Determine the practicality of peen plating as a means of applying copper to an aluminum surface.

This report documents the work conducted through both phases of the program and presents the results, conclusions, and recommendations.

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.

To achieve the objectives of Phase II as stated in Section 1, 40 test panels of 2219-T87 aluminum were copper coated on one edge (abutting surfaces during welding) and subsequently held in storage for 60 days. The copper was deposited approximately 5.08×10^{-6}m (2×10^{-4} in.) thick by vacuum vapor deposition. Upon completion of the 60-day storage time, the panels were welded together by the same technique and parameters as employed in Phase I.

In a parallel effort, 20 panels were prepared without a copper coating and welded to make 10 welded specimens. Both of the uncoated and the copper coated panels were welded in the same manner, with a zone of tapered incomplete penetration for approximately 0.15 m (6 in.) at one end of the 0.61-m (24-in.) long panel.

Nondestructive testing of the welded test panels consisted of x-ray and ultrasonic Delta-scan methods. Mechanical tests included tensile and bend tests to determine the effect of copper on weldment properties. In addition, peen plating was investigated and experiments conducted with several test samples.

Altogether, the Phase II effort was aimed at verifying the effect of a copper additive on the nondestructive tests and on the mechanical properties of the weldments; and determining the feasibility of peen plating as a means of applying copper to the aluminum

Section 3
PROCEDURES AND RESULTS

3.1 MATERIAL AND MATERIAL CODING PLAN

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.

The samples for the Phase II effort were machined as follows:

Sixty panels, 0.152 by 0.610 by 0.127-m thick (6 by 24 by 0.5-in. thick), were machined for the Phase II effort. Twenty of these were reserved for control weldments which would contain no copper additive. The remaining 40 were to be copper coated. In each case, half of each group had been cut so that the weldment would be transverse to the plate rolling direction and half were cut so that the weldment would be parallel to the plate rolling direction.

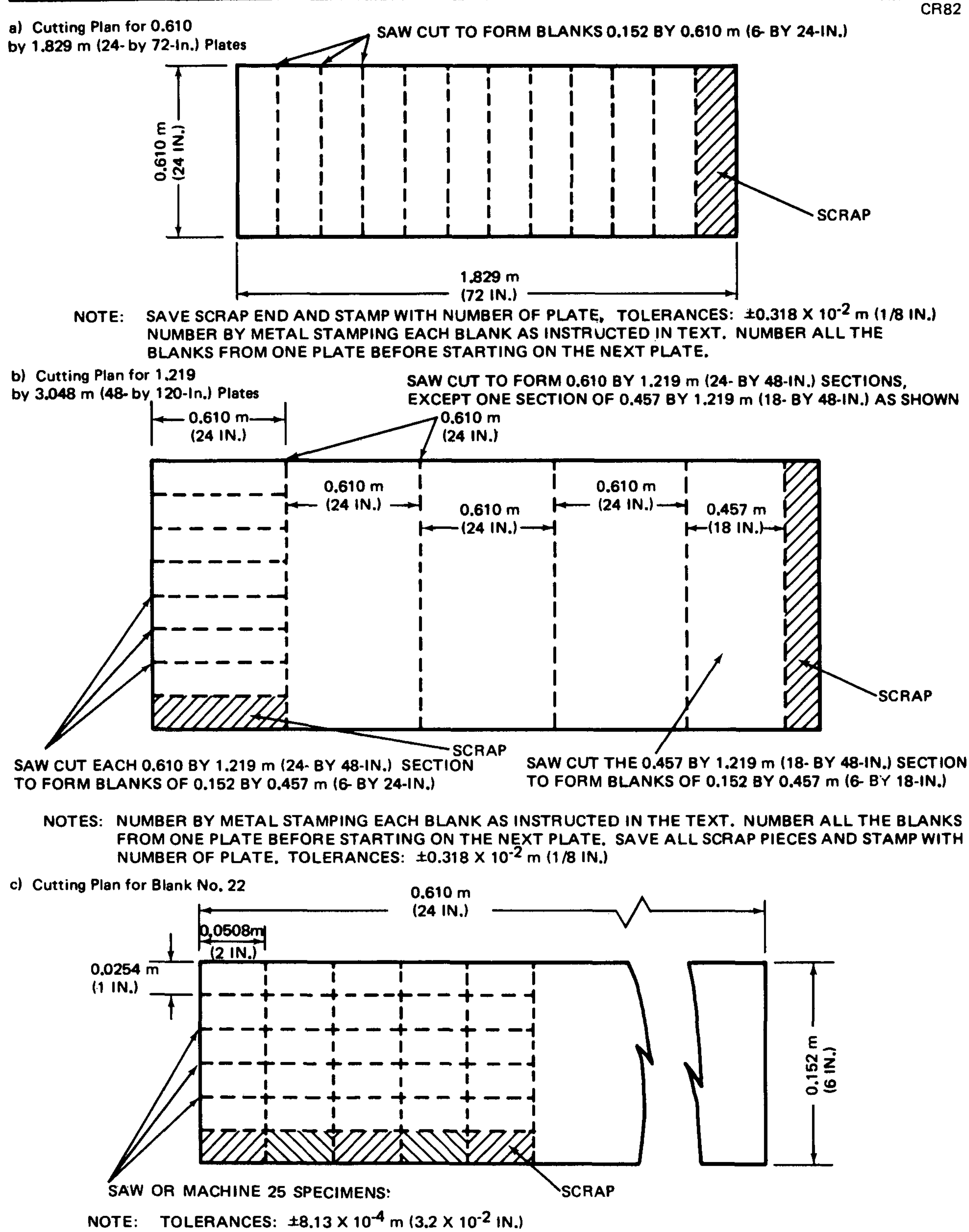


Figure 1. Cutting Plans for Aluminum Plates

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 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 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 by 3.048-m (4 by 10-ft) plates were numbered B1 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 0.152-m (6-in.) wide by 0.457-m (18-in.) long were cut from Plates B1 and B2, as shown in Figure 1. These 0.457-m (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 fabricated by machining several small samples from blank No. 22, as shown in Figure 1. These 25 samples were metal stamped 01 through 25 in sequence.

3.2 COPPER DEPOSITION TECHNIQUES

3.2.1 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 considered as a potential problem for the plasma-spray approach.

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.) 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.

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 1 lists the specimens and panels which were coated by plasma spray along with the coating thicknesses reported by General Plasma.

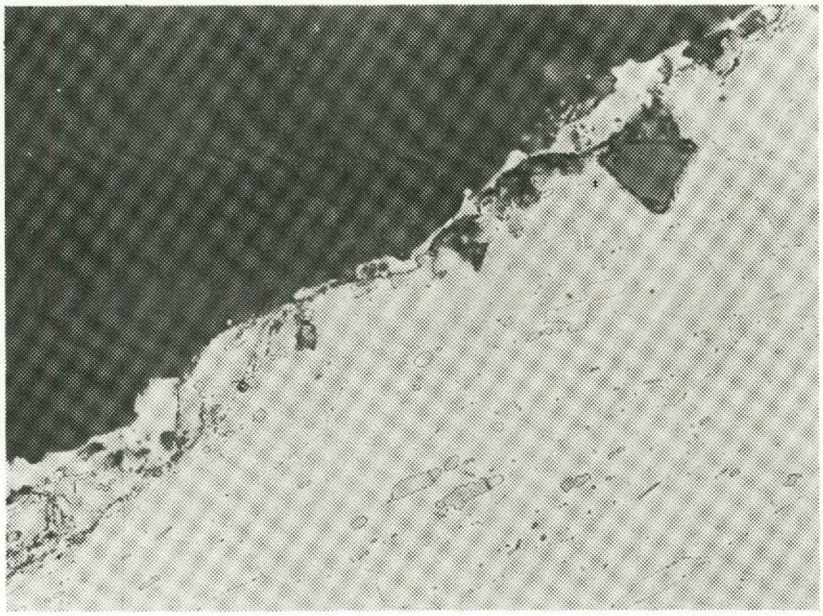
The 0.00127-m (0.050-in.) thick samples were used to assess the nature of the plasma-sprayed copper coating and to determine thickness uniformity. Several were submitted for sectioning, mounting, and photomicrographs.

The appearance of the plasma-sprayed coatings to the unaided eye was good, and the coated surfaces were a uniform copper color. The sections of the plasma-sprayed samples however (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

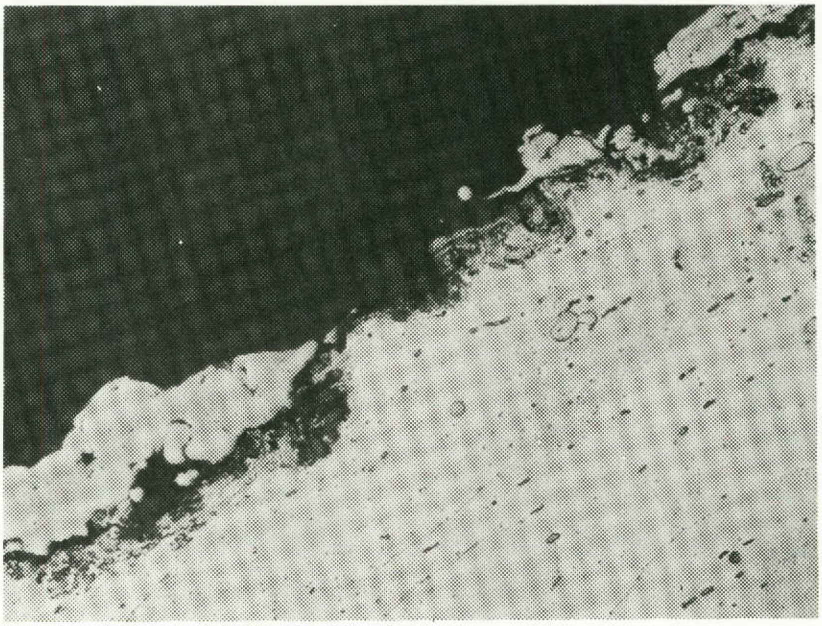
Table 1

SUMMARY OF PLASMA SPRAY DEPOSITION RESULTS

Items	Sample No.	Original Thickness	Plasma Process	Coating Nominal Thickness	Remarks
10 pieces 0.0254 by 0.0508 m (1 by 2 in.)	01	1.29×10^{-3} m (5.07×10^{-2} in.)	Air	7.6×10^{-5} m (3×10^{-3} in.)	Parts 01 through 06 sprayed for good coverage dis-regarding thick-ness
	02-06	1.29×10^{-3} m (5.07×10^{-2} in.)	Argon Atmosphere	7.6×10^{-5} m (3×10^{-3} in.)	
	07-10	1.29×10^{-3} m (5.07×10^{-2} in.)	Argon Atmosphere	2.54×10^{-5} m (1×10^{-3} in.)	Parts 07 through 10 plasma-sprayed to 2.54×10^{-5} m (1×10^{-3} in.) nominal thickness
10 pieces 0.152 by 0.458 m (6 by 18 in.)	23-26	0.152 m (6.002 in.)	Air	2.54×10^{-5} m (1×10^{-3} in.)	Parts 23 through 26 2.54×10^{-5} m (1×10^{-3} in.)
	27-32	0.152 m (6.002 in.)	Air	7.6×10^{-5} m (3×10^{-3} in.)	Parts 27 to 82 sprayed for good coverage disre-garding thickness



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

copper. Apparently the estimate of coating thickness provided by General Plasma was in error because the sectioned sample revealed a maximum thickness 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, the coating on the sectioned sample did not approach the 2.54×10^{-5}-m (1×10^{-3}-in.) thickness reported by General Plasma.

Samples 03 and 07 were examined using the MDAC electron microprobe. Two series of tests were conducted: the first was to assess the extent of the aluminum not covered by the copper coating and 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 substantial areas of the aluminum 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 did not completely cover the aluminum surface. However, these tests were conducted under one set of parameters, and there was no effort toward optimization of the procedure. It may be possible to develop plasma-spray parameters which will provide uniform and complete coverage of copper on aluminum in the thickness range between 2.54×10^{-5} and 5.08×10^{-5} m (1×10^{-3} and 2×10^{-3} in.).

3.2.2 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 were coated on only one 0.0254-m (1-in.) by 0.0508-m (2-in.) surface. Table 2 lists the panels and specimens and the resulting thickness of the copper coating.

Table 2

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.)
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 42155S chromated nonsilicated cleaner	16.3×10^{-5} m^3 to 20.7×10^{-5} m^3 per $3.78 \times 10^{-3} m^3$ (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
	Hydrocholoric 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.

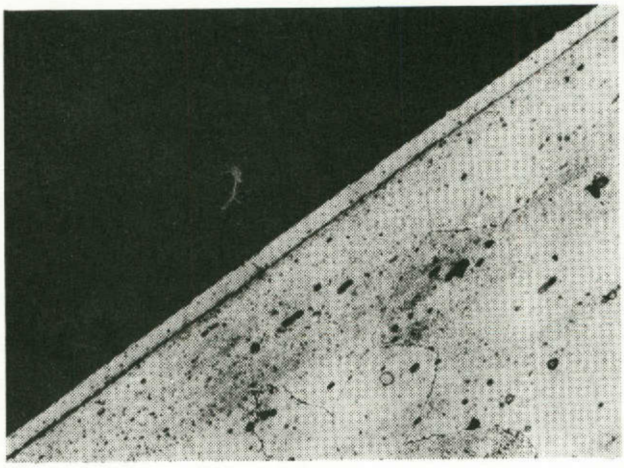
Copper deposition was started immediately after pumpdown following the glow discharge cleaning. The copper was deposited from a single self-resistance-heated molybdenum boat. The aluminum plates were held stationary 0.30 m (12 in.) above the boat, and during coating the boat was traversed horizontally 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 pre-weighed 0.05 by 0.08-m (2 by 3-in.) aluminum sheet specimens were weighed after plating. The amount and thickness of the copper were then calculated. Six weight specimens were used for each coating run. These specimens were equally spaced adjacent to the aluminum plate specimens.

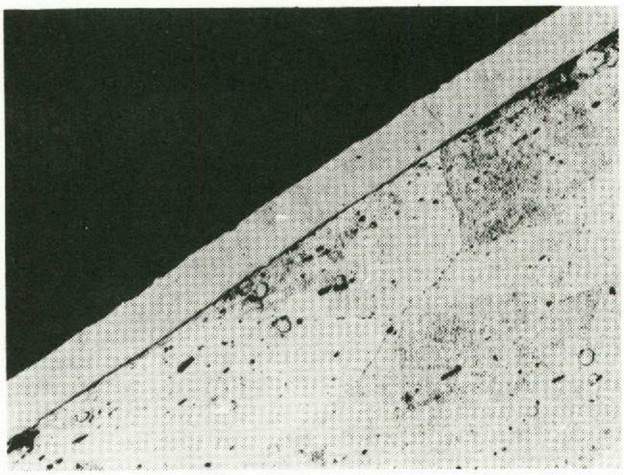
Adhesion of the copper coating was measured by tape peel testing 0.03 by 0.08-m (1 by 3-in.) specimens placed along side the subject aluminum panels. This test was made by placing a 0.08-m (3-in.) long strip of No. 250 Scotch tape on the copper surface and hand-pressing firmly in place. The loose end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

The specimens coated by vacuum vapor deposition showed a very 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.

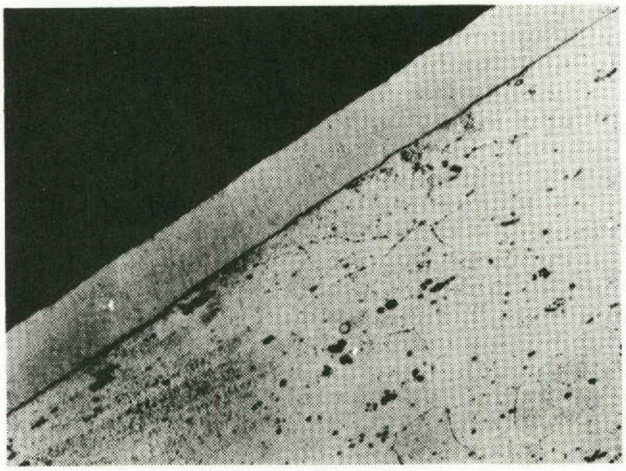
Comparison of the photomicrographs in Figures 2 and 3 clearly indicates the superiority of the vacuum-vapor-deposited copper coating. Copper coating as thin as 5.08×10^{-6} m (2×10^{-4} in.) was deposited with excellent uniformity and no cracks or porosity.



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.)

Based on this comparison of plasma spray and vacuum vapor deposition, the latter was selected as the means to coat the panels to be welded in both subsequent phases of the program. For the Phase I effort, 12 panels were coated on one long edge, 4 at each of 3 thickness of copper, 5.08×10^{-6} m (2×10^{-4} in.), 12.7×10^{-6} m (5×10^{-4} in.), and 20.32×10^{-6} (8×10^{-4} in.).

For the Phase II effort, copper was applied to one long edge of each of 40 panels. The procedure was identical to that employed for the Phase I panels as previously described. The copper thickness was approximately 5.08×10^{-6} m (2×10^{-4} in.).

Some trouble was encountered in the coating procedure. Several panels exhibited peeling and spallation of the copper coating, and it was decided to strip all copper and repeat the procedure. While the exact cause of the peeling and spallation was not determined, it was probably a cleaning problem. Special care was exercised during the second coating sequence in both the chemical cleaning and the glow discharge procedure. After the second coating, all panels except two appeared to have a satisfactory coating. The two displayed some small blistering near one end. It was decided not to attempt further stripping and recoating on these two panels since the blistered areas were near the ends of the panels and could be positioned away from the incomplete penetration zone during welding.

3.2.3 Peen Plating Investigation

Peen plating is the deposition of one metal upon another by the peening action of glass shot. In practice, metal powder is mixed with glass shot and the mixture is propelled by compressed gas at high velocity against the surface to be coated. The metal powder is literally "hammered" into the receiving surface.

When it had been established during the Phase I effort that the copper additive concept was successful, it was necessary to investigate methods of copper application which were rapid and inexpensive. Peen plating had been considered a possible approach during the original planning of the contract and was selected because of the high potential for success. Peen plating of one metal on another had been investigated by NASA personnel at Lewis Research Center (Reference 3). The work reported here was conducted during Phase II of the program.

A review was made of the NASA patent disclosure regarding peen plating. The following items summarize the technical details of the disclosure.

A. Peening particle (glass bead) size may range from 2.54×10^{-5}-m (1×10^{-3}-in.), to 1.78×10^{-3}-m (7×10^{-2}-in.) diameter. For large, thick substrates, even larger beads up to 2.54×10^{-3}-m (1×10^{-1}-in.) diameter could be employed.

B. The metallic powder size should be no greater than one half the penning bead size. The thinner the desired coating, the smaller the ratio of metal powder size to peening bead size.

C. The mixture of peening beads to metal powder should be approximately one-to-one if the emphasis is on coating. A greater fraction of metal powder than this is probably not efficient.

D. Experimental work indicates that a 0.0262-m^2 (3-in.^{2}) area can be coated to a thickness of 2.54×10^{-5} m (1×10^{-3} in.) in approximately 30 seconds.

It was established that facilities were available within the corporation for conducting the peen plating investigation. A small S. S. White airbrasive unit was available and was used for the preliminary feasibility tests.

Although the unit is designed for abrasive cutting and surface cleaning and is effective over only a very small surface area, it was considered sufficient for the first tests.

Copper powder and glass beads were procured. Five pounds of copper powder, -170 + 325 mesh and 99.9-percent pure, were obtained. Four pounds of glass beads were obtained, in the size range 14.99×10^{-5} to 24.89×10^{-5}-m (5.9×10^{-3} to 9.8×10^{-3}-in.) diameter. The copper powder size range is approximately 12.7×10^{-5} to 5.08×10^{-5}-m (5×10^{-3} to 2×10^{-3} in.); on the average about one half the size of the glass beads. This is one of the conditions necessary (Reference No. 3) for successful plating by this method.

The tests were conducted on several small hand-held aluminum samples. The surfaces were cleaned using emery paper and then rinsed with MEK. Only a very small surface area was treated, approximately 0.0064-m (1/4-in.) square. The nozzle on the S. S. White airbrasive unit was approximately 7.62×10^{-4} m (0.030-in.) diameter, and consequently the rate of deposition was quite slow.

The ratio of glass beads to copper powder was listed as one-to-one by the NASA disclosure (Reference 3). However, it was not clear whether this was on a weight or volume basis. Therefore, both approaches were tried. Samples were peen plated with both mixture ratios; one-to-one by weight and one-to-one by volume.

The one-to-one by weight combination appeared to provide the best and most uniform coverage of the samples. Because of the difference in material density, the volume of glass beads was over three times greater than the copper. This apparently resulted in more rapid deposition and retention of copper on the aluminum surface. Subsequent to the peening tests, the samples were sectioned and observed under a microscope to assess copper coverage and thickness. Figure 4 shows the section coated with the one-to-one by weight mixture of copper and glass beads. Figure 5 shows the section coated with the one-to-one by volume mixture. While neither section is ideal, Figure 4 shows the best surface coverage and thickest copper deposit.

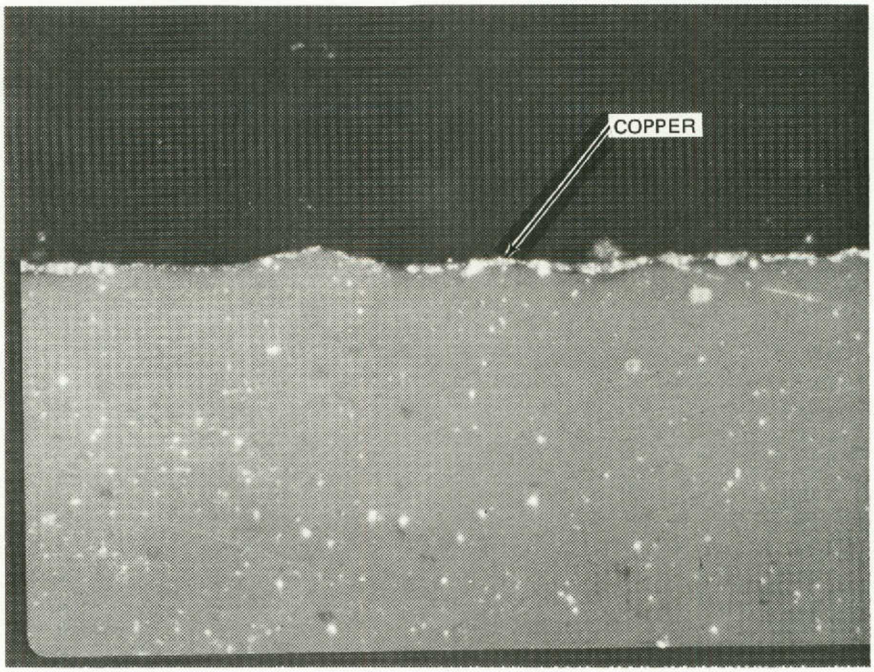


Figure 4. Copper Coating an Peen Plated Aluminum Sample (400X) Using One-to-One by Weight Mixture of Glass Beads and Copper Powder

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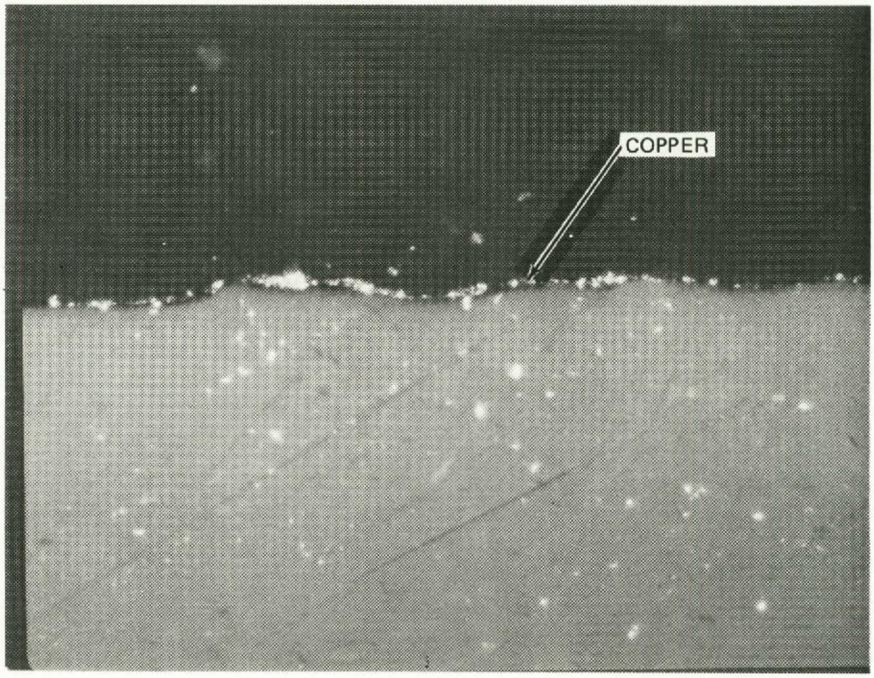


Figure 5. Copper Coating on Peen Plated Aluminum Sample (400X) Using One-to-One by Volume Mixture of Glass Beads and Copper Powder

Because of the lack of a one-to-one correspondence of parameters in scaling up the process from the laboratory to a shop system (large nozzle), it was decided to conduct subsequent studies with the shop system.

The next series of tests were conducted in the glass bead peening facilities at the Douglas Aircraft Company plant in Torrance, California. A mixture of 22.7 kg (50 lb) each of copper powder and glass beads were placed in the peening unit which had a nozzle 9.5 by 10^{-3} in. (3/8 in.) in diameter.

Four samples, 0.03 by 0.05 m (1 by 2 in.), were peen plated at four different times; 30 seconds, 1 minute, 2 minutes, and 4 minutes. The holding chamber of the abrasive blasting equipment was loaded with 22.7 kg (50 lb) each of copper powder and glass beads. The unit was then started and allowed to run for several minutes to mix the load of copper and beads. Even then however there was visual evidence of uneven flow from the nozzle. Periodically the color of the stream would change to more copper color, indicating that the copper was not mixing uniformly as the recycled material settled to the bottom of the reservoir below the blast chamber. This did not seem to affect the appearance of the sample surface however. In all tests, the aluminum surface appeared satiny without any indication of a copper color. The surface also appeared very uniform in shade and texture.

In addition to the four small samples, four plate specimens were peened along one edge. These samples were 0.3-m (12-in.) long by 0.05-m (2-in.) wide by 0.01-m (0.5-in.) thick. They were peened on one 0.3-m (12-in.) by 0.01-m (0.5-in.) edge for 3 minutes.

These peen plating tests were not as successful as had been anticipated. Cross sections of the four small specimens showed very little copper at all. Only on the specimen exposed for four minutes was there any clear indication of copper on the surface, and these areas were very limited.

The limited scope of the program precluded further effort in developing application parameters. Additional work is necessary to determine the effect of the several peening variables and to develop an effective peening procedure.

There are several factors which could account for the failure of the work with the larger nozzle system. The air pressure behind the nozzle was 85 psi, and this may have been too high. The high air pressure may have imparted a velocity that was too high to the stream of shot and copper powder. This could have resulted in the copper powder bouncing off the surface before the glass beads could affect the peening actions. Reducing the air pressure to a lower value would decrease the average particle velocity, perhaps increasing peening efficiency.

Another factor which is probably very critical is the ratio of glass bead size to copper powder size. It may be that the smaller the copper powder size with respect to bead size, the more effective the plating action. Since the glass bead must peen the copper on to the surface, it must be large enough to flatten the copper particle and cause it to hold to the surface until another bead can come along and continue the job. If the copper powder particle is relatively large, it offers more resistance to the peening action and may be more easily dislodged or deflected away from the surface.

The third factor is the amount of peening beads with respect to the copper powder. Higher ratios of glass beads would probably provide a more rapid buildup of copper on the surface since any given particle of copper would be peened into place more effectively and rapidly.

While these peen plating experiments were not totally successful, they have pointed to some of the critical factors which must be explored during further work in this area.

Despite the marginal results of the peen plating effort, it is still an interesting and attractive approach to depositing copper on aluminum. In contrast to the requirements for vacuum vapor deposition, peen plating requires no vacuum, no seals, no special environment, no heat, and no super-critical cleaning procedures. The equipment is relatively inexpensive and can be run with compressed air. Ideally, the system should employ a separate means of introducing the peening beads and the copper powder. In this way, better control can be maintained on the mixture of the two. Further investigations of the specific application parameters should be made as rapidly as possible.

3.3 WELDING

3.3.1 Approach

The objective of the welding effort on this program was to provide test panels with controlled lack of fusion defects. The panels were welded in two separate passes, one from each surface. By this means, it would be possible to incorporate intentional incomplete penetration defects in the center of the panel weldments. In addition, this two-pass approach would simulate the welding approach that has been employed frequently on thick-section aluminum structure, 0.0127-m (0.5-in.) thick and heavier. Since these incomplete penetration defects would not be open to the surface, no visual detection would be possible, as with single-pass welds. It was also desired that these intentional defects be tapered to provide changing areas of incomplete penetration.

The gas metal arc (GMA) 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 6. 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 inprocess 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 (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.

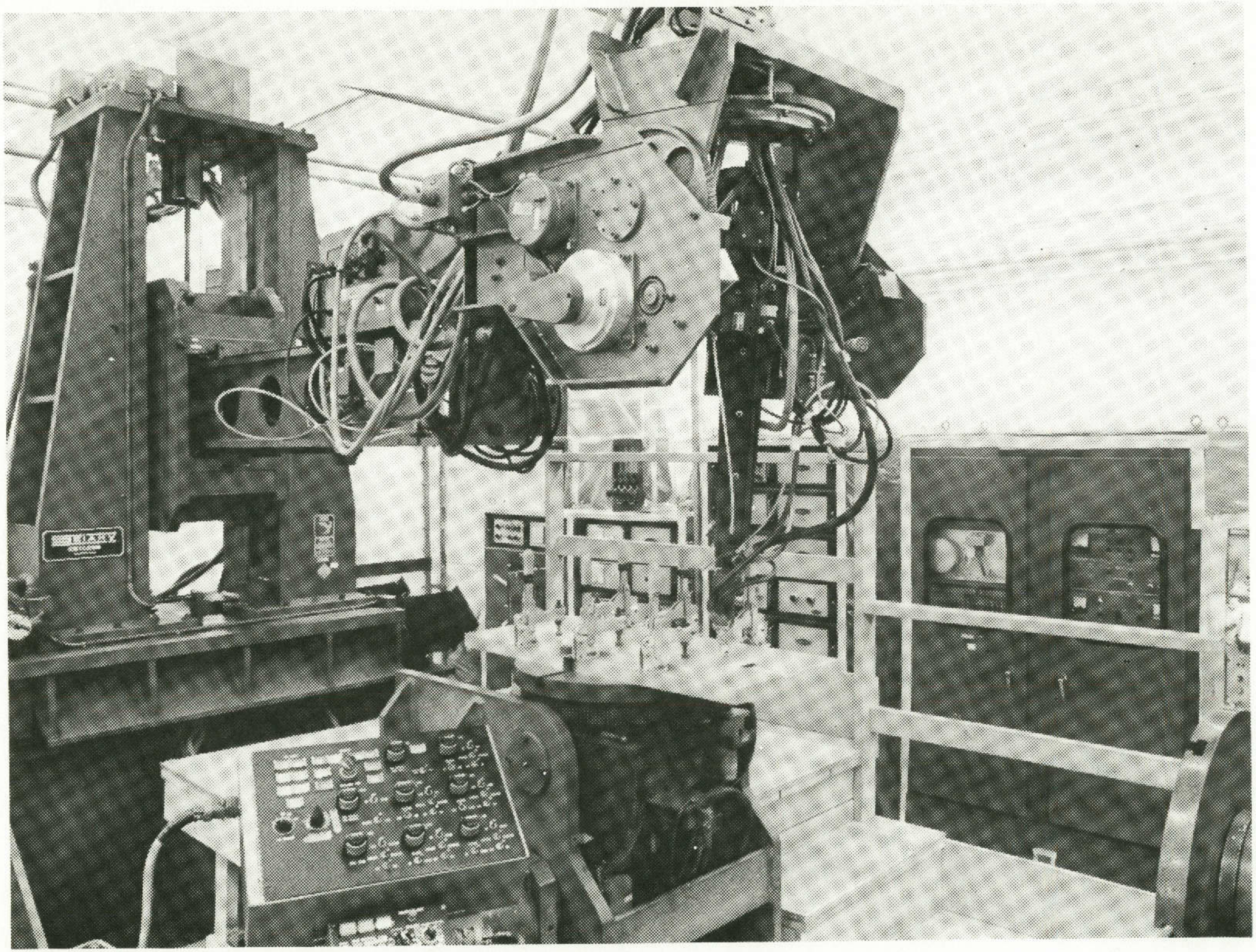


Figure 6. Eight-Axis Numerically Controlled Welding Machine

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 5) 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 deionized 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.

3.3.2 Experimental Procedure

Preliminary Setup

The eight-axis N/C welder was converted from the gas tungsten arc (GTA) 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 level-type toggle clamps for securing the specimens was mounted to the positioner baseplate, as shown in Figure 7. 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.

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 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 (5×10^{-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.).

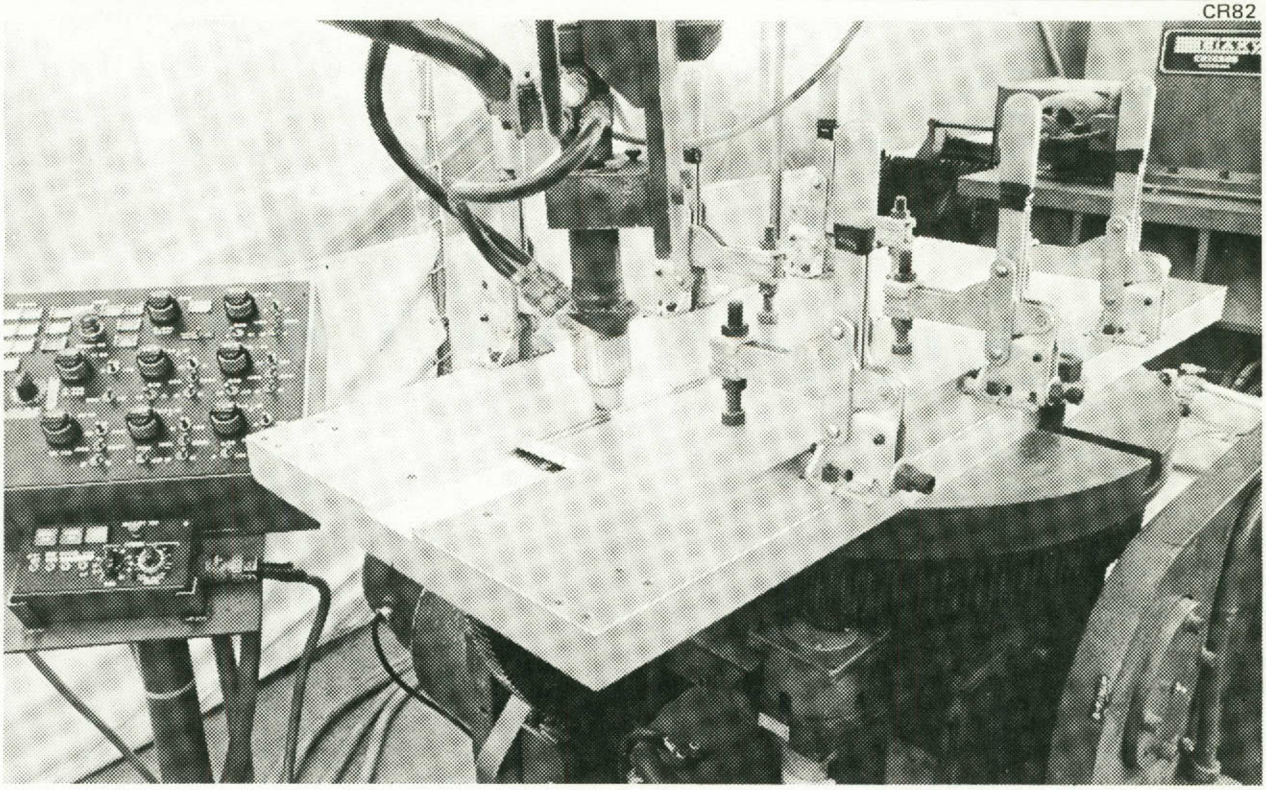


Figure 7. Welding Arrangement for Test Panels with Tapered Lack of Penetration

Both sets of control panels, 0102 and 0304, were tack-welded 0.038 m (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 in Table A-1 of the Appendix.

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 0.86m/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 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 electro-mechanical 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.

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 because 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 A-1 of the Appendix, along with the values of arc voltage and wire-feed speed employed. The upper 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 9.75 m/minute (345 imp) on the second. These weld segments were sectioned both transversely and longitudinally as shown in Figure A-2 of the Appendix. 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.

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 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 A-2 of the Appendix 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 A-3 of the Appendix.

Having verified penetration and taper, the vacuum-vapor-deposited specimens were prepared for welding. Each specimen was wiped clean with clean, lintfree 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 A-2 and A-3. 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 (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.).

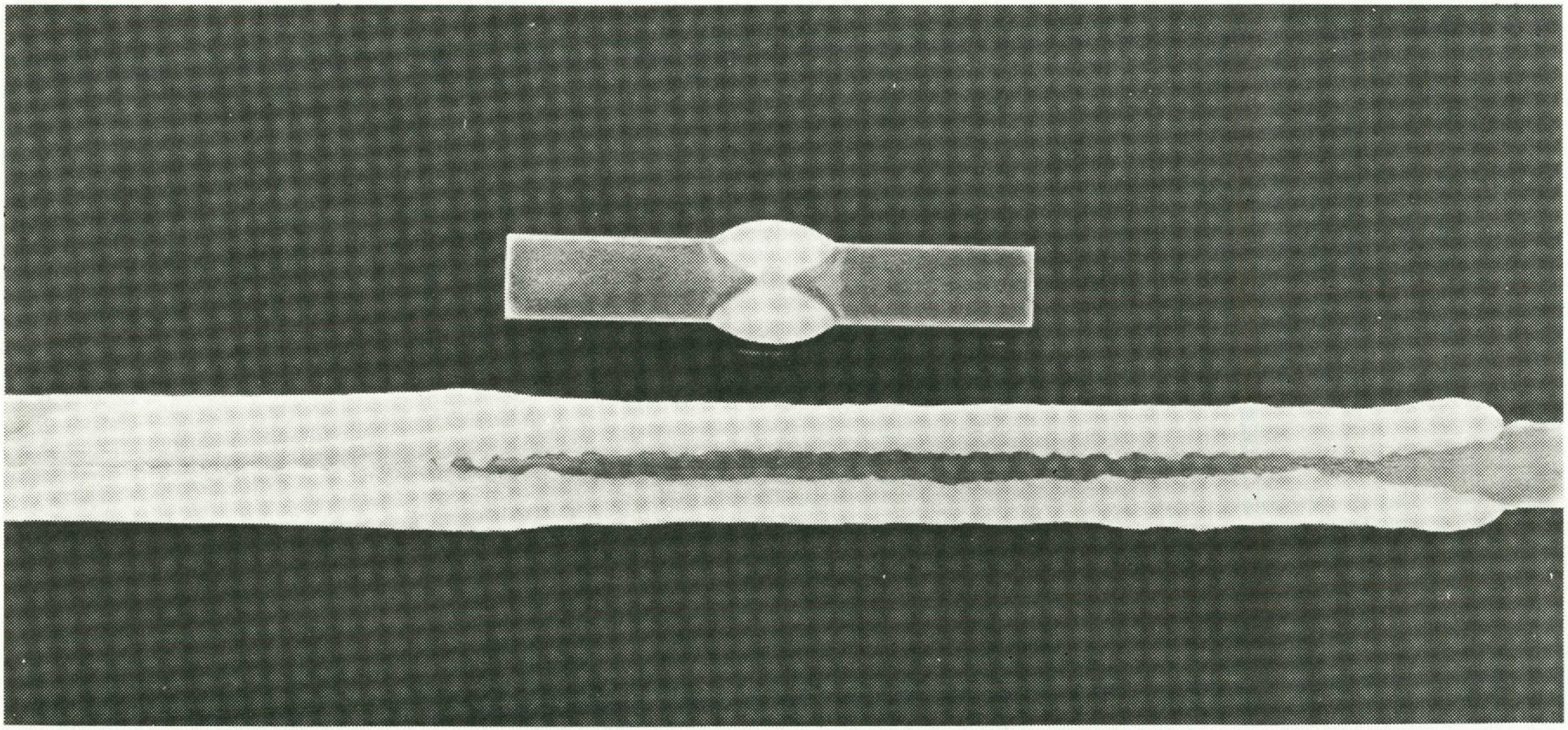


Figure 8. Longitudinal and Transverse Sections of Tapered Lack-of-Fusion with a 1-Mil Copper Implant

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.

3.3.3 Phase II Welding

The welding effort on Phase II consisted of the welding of 10 uncoated and 20 copper-coated panels. Half of the panels in each lot were welded with the rolling direction parallel to the weld joint, and the remaining were welded perpendicular to the rolling direction.

The tapered, incomplete penetration gas metal arc (GMA) numerically controlled welding procedure developed in Phase I was used to weld all panels in Phase II. This was accomplished by employing the same punched tape containing the previously developed welding parameters and travel-speed changes on the same equipment with 2369 A-1 filler wire and He-A-O_2 shielding gas mixture.

The uncoated panels were cleaned prior to welding in exactly the same manner as were the control panels in Phase I. The surfaces on the joint edge were wiped with a clean, lint-free cloth dampened with acetone. They were then etched with a tin-etch (chronic, nitric, and hydrofluoric acids) for a minimum of 5 minutes, agitating frequently. After water rinsing, the edges were neutralized with a solution of sulfuric acid and sodium dichromate and rinsed with deionized water until a pH value of 5.0 to 8.0 was reached. After drying, the top and bottom surfaces adjacent to the edge were mechanically cleaned with a power-driven, small-bristle, stainless-steel brush. Then, the faying surface was draw filed with a Vixen file, at the same time removing any burrs from the corners. The assembled joint was inspected with a black light for any remaining organic contaminants just prior to welding.

The air in the environmental enclosure surrounding the welding equipment was examined for particulate matter. It was found to contain no more than 6,179 particles per cubic meter (175 particles per cubic foot) larger than

10 microns in diameter. This compares with a level of 21,186 particles per cubic meter (600 particles per cubic foot) 10 microns or larger, allowed before welding the Saturn S-IVB vehicle.

The dewpoint of the shielding gas was tested as it left the welding torch and was found to have only 10 ppm of water vapor, well below the 17 ppm pertmitted for the Saturn S-IVB welding.

After welding, the control panels were mechanically shaved to within 2.54×10^{-4}m (1×10^{-2} in.) of the panel surface on both sides, and then submitted for nondestructive inspection.

The copper-coated panels were held in storage for 60 days between the coating and welding operations. Each panel was wrapped in an unsealed polyurethane bag and the entire 40 panels were kept in wooden boxes stored in the welding laboratory.

Just prior to welding, each numbered set of panels were removed from storage and power-wire-brushed as an assembly in a band approximately 0.10-m (4-in.) wide on both surfaces so as to prevent disturbing the copper-coated faying surfaces. Upon disassembly, the corners of the specimens were broken with a Vixen file and the coating wiped with a clean, lint-free cloth dampened with acetone. The panels were then assembled in the weld fixture and the joint was black-light inspected just prior to welding on each side. The environment was again sampled for particulate matter and was found to be the same as before. The shielding gas employed to weld these panels was from the same gas cylinder as used to weld the uncoated panels.

The 20 panels were welded satisfactorily except for a few minor problems. The 20 panels with comments on problems and the welding parameters are listed in Table 4.

Panels 3738 through 103104 were welded on the 61st day after coating with copper. The welding characteristics were excellent with the exception of the first pass on panel 3738. The arc instability experienced at the end of the tapered region was later found to be the result of a cup-to-work distance

Table 4

COMMENTS ON 20 WELDED PANELS WITH COPPER ADDED

Panel No.	Pass No.	Operational Characteristics
3738	1	Gouged at end of taper—manually GTA repaired.
	2	OK except slight disturbance opposite repair.
3940	1	OK
	2	OK
4142	1	OK
	2	OK
4344	1	OK
	2	OK
4546	1	OK
	2	OK
4748	1	OK
	2	OK
4950	1	Slight arc disturbance at end of taper.
	2	OK
5152	1	OK
	2	OK
5354	1	OK
	2	OK
5556	1	OK
	2	OK
99100	1	OK
	2	OK
101102	1	OK
	2	OK
103104	1	OK
	2	Gouged first 3.5 inches
105106	1**	OK
	2**	Gouged first 4.0 inches
107108	1**	OK
	2*	OK

Table 4

COMMENTS ON 20 WELDED PANELS
WITH COPPER ADDED (Continued)

Panel No.	Pass No.	Operational Characteristics
109110	1**	OK
	2*	OK
111112	1**	Gouged first 5.0 inches
	2**	Gouged between first 1 to 3.5 inches
113114	1**	Gouged between first 1 and 2 inches
	2**	OK
115116	1	Gouged between first 1 and 2 inches
	2*	OK
117118	1**	OK
	2*	Slight disturbance at 2 inches from start

Tape No. - 92972 mylar
Torch lead angle - 0.087 radians (5 deg) for panels 3738 through 103104
0.105 radians - (6 deg) for passes**
0.070 radians - (4 deg) for passes*
Gas type and flow - He-A-O_2 at 2.12 cubic meters per hour (75 CFH)
Cup size No. 10 (slightly enlarged)
Contact tip bore - 2.06×10^{-3} m (0.081 - inch) diameter
Cup-to-work distance - 0.024 to 0.010 m (23/24 to 3/8 inch)
Contact tip recess in cup - 0.005 m (3/16 inch)
Welding current - 300 amps
Arc Voltage - 28.5 volts
Wire Feed Speed - 8.6 meters per minute (340 ipm)

setting that was too short, resulting in an overall increase of arc current. The cavitated region was ground smooth with a rotary file and filled with 2319 filler wire using manual GTA welding with polarity. After cooling to room temperature, the second side was welded quite successfully with only a slight disturbance occurring opposite the point of repair.

On the 62nd day after coating, panels 105106 through 117118 were welded. As indicated in Table 4, some difficulty was experienced in the tapered incomplete penetration region of passes identified with a double asterisk.

It was found that the torch lead angle was set at 0.105 radian (6 deg) rather than the previously used 0.087 radian (5 deg) lead angle. Since the arc is quite harsh in the tapered region, a very slight unbalance of the settings can cause arc gorging to occurr. Therefore, the torch lead angle was reduced to 0.070 radian (4 deg) for the remaining welds and the arc gorging disturbance was eliminated. The completed panels were subsequently shaved to within 2.54×10^{-4}-m (1×10^{-2}-in.) of the panel surface on both sides and submitted for nondestructive inspection.

3.3.4 Summary

The welding development portion of this 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 because a reduction in arc voltage is usually accompanied by a penetration reduction in spray arc welding of aluminum.

3.4 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.

In Phase I, the two test panels welded to produce a satisfactory full-penetration weldment contained only a few scattered indications of porosity, but none of these 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 in Phase I are summarized in Table 5. 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.

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 2-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.

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 seemed the most logical selection for the work to be performed in Phase II. 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 both empirically and by analysis and should be settled before the opaque additive concept is put to practical use.

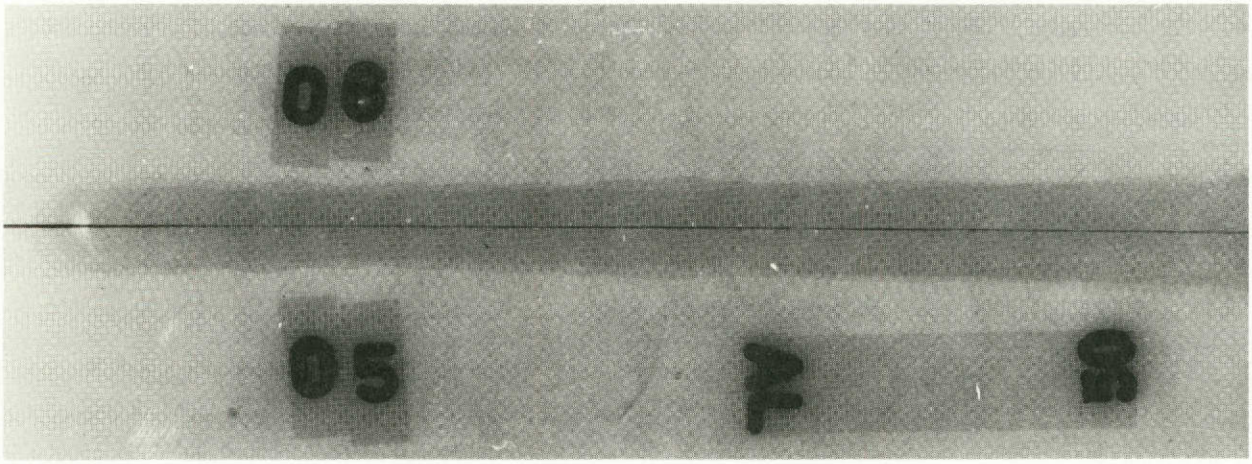
Table 5

SUMMARY OF X-RAYS OF WELDED PANELS CONTAINING COPPER

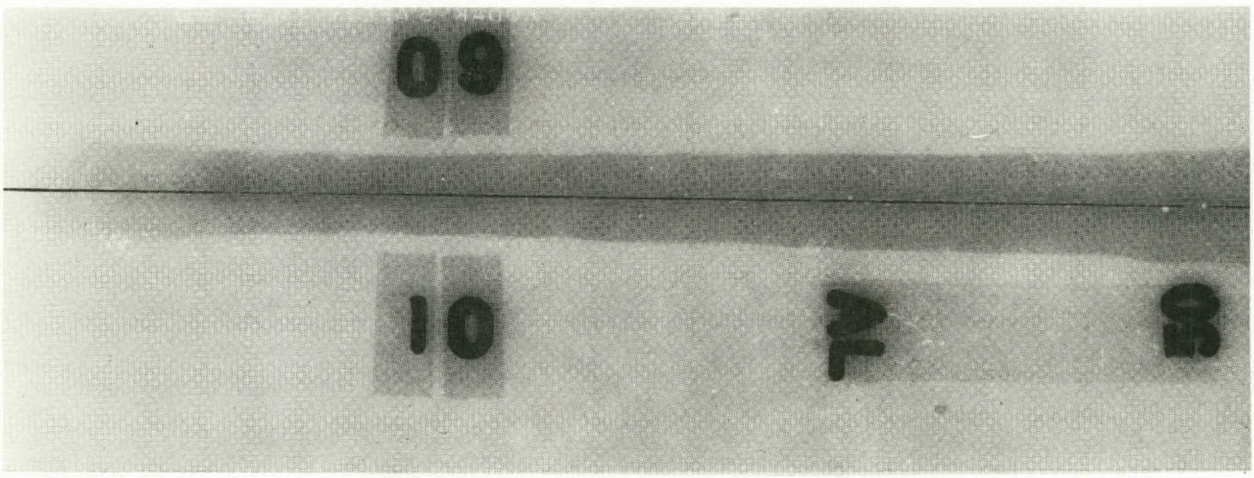
Panel No.	Comments	
0506 5.08×10^{-6} m Cu (2×10^{-4} in.)	Clear indication of remaining copper	One small pore in remainder of weldment
0708 5.08×10^{-6} m Cu (2×10^{-4} in.)	Clear indication of remaining copper	Three small pores in remainder of weldment
0910 12.7×10^{-6} m Cu (5×10^{-4} in.)	Very clear 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

The 10 control panels for the Phase II effort were inspected by film radiography using the same exposure parameters as previously employed in Phase I.

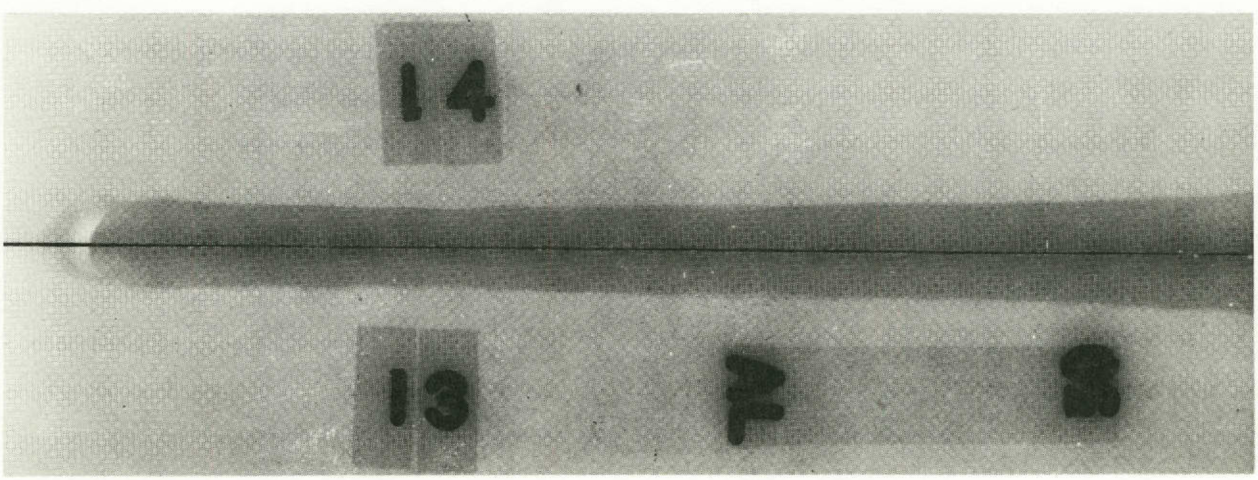
Examination of the x-ray film showed only limited indication of the intentional incomplete penetration zone. These indications appeared on the end of the panel at the start of the weldment. In no case was there any indication of the incomplete penetration beyond 2 in. from the end of the panel. Figure 10 shows a typical example of the x-ray film indications obtained.



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

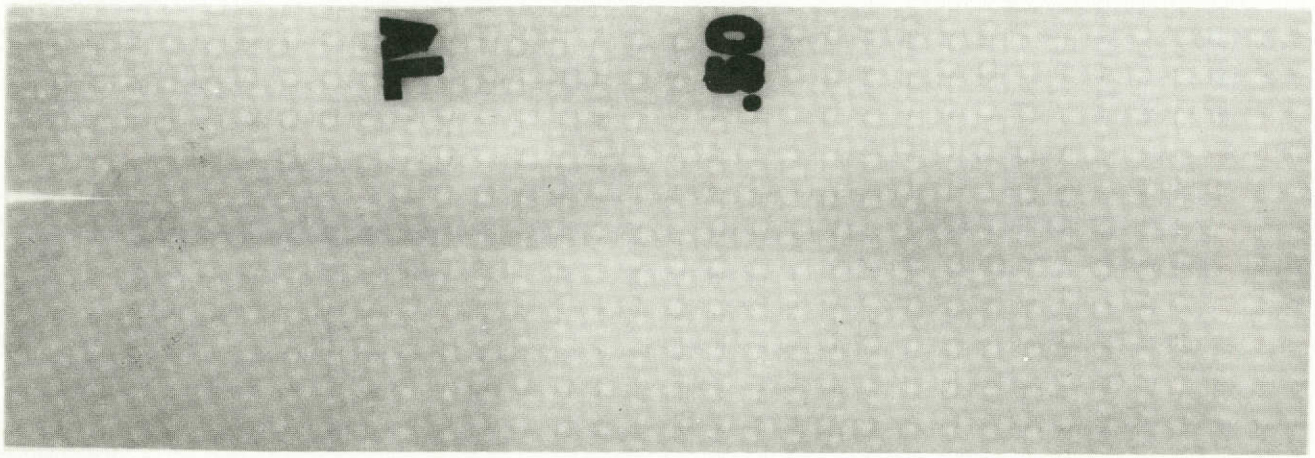


Figure 10. X-Ray Positive Print of Panel 8182 Zone of Incomplete Penetration

In addition to the x-ray inspection, ultrasonic tests were also conducted on the 10 control panels. Manual shear-wave tests were made to detect the incomplete penetration defects. In those areas which were seen on the x-ray film, the manual shear-wave approach was able to obtain a clear signal from the unwelded interface. All these indications were within 2 in. of the ends of the panels.

Neither the x-ray nor ultrasonic shear-wave techniques were able to detect any incomplete penetration over 2 in. from the end of any panel nor in the area of transition from partial penetration to full penetration weldment. To verify that such defects were present, several tensile specimens were cut cut from these areas. Figure 11 shows the fracture surfaces of two such specimens which indicate clearly the areas of incomplete penetration. Both of these specimens were taken from areas which gave no indication whatever (by x-ray or ultrasonic techniques) of the defect condition present.

One control panel which had provided strong signals during the shear-wave inspection was investigated using the Delta approach. The immersed testing arrangement is shown in the sketch in Figure 12. The test parameters were extracted from previous work (Reference 6) and the panel was manually scanned in the weldment area while observing the oscilloscope display.

The Delta technique did provide indication of the incomplete penetration defect but only in those areas where the x-ray and shear-wave tests had also indicated a defect present. The incomplete penetration near the transition zone between incomplete and full penetration weldment could not be discerned.

While the weld bead had been machined to within 2.54×10^{-4} m (1×10^{-2} in.) of the parent plate surface, the surface of the weldment was not perfectly smooth, and there were signals coming from the weldment which made data difficult to understand. Review of some of the available literature (Reference 7) on ultrasonic Delta techniques indicated that a very smooth surface was necessary for the approach to work. Direct contact was made with two organizations (References 8 and 9) experienced in Delta work. Both indicated that surface finish was a critical factor and that roughness remaining after the removal of the weld head make the approach impractical. It

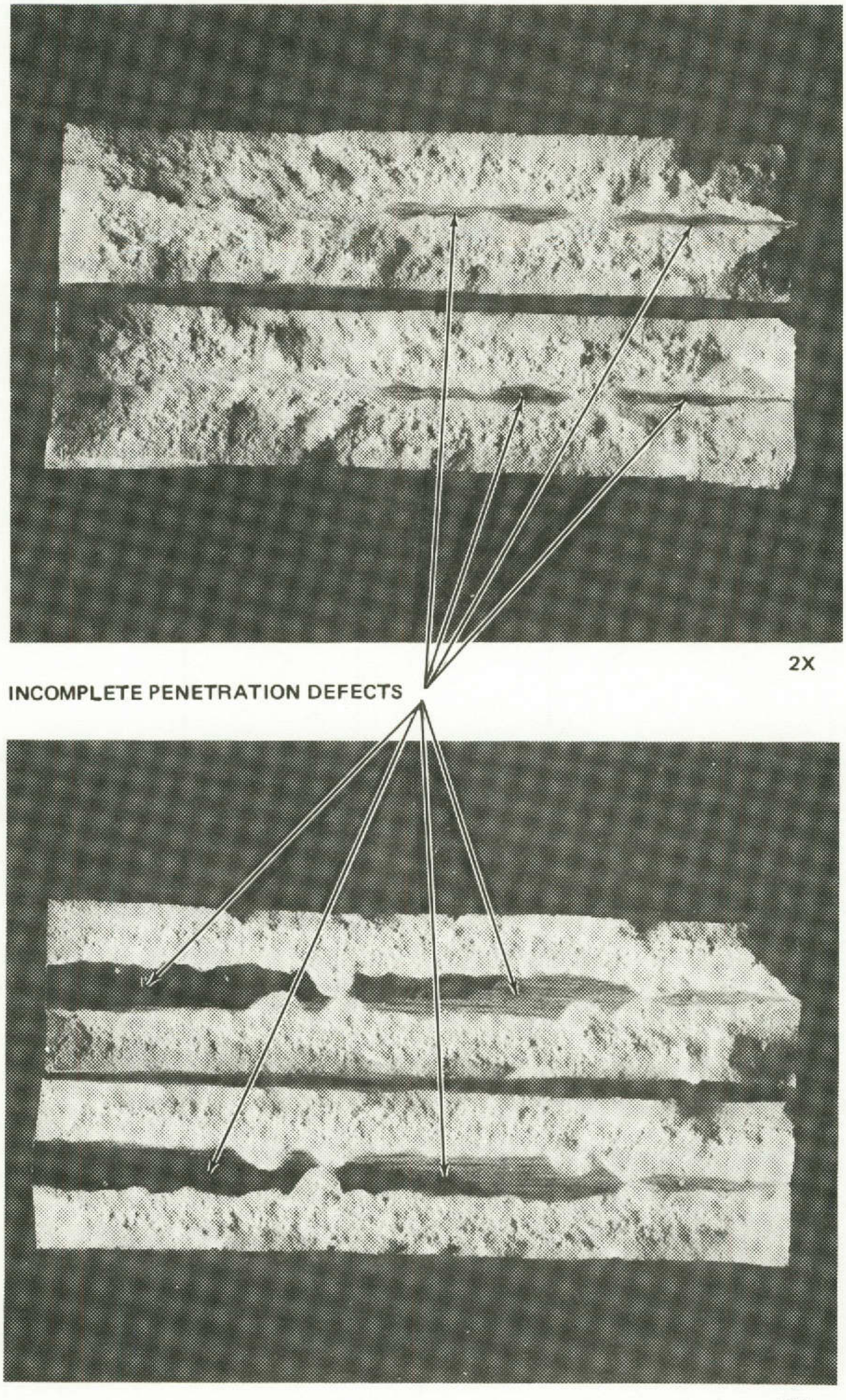
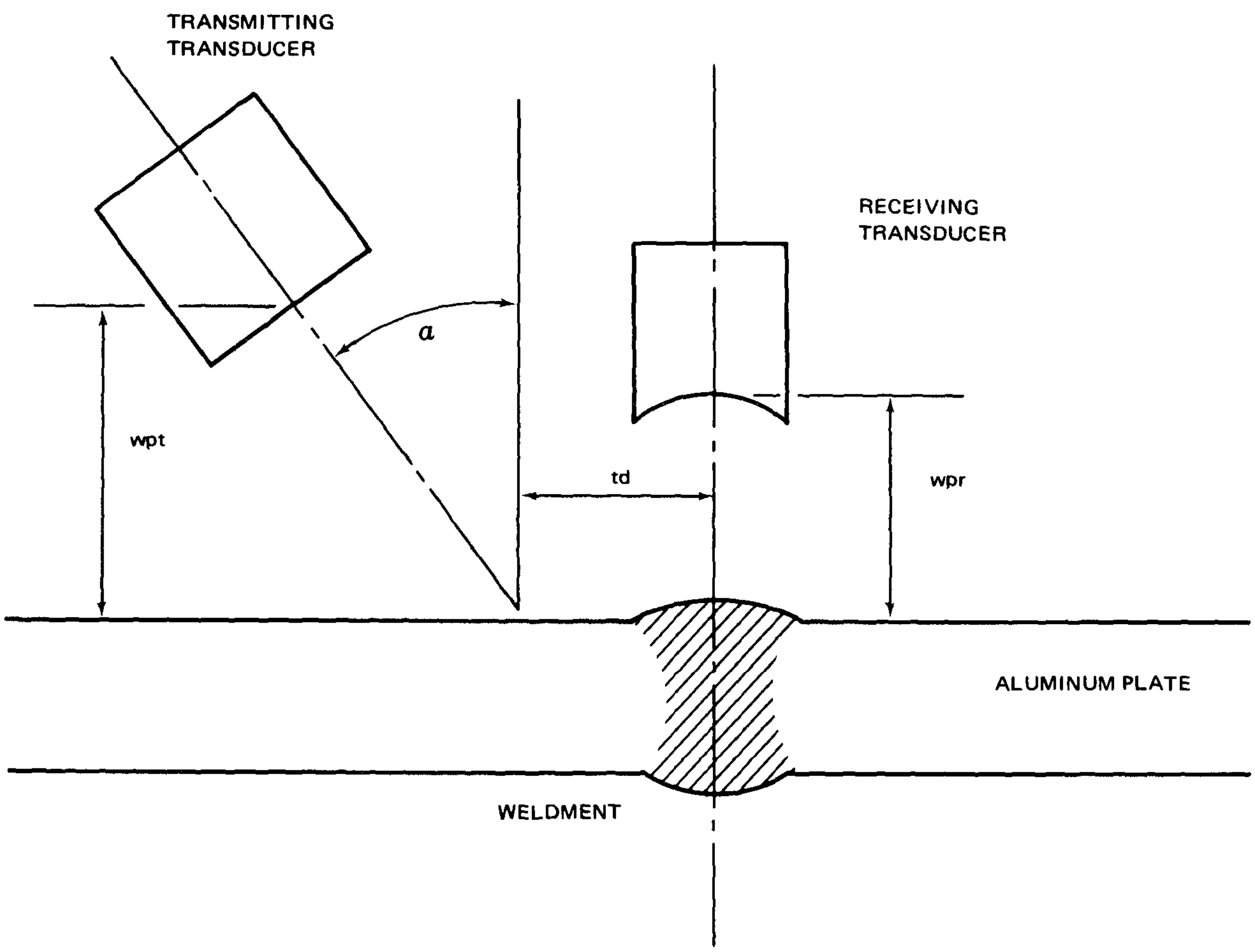


Figure 11. Fracture Surfaces of Two Tensile Specimens Taken from Zone of Incomplete Penetration on Panel 135136



VALUES FOR TEST ARRANGEMENT

a = 0.428 RADIANS (24.5°)
wpt = 0.035 METER (1–3/8 IN.)
td = 0.011 METER (7/16 IN.)
wpr = 0.041 METER (1–5/8 IN.)

Figure 12. Immersed Delta-Scan Test Arrangement Including Parameters Used in Tests for Incomplete Penetration of Aluminum Weldments (Reference No. 4)

was also indicated that high instrumentation sensitivity was necessary, which also compounds the problem of a noisy background.

The 20 welded panels (from plates which were copper coated) were inspected using the same radiographic technique as was used on the control panels. Examination of the x-ray film showed clear indication of the copper remaining in the zone of incomplete penetration. In several panels, the attempt at a tapered incomplete penetration defect resulted in intermittent penetration. This is shown very clearly by the presence of copper, as seen in Figure 13. A typical transition from incomplete to full penetration weldment is seen in Figure 14. It is very obvious that the copper provides an extremely clear indication of the incomplete penetration defect. This is quite important since incomplete penetration defects are virtually impossible to detect by either radiography or ultrasonic techniques as shown in the tests on the control panels.

Attempts to employ the ultrasonic Delta technique on weldments containing the copper additive were generally unsuccessful. Only those areas which were very near the end of the welded panel could be seen among all the signals from the weldment. In no case was it possible to pick up any signals near the transition from incomplete to full penetration weldment.

With the clear success of the copper additive as a means of detecting incomplete penetration, it does not seem worthwhile to pursue a less discriminating approach, such as Delta-scan. While Delta certainly has its application, such an immersed ultrasonic technique requiring special specimen surface conditions and very high instrumentation sensitivity does not seem the logical approach in this case.

3.5 MECHANICAL PROPERTIES TESTING

The welded panels were all coded with four- or six-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.

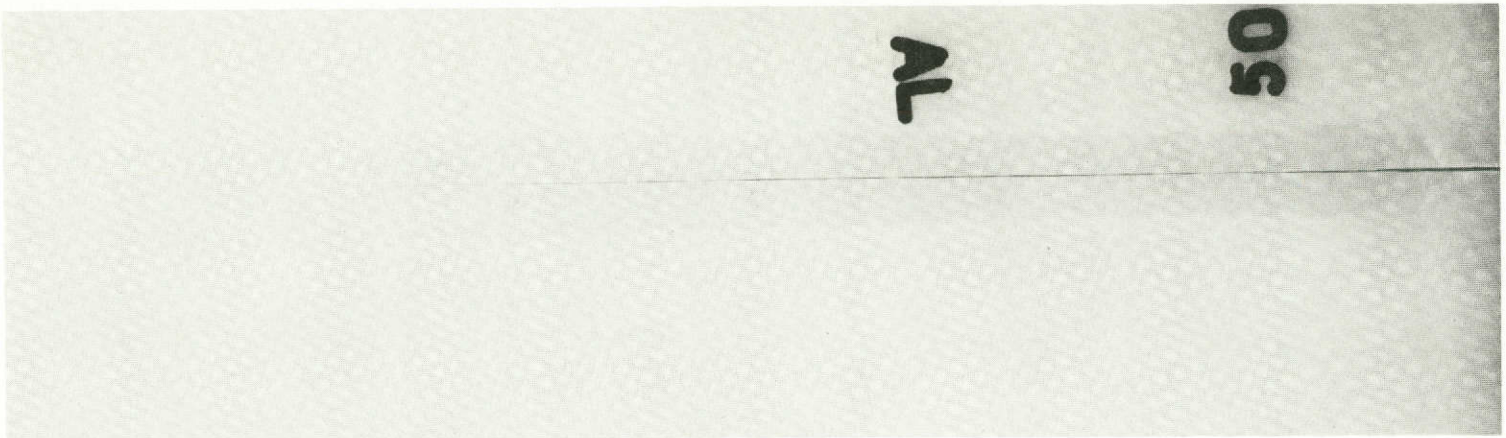


Figure 13. X-Ray Positive Print of Panel 107108 Showing Intermittent Incomplete Penetration

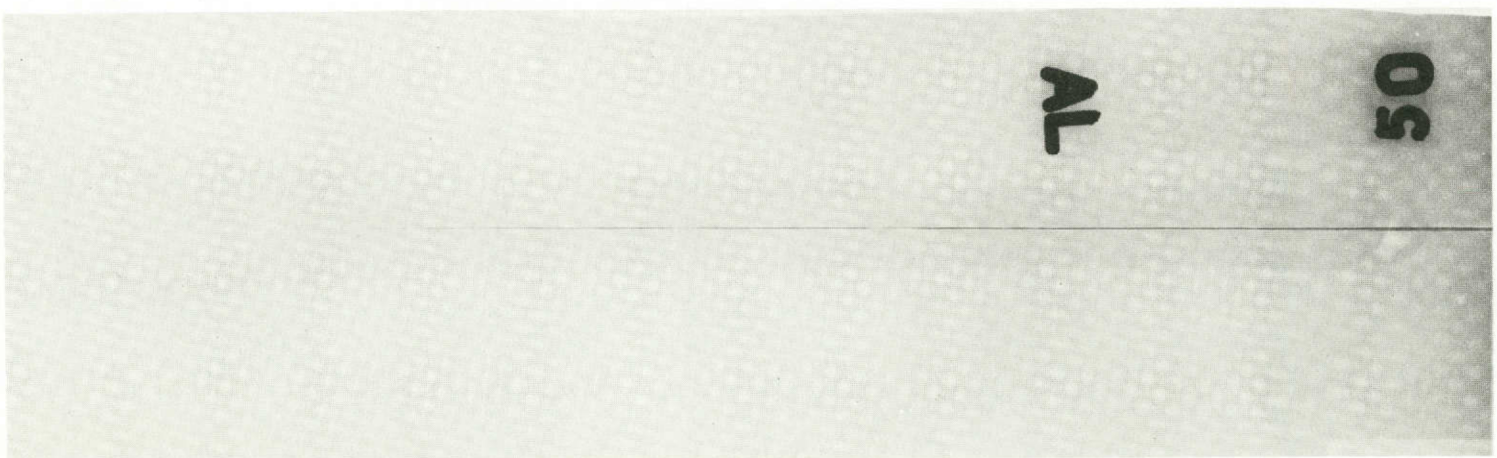


Figure 14. X-Ray Positive Print of Panel 3940 Showing Continuous Incomplete Penetration

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.

The tensile tests were conducted on a Baldwin Universal Testing Machine of 266,880 N (60,000 lb) maximum capacity. The 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.

3.5.1 Results of Phase I Tests

The average results of the tensile tests of the control specimens from panel 0102 are presented in Table 6. The results of the tensile tests of the weldments made with copper deposited on the faying surfaces are presented in Table 6. Complete data on individual specimens are presented in Tables A-4 and A-5 of the Appendix.

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 in both groups of specimens, the control group which had no copper added and the remainder of samples which were taken from the panels having copper on the faying surfaces.

Data from the control group are presented in Table 7. Also, data from the group having a copper additive are presented in Table 7. Complete bend test data in individual specimens are presented in Tables A-10 and A-11 in the Appendix. 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.

Table 6

TENSILE DATA FOR WELDMENTS

Panel 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
Without Copper					
Average, 0102	154.8×10^6	22.5×10^3	270.3×10^6	39.3×10^3	5.3
With Copper					
Average, 0506	144.7×10^6	21.0×10^3	263.2×10^6	38.2×10^3	6.3
Average, 0708	145.9×10^6	21.2×10^3	260.5×10^6	32.8×10^3	5.8
Average, 0910	147.8×10^6	21.4×10^3	262.3×10^6	38.1×10^3	5.9
Average, 1112	148.0×10^6	21.4×10^3	263.7×10^6	38.3×10^3	5.4
Average, 1314	147.4×10^6	21.3×10^3	261.2×10^6	37.9×10^3	5.2
Average, 1516	153.2×10^6	22.2×10^3	261.5×10^6	37.9×10^3	5.1
Average, 2728	146.9×10^6	21.3×10^3	253.3×10^6	36.7×10^3	5.2

Table 7

BEND TEST DATA

Panel Specimen Code	Load at Failure		Percent Elongation 0.0127-m (1/2-in.) Gage	Included Angle	
	N	lb		rad	deg
Control Specimens					
Average, 0102	13,108	2,947	29	2,455	141
With Copper					
Average, 0506	14,189	3,190	26	2,487	143
Average, 0708	15,462	3,476	24	2,509	144
Average, 0910	15,368	3,455	24	2,618	150
Average, 1112	16,408	3,689	27	2,487	143
Average, 1314	15,535	3,493	26	2,495	143
Average, 1516	13,962	3,139	22	2,609	150

3.5.2 Results of Phase II Tests

In the Phase II effort, 10 control panels were welded as described in Subsection 3.3. Nine of these were cut into tensile and bend specimens of the same configuration described in Subsection 3.5.1. Two tensile specimens were tested from each panel, and four bend specimens. Two bend specimens were tested with the top surface in compression, and two with the bottom surface in compression.

Results of the control panel tests are presented in Tables 8 and 9 for tensile and bend results, respectively. These are average values. The complete data are presented in Tables A-8 and A-9 of the Appendix.

Twenty panels were welded containing copper as an opaque additive. Ten of these had the weldment transverse to the original plate rolling direction (Panels 99100 through 117118). Two tensile specimens and four bend specimens from each panel were tested, as previously described for the control panel.

Table 8

AVERAGES OF TENSILE TEST DATA - CONTROL PANELS (NO COPPER ADDED)

Panel No.	Yield Strength N/m^2	Yield Strength psi	Ultimate Strength N/m^2	Ultimate Strength psi	% Elongation 0.0508 m (2 in.)
7778	143.7×10^6	20.9×10^3	268.4×10^6	38.9×10^3	6
7980	153.7×10^6	22.6×10^3	264.8×10^6	38.4×10^3	6
8182	149.1×10^6	21.7×10^3	271.4×10^6	39.4×10^3	6
8384	149.8×10^6	21.8×10^3	266.5×10^6	38.7×10^3	6
8586	146.2×10^6	21.2×10^3	259.2×10^6	37.6×10^3	6
Average of all transverse weldments	148.5×10^6	21.6×10^3	266.0×10^6	38.6×10^3	6
133134	148.0×10^6	21.5×10^3	260.3×10^6	37.8×10^3	6
135136	149.2×10^6	21.6×10^3	255.7×10^6	37.1×10^3	6
139140	144.7×10^6	21.0×10^3	256.5×10^6	37.2×10^3	6
141142	131.5×10^6	19.1×10^3	258.2×10^6	37.5×10^3	6
Average of all longitudinal weldments	143.3×10^6	20.8×10^3	257.6×10^6	37.4×10^3	6

The tensile results are presented (average values for each panel) in Table 10 and bend test data in Table 11. Complete data are shown in Table A-10 and A-11 of the Appendix.

The statistical evaluation was based on tensile yield (0.2-percent offset) data which has been presented in Tables 6, 8, and 10.

It was necessary to determine if the addition of copper had caused a significant change in the mechanical properties of the weldments. Calculations were made to determine whether there was a significant difference between the means of two samples being compared.

Table 9

AVERAGES OF BEND TEST DATA - CONTROL PANELS
(NO COPPER ADDED)

Panel No.	Failure Load		Included Angle		% Elongation 0.0508m (1/2 in.)
	Newtons	Pounds	Radians	Degrees	
7778	14,439	3,246	2.487	142.5	29
7980	13,967	3,140	2.541	145.6	29
8182	13,733	3,088	2.509	143.8	26
8384	14,595	3,281	2.444	140.0	32
8586	14,189	3,190	2.476	141.9	27
Average of all transverse weldments	14,185	3,189	2.491	142.8	29
133134	12,777	2,873	2.476	141.9	28
135136	14,367	3,230	2.448	140.3	28
139140	12,620	2,838	2.467	141.4	27
141142	12,726	2,760	2.487	142.5	24
Average of all longitudinal weldments	13,123	2,925	2.470	141.5	27

The value of the t statistic was calculated by the formula:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^{1/2}}$$ (Reference 10)

Table 10

AVERAGES OF TENSILE SPECIMENS FROM TEST PANELS WITH COPPER ADDED

Weldments Transverse to Plate Rolling Direction

Panel Code	Yield N/m^2	Yield psi	Ultimate N/m^2	Ultimate psi	% Elongation 0.0508m (2 in.)
3738	151.5×10^6	22.0×10^3	264.9×10^6	38.5×10^3	5.8
3940	143.4×10^6	20.8×10^3	262.8×10^6	38.1×10^3	5.8
4142	143.8×10^6	20.9×10^3	263.4×10^6	38.2×10^3	6.0
4344	146.4×10^6	21.3×10^3	263.0×10^6	38.2×10^3	6.0
4546	150.3×10^6	21.8×10^3	267.0×10^6	38.8×10^3	6.3
4748	140.8×10^6	20.4×10^3	259.9×10^6	37.7×10^3	5.5
4950	149.5×10^6	21.7×10^3	258.2×10^6	37.5×10^3	5.8
5152	144.3×10^6	21.0×10^3	265.8×10^6	38.6×10^3	6.0
5354	143.1×10^6	20.8×10^3	267.4×10^6	38.8×10^3	6.3
5556	144.9×10^6	21.0×10^3	261.9×10^6	38.0×10^3	6.3
Average	145.8×10^6	21.2×10^3	263.4×10^6	38.2×10^3	6.0

Weldments Parallel to Plate Rolling Direction

Panel Code	Yield N/m^2	Yield psi	Ultimate N/m^2	Ultimate psi	% Elongation 0.0508m (2 in.)
99100	140.1×10^6	20.4×10^3	261.3×10^6	37.9×10^3	6.5
101102	147.0×10^6	21.3×10^3	260.0×10^6	37.7×10^3	6.5
103104	141.1×10^6	20.5×10^3	253.7×10^6	36.8×10^3	6.0
105106	153.8×10^6	22.3×10^3	278.0×10^6	40.4×10^3	6.5
107108	141.1×10^6	20.5×10^3	266.3×10^6	38.6×10^3	6.0
109110	151.5×10^6	22.0×10^3	275.0×10^6	39.9×10^3	6.0
111112	148.0×10^6	21.5×10^3	251.9×10^6	36.6×10^3	5.3
113114	140.6×10^6	20.4×10^3	259.9×10^6	37.7×10^3	5.3
115116	142.6×10^6	20.7×10^3	271.0×10^6	39.4×10^3	6.0
117118	147.6×10^6	21.4×10^3	271.3×10^6	39.4×10^3	6.0
Average	145.3×10^6	21.1×10^3	264.8×10^6	38.4×10^3	6.0

Table 11

AVERAGES OF BEND TEST SPECIMENS FROM TEST PANELS WITH COPPER ADDED

Weldments Transverse to Plate Rolling Direction

Number	Failure Load		Included Angle		% Elongation 0.0127m (1/2 in.)
	Newtons	Pounds	Radians	Degress	
3738	15, 368	3, 455	2. 548	146	26
3940	14, 384	3, 234	2. 613	150	23
4142	15, 271	3, 433	2. 563	147	25
4344	15, 123	3, 400	2. 570	147	21
4546	15, 357	3, 453	2. 530	145	24
4748	14, 167	3, 185	2. 544	146	25
4950	14, 678	3, 300	2. 535	145	25
5152	14, 245	3, 203	2. 478	142	28
5354	14, 390	3, 235	2. 570	147	21
5556	14, 462	3, 251	2. 509	144	28
Average	14, 745	3, 315	2. 546	146	25
	Weldments Parallel to Plate Rolling Direction				
99100	13, 105	2, 946	2. 578	148	23
101102	13, 711	3, 083	2. 504	144	22
103104	13, 289	2, 988	2. 583	148	23
105106	14, 295	3, 214	2. 426	139	29
107108	14, 017	3, 151	2. 530	145	23
109110	13, 806	3, 104	2. 539	146	23
111112	14, 006	3, 149	2. 482	142	28
113114	14, 272	3, 209	2. 513	144	25
115116	13, 594	3, 056	2. 535	145	25
117118	14, 462	3, 251	2. 508	144	26
Average	13, 856	3, 115	2. 520	145	25

where

$\overline{X}$ = the mean of a sample

S^2 = variance of a sample

n = number of specimens in a sample

The resulting value of t is then compared to those obtained from a t Table (Reference 11). The degrees of freedom is calculated by the formula:

$$df = \left[\frac{C^2}{n_1 - 1} + \frac{(1 - C)^2}{n_2 - 1} \right]^{-1} \qquad \text{(Reference 10)}$$

where the value of C is calculated by:

$$C = \frac{\dfrac{S_1^{\,2}}{n_1}}{\dfrac{S_1^{\,2}}{n_1} + \dfrac{S_2^{\,2}}{n_2}} \qquad \text{(Reference 10)}$$

Data from Phase I was in two samples, one control and one which employed copper as an additive. The value of t was 2.86 and the degrees of freedom was 8. In the t table of Reference 11, at 8 degrees of freedom, the following data were presented.

Level of Significance (%)	Value
10	1.86
5	2.31
2	2.90
1	3.36

The above value of t = 2.86 is greater than the table value at a 5-percent level of significance, and it can be assumed there is a significant difference between the means. However, the t = 2.86 is less than the value at a 2-percent level of significance and therefore the means are not significantly different at that level of significance.

In the Phase II effort, comparisons were made between control and copper coated panels for weldments transverse to the original plate rolling direction, and for weldments parallel to the plate rolling direction. The calculated t values and degrees of freedom are given below:

Transverse weldments:	t = 1.04	df = 13
Parallel weldments:	t = 0.704	df = 10

In each case, the values were less than those listed at the 5-percent level of significance. Therefore, it can be stated that the means of the two samples were not significantly different at the 5-percent level of significance.

3.6 METALLOGRAPHIC AND CHEMICAL 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.

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.

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

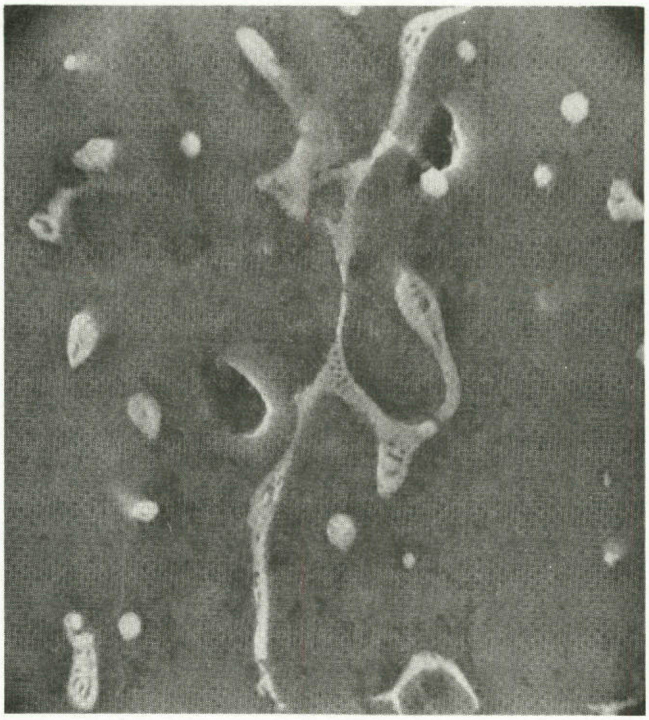
Table 12

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

segregate in the microstructure in a detrimental manner. As shown in Figure 15, however, the microstructures of the two weldments are very similar.

To verify the similarity further, the scanning electron microscope was used to determine the relative copper content of the matrix and precipitate in both microstructures. Figure 16 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.



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 15. Comparison of Weldment Microstructure With and Without Copper Additive

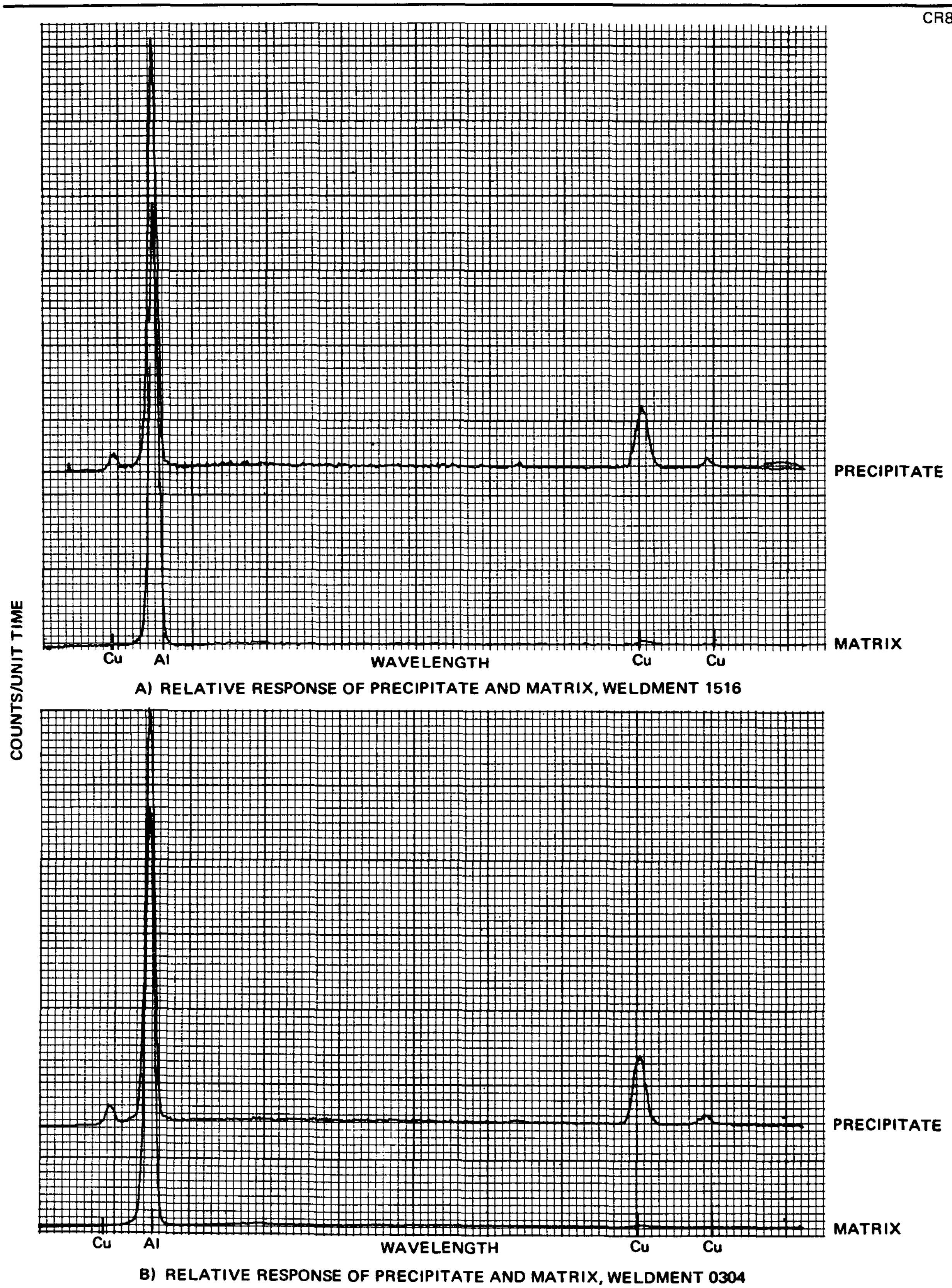


Figure 16. X-Ray Response of Aluminum and Copper in Precipitate and Matrix of Microstructure of Weldments 0304 and 1516

Section 4
DISCUSSION AND CONCLUSIONS

The results of this effort are very positive and encouraging. Copper addition to weldments in the form of vacuum-vapor-deposited coatings on the abutting surfaces has met the primary objective of the effort, the enhancement of x-ray detection of incomplete weldment penetration.

The vacuum-vapor-deposition process proved 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 did 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. The plasma-spray procedure, however, was not fully optimized. Laboratory experiments with peen plating were partially successful, the concept was shown as a potentially suitable means of plating copper on an aluminum surface. It became apparent however, that additional work is needed to work out optimum procedure.

The addition of copper to the faying surfaces has a distinct effect upon the welding process. The parameters developed for uncoated panels had to be changed for panels which had been copper coated along the joined edges. This effect seemed to be a function of copper thickness since panels coated with a 5.08×10^{-5}-m (2×10^{-3}-in.) thick layer were considerably more difficult to weld than those with a copper coating under 2.54×10^{-5}-m (1×10^{-3}-in.) thick. The thickest copper coating of 5.08×10^{-5}-m (2×10^{-3}-in.) made the welding operation very difficult, and a consistent weldment could not be produced. A very thin layer of copper, however, 5.08×10^{-6}-m (2×10^{-4}-in.) thick had very minor effects, and when the parameters had been adjusted, welding continued without problems. A thin layer of copper of uniform thickness, therefore, is most advantageous from a welding standpoint.

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 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. The results of the Phase II effort prove beyond any doubt the applicability of the opaque additive concept to aluminum weldment inspection. When thick section weldments require passes from each surface, the possibility of an incomplete penetration defect exists. It has been clearly shown by this work, and past effort, (Reference 1) that such buried defects are virtually impossible to detect during inspection. The addition of as little as 5.08×10^{-6} m (2×10^{-4} in.) of copper to the faying surfaces, however, significantly enhances the x-ray inspection. Visual interpretations of the x-ray film is very easy; any areas of incomplete penetration are clearly shown. While it is not known how long unprotected aluminum can be stored and satisfactorily welded, the copper certainly prevents or slows oxidation and therefore is beneficial as a protective coating.

Application of the opaque additive concept depends upon some reasonable means of applying the copper to the faying surfaces of the two members to be welded. In this program, vacuum vapor deposition was employed and worked very well. This approach provides a very smooth, uniform copper layer that can be applied in very thin sections. The only problem with this approach is in the equipment and procedures for applying the copper. A vacuum system must be provided and a means of heating the copper to the molten state. Stationary equipment limits the size of the parts to be coated. Portable and sliding seal equipment has been developed and used for electron beam welding and could conceivably be adapted to vacuum vapor deposition requirements of copper on aluminum.

It seems that another less complex approach to copper deposition on aluminum should be available. This program explored the possibility of employing peen plating as a means of applying the copper. The work showed that copper can be peened on aluminum, although the resultant coating was not uniform and did not provide complete coverage. Sufficient information to determine optimum stream velocity, bead and particle size, and quantity ratios of glass beads to copper powder was not obtained. Therefore, it was not possible to make any prediction of actual deposition rates. Clearly more work need to be done in this area.

However, the peen plating approach does appear to be a viable means of applying an opaque additive to faying surfaces of large structural members prior to welding. The peen plating process is quite simple. There are no atmosphere requirements, no heating requirements, no vacuum seals, and no severe cleaning criteria. The only critical items are a means of introducing the glass beads and copper powder into the airstream separately, and a particle and dust retention and collecting system capable of moving along the edge of a large structural panel. The cost of such a system should be minor. This approach appears within the current state-of-the-art but requires additional effort to make it applicable on a practical basis.

Based upon the work conducted in this program and the factors which have been discussed, several significant conclusions can be made.

A. Film radiography of weldments can be significantly enhanced by addition of a very thin copper coating, 5.08×10^{-6} m (2×10^{-4} in.), on each faying surface. The appearance of incomplete penetration defects is very distinct on the x-ray film.

B. There are no significant effects in alloy chemistry or mechanical properties as a result of the addition of copper to the weldment.

C. The addition of copper to the faying surfaces does affect the welding parameters and must be taken into account. The thinner the copper coating, the less the influence on the welding parameters. Copper coatings 5.08×10^{-6}-m (2×10^{-4}-in.) thick have a relatively minor effect and the welding parameters can be easily adjusted.

D. Peen plating is a simple, viable approach worthy of further study. Additional effort is needed to develop efficient application practice.

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Section 5
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Appendix A

This appendix presents detailed data regarding the welding parameters and procedure; and complete mechanical properties data from both phases of the program.

Table A-1

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

Table A-2

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

	Arc-Volts	Wire Speed (m/minute)	Wire Speed (ipm)	Travel Speed (m/minute)	Travel Speed (ipm)	
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						
m81						
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 A-3

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^{o} Torch Lead Angle

Table A-4

TENSILE DATA FOR WELDMENTS WITHOUT COPPER – PHASE I

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 A-5

TENSILE DATA FOR WELDMENTS WITH VARIOUS THICKNESSES OF COPPER ADDED – PHASE I

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
0506T1	142.7×10^6	20.7×10^3	260.0×10^6	37.7×10^3	6.0
0506T2	144.3×10^6	20.9×10^3	267.5×10^6	38.8×10^3	7.0
0506T3	143.7×10^6	20.8×10^3	266.5×10^6	38.7×10^3	6.0
0506T4	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
0708T1	145.1×10^6	21.0×10^3	256.1×10^6	37.2×10^3	6.0
0708T2	140.7×10^6	20.4×10^3	258.0×10^6	37.4×10^3	5.5
0708T3	145.7×10^6	21.1×10^3	267.6×10^6	38.8×10^3	6.5
0708T4	147.3×10^6	21.4×10^3	252.6×10^6	36.6×10^3	5.0
0708T5	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 A-5

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 A-5

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 A-5

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)	
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

Table A-6

BEND TEST DATA FOR CONTROL SPECIMENS, PANEL 0102 – PHASE I

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 A-7

BEND TEST DATA FOR SPECIMENS WELDED WITH COPPER ADDITIVE – PHASE I

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

Table A-8

INDIVIDUAL SPECIMEN TENSILE DATA, CONTROL PANELS—PHASE II

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
7778T1	134.5×10^6	19.5×10^3	269.0×10^6	39.0×10^3	6
7778T2	152.9×10^6	22.2×10^3	267.8×10^6	38.8×10^3	6
Average	143.7×10^6	20.9×10^3	268.4×10^6	38.9×10^6	6
7980T1	153.6×10^6	22.8×10^3	264.9×10^6	38.4×10^3	6
7980T2	153.7×10^6	22.3×10^3	264.6×10^6	38.4×10^3	6
Average	153.7×10^6	22.6×10^3	264.8×10^6	38.4×10^3	6
8182T1	144.0×10^6	20.9×10^3	266.7×10^6	38.7×10^3	6
8182T2	154.2×10^6	22.4×10^3	276.0×10^6	40.0×10^3	6
Average	149.1×10^6	21.7×10^3	271.4×10^6	39.4×10^3	6
8384T1	141.8×10^6	20.6×10^3	249.8×10^6	36.2×10^3	6
8384T2	157.8×10^6	22.9×10^3	283.1×10^6	41.1×10^3	6
Average	149.8×10^6	21.8×10^3	266.5×10^6	38.7×10^3	6
8586T1	142.7×10^6	20.7×10^3	259.4×10^6	37.6×10^3	6
8586T2	149.6×10^6	21.7×10^3	259.0×10^6	37.6×10^3	
Average	146.2×10^6	21.2×10^3	259.2×10^6	37.6×10^3	6

Table A-8

INDIVIDUAL SPECIMEN TENSILE DATA, CONTROL PANELS—PHASE II (Continued)

Specimen Code	Yield N/m^2	Yield psi	Ultimate N/m^2	Ultimate psi	% Elongation 0.0508m (2 in.)
133134T1	147.2×10^6	21.4×10^3	255.2×10^6	37.0×10^3	6
133134T2	148.7×10^6	21.6×10^3	265.3×10^6	38.5×10^3	6
Average	148.0×10^6	21.5×10^3	260.3×10^6	37.8×10^3	6
135136T1	147.1×10^6	21.3×10^3	247.7×10^6	35.9×10^3	6
135136T2	151.3×10^6	21.9×10^3	263.6×10^6	38.2×10^3	6
Average	149.2×10^6	21.6×10^3	255.7×10^6	37.1×10^3	6
139140T1	142.4×10^6	20.7×10^3	250.0×10^6	36.3×10^3	6
139140T2	146.9×10^6	21.3×10^3	262.9×10^6	38.1×10^3	6
Average	144.7×10^6	21.0×10^3	256.5×10^6	37.2×10^3	6
141142T1	131.6×10^6	19.1×10^3	256.4×10^6	37.2×10^3	6
141142T2	131.3×10^6	19.1×10^3	259.9×10^6	37.7×10^3	6
Average	131.5×10^6	19.1×10^3	258.2×10^6	35.5×10^3	6

Table A-9

INDIVIDUAL SPECIMEN BEND DATA, CONTROL PANELS—PHASE II

Specimen Code	Failure Load		Included Angle		% Elongation
	Newtons	Pounds	Radians	Degrees	0.0127 m (1/2 in.)
7778B1	14,278	3,210	2.513	144.0	29
7778B2	14,678	3,300	2.513	144.0	29
7778B3	14,456	3,250	2.460	141.0	29
7778B4	14,345	3,225	2.460	141.0	30
Average	14,439	3,246	2.487	142.5	29
7980B1	13,900	3,125	2.548	146.0	29
7980B2	12,677	2,850	2.583	148.0	25
7980B3	14,723	3,310	2.574	147.5	29
7980B4	14,567	3,275	2.460	141.0	34
Average	13,967	3,140	2.541	145.6	29
8182B1	14,456	3,250	2.548	146.0	29
8182B2	13,522	3,040	2.548	146.0	25
8182B3	13,388	3,010	2.522	144.5	25
8182B4	13,566	3,050	2.417	138.5	25
Average	13,733	3,088	2.509	143.8	26
8384B1	14,567	3,275	2.460	141.0	30
8384B2	13,789	3,100	2.443	140.0	34
8384B3	15,234	3,425	2.382	136.5	34
8384B4	14,790	3,325	2.487	142.5	30
Average	14,595	3,281	2.444	140.0	32

Table A-9

INDIVIDUAL SPECIMEN BEND DATA, CONTROL PANELS—PHASE II (Continued)

Specimen Code	Failure Load		Included Angle		% Elongation
	Newtons	Pounds	Radians	Degrees	0.0127m (1/2 in.)
8586B1	14,011	3,150	2.513	144.0	30
8586B2	14,456	3,250	2.426	139.0	25
8586B3	14,723	3,310	2.504	143.5	25
8586B4	13,566	3,050	2.460	141.0	29
Average	14,189	3,190	2.476	141.9	27
133134B1	12,410	2,790	2.443	140.0	25
133134B2	12,010	2,700	2.434	139.5	29
133134B3	14,011	3,150	2.504	143.5	29
133134B4	12,677	2,850	2.522	144.5	29
Average	12,777	2,873	2.476	141.9	28
135136B1	13,967	3,140	2.443	140.0	30
135136B2	14,634	3,290	2.391	137.0	30
135136B3	14,189	3,190	2.487	142.5	25
135136B4	14,678	3,300	2.469	141.5	25
Average	14,367	3,230	2.448	140.3	28
139140B1	12,561	2,825	2.495	143.0	25
139140B2	12,454	2,800	2.460	141.0	29
139140B3	12,232	2,750	2.443	140.0	25
139140B4	13,233	2,975	2.469	141.5	30
Average	12,620	2,838	2.467	141.4	27

Table A-9

INDIVIDUAL SPECIMEN BEND DATA, CONTROL PANELS—PHASE II (Continued)

Specimen Code	Failure Load		Included Angle		% Elongation
	Newtons	Pounds	Radians	Degrees	0.0127 m (1/2 in.)
141142B1	13,010	2,925	2.504	143.5	25
141142B2	12,454	2,800	2.522	144.5	21
141142B3	11,298	2,540	2.443	140.0	25
141142B4	12,343	2,775	2.478	142.0	25
Average	12,726	2,760	2.487	142.5	24

Table A-10

INDIVIDUAL SPECIMEN TENSILE DATA, PANELS WITH COPPER ADDED—PHASE II

Specimen Code	Yield		Ultimate		% Elongation 0.0508m (2 in.)
	N/m^2	psi	N/m^2	psi	
3738T1	149.1×10^6	21.6×10^3	268.4×10^6	38.9×10^3	6.0
3738T2	153.8×10^6	22.3×10^3	261.4×10^6	38.0×10^3	5.5
Average	151.5×10^6	22.0×10^3	264.9×10^6	38.5×10^3	5.8
3940T1	147.6×10^6	21.4×10^3	262.0×10^6	38.0×10^3	5.5
3940T2	139.2×10^6	20.2×10^3	263.5×10^6	38.2×10^3	6.0
Average	143.4×10^6	20.8×10^3	262.8×10^6	38.1×10^3	5.8
4142T1	144.4×10^6	20.9×10^3	262.0×10^6	38.0×10^3	6.0
4142T2	143.2×10^6	20.8×10^3	264.8×10^6	38.4×10^3	6.0
Average	143.8×10^6	20.9×10^3	263.4×10^6	38.2×10^3	6.0
4344T1	143.8×10^6	20.9×10^3	262.6×10^6	38.1×10^3	6.0
4344T2	148.9×10^6	21.6×10^3	263.4×10^6	38.2×10^3	6.0
Average	146.4×10^6	21.3×10^3	263.0×10^6	38.2×10^3	6.0
4546T1	148.9×10^6	21.6×10^3	265.3×10^6	38.5×10^3	6.5
4546T2	151.7×10^6	22.0×10^3	268.6×10^6	39.0×10^3	6.0
Average	150.3×10^6	21.8×10^3	267.0×10^6	38.8×10^3	6.3

Table A-10

INDIVIDUAL SPECIMEN TENSILE DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
4748T1	137.9×10^6	20.0×10^3	257.8×10^6	37.4×10^3	5.5
4748T2	143.6×10^6	20.8×10^3	261.9×10^6	38.0×10^3	5.5
Average	140.8×10^6	20.4×10^3	259.9×10^6	37.7×10^3	5.5
4950T1	145.9×10^6	21.2×10^3	259.7×10^6	37.7×10^3	5.5
4950T2	153.0×10^6	22.2×10^3	256.7×10^6	37.2×10^3	6.0
Average	149.5×10^6	21.7×10^3	258.2×10^6	37.5×10^3	5.8
5152T1	139.8×10^6	20.3×10^3	259.9×10^6	37.7×10^3	6.0
5152T2	148.7×10^6	21.6×10^3	271.7×10^6	39.4×10^3	6.0
Average	144.3×10^6	21.0×10^3	265.8×10^6	38.6×10^3	6.0
5354T1	139.7×10^6	20.3×10^3	266.8×10^6	38.7×10^3	6.0
5354T2	146.4×10^6	21.2×10^3	267.9×10^6	38.9×10^3	6.5
Average	143.1×10^6	20.8×10^3	267.4×10^6	38.8×10^3	6.3
5556T1	147.1×10^6	21.3×10^3	255.1×10^6	37.0×10^3	6.0
5556 T2	142.7×10^6	20.7×10^3	268.7×10^6	39.0×10^3	6.5
Average	144.9×10^6	21.0×10^3	261.9×10^6	38.0×10^3	6.3

Table A-10

INDIVIDUAL SPECIMEN TENSILE DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
99100T1	141.3×10^6	20.5×10^3	260.4×10^6	37.7×10^3	6.5
99100T2	138.9×10^6	20.2×10^3	262.1×10^6	38.0×10^3	6.5
Average	140.1×10^6	20.4×10^3	261.3×10^6	37.9×10^3	6.5
101102T1	-	-	260.6×10^6	37.8×10^3	6.5
101102T2	147.0×10^6	21.3×10^3	259.4×10^6	37.6×10^3	6.5
Average	147.0×10^6	21.3×10^3	260.0×10^6	37.7×10^3	6.5
103104T1	140.9×10^6	20.4×10^3	263.6×10^6	38.2×10^3	6.0
103104T2	141.3×10^6	20.5×10^3	243.7×10^6	35.4×10^3	6.0
Average	141.1×10^6	20.5×10^3	253.7×10^6	36.8×10^3	6.0
105106T1	154.3×10^6	22.4×10^3	277.0×10^6	40.2×10^3	6.5
105106T2	153.3×10^6	22.2×10^3	278.9×10^6	40.5×10^3	6.5
Average	153.8×10^6	22.3×10^3	278.0×10^6	40.4×10^3	6.5
107108T1	144.1×10^6	20.9×10^3	268.4×10^6	38.9×10^3	6.0
107108T2	138.0×10^6	20.0×10^3	264.2×10^6	38.3×10^3	6.0
Average	141.1×10^6	20.5×10^3	266.3×10^6	38.6×10^3	6.0

Table A-10

INDIVIDUAL SPECIMEN TENSILE DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Yield		Ultimate		% Elongation 0.0508 m (2 in.)
	N/m^2	psi	N/m^2	psi	
109110T1	150.9×10^6	21.9×10^3	276.4×10^6	40.1×10^3	6.0
109110T2	152.0×10^6	22.0×10^3	273.5×10^6	39.7×10^3	6.0
Average	151.5×10^6	22.0×10^3	275.0×10^6	39.9×10^3	6.0
111112T1	144.4×10^6	20.9×10^3	261.0×10^6	37.9×10^3	5.0
111112T2	151.5×10^6	22.0×10^3	242.8×10^6	35.2×10^3	5.5
Average	148.0×10^6	21.5×10^3	251.9×10^6	36.6×10^3	5.3
113114T1	139.2×10^6	20.2×10^3	262.9×10^6	38.1×10^3	5.5
113114T2	141.9×10^6	20.6×10^3	256.8×10^6	37.3×10^3	5.0
Average	140.6×10^6	20.4×10^3	259.9×10^6	37.7×10^3	5.3
115116T1	142.0×10^6	20.6×10^3	273.4×10^6	39.7×10^3	6.0
115116T2	143.1×10^6	20.8×10^3	268.6×10^6	39.0×10^3	6.0
Average	142.6×10^6	20.7×10^3	271.0×10^6	39.4×10^3	6.0
117118T1	146.2×10^6	21.2×10^3	263.4×10^6	38.2×10^3	6.0
117118T2	148.9×10^6	21.6×10^3	279.2×10^6	40.5×10^3	6.0
Average	147.6×10^6	21.4×10^3	271.3×10^6	39.4×10^3	6.0

Table A-11

INDIVIDUAL SPECIMEN BEND DATA, PANELS WITH COPPER ADDED—PHASE II

Specimen Code	Failure Load		Included Angle		% Elongation
	Newtons	lb	Radians	Degrees	0.0127m (1/2 in.)
3738B1	14, 234	3, 200	2. 652	152	21
3738B2	15, 835	3, 560	2. 512	144	25
3738B3	15, 835	3, 560	2. 478	142	29
3738B4	15, 568	3, 500	2. 548	146	29
Average	15, 368	3, 455	2. 548	146	26
3940B1	12, 566	2, 825	2. 705	155	25
3940B2	15, 879	3, 570	2. 530	145	25
3940B3	14, 767	3, 320	2. 565	147	25
3940B4	14, 323	3, 220	2. 652	152	18
Average	14, 384	3, 234	2. 613	150	23
4142B1	-	-	-	-	-
4142B2	16, 013	3, 600	2. 460	141	30
4142B3	15, 234	3, 425	2. 548	146	25
4142B4	14, 567	3, 275	2. 687	154	21
Average	15, 271	3, 433	2. 565	147	25
4344B1	14, 122	3, 175	2. 722	156	15
4344B2	14, 901	3, 350	2. 513	144	18
4344B3	16, 013	3, 600	2. 513	144	25
4344B4	15, 457	3, 475	2. 530	145	25
Average	15, 123	3, 400	2. 570	147	21
4546B1	15, 435	3, 470	2. 548	146	25
4546B2	15, 346	3, 450	2. 495	143	21
4546B3	15, 346	3, 450	2. 495	143	29
4546B4	15, 301	3, 440	2. 583	148	21
Average	15, 357	3, 453	2. 530	145	24

Table A-11

INDIVIDUAL SPECIMEN BEND DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

Specimen Code	Failure Load		Included Angle		% Elongation
	Newtons	lb	Radians	Degrees	0.0127m (1/2 in.)
4748B1	12, 899	2, 900	2. 670	153	22
4748B2	14, 234	3, 200	2. 635	151	20
4748B3	14, 634	3, 290	2. 443	140	28
4748B4	14, 901	3, 350	2. 426	139	28
Average	14, 167	3, 185	2. 544	146	25
4950B1	14, 189	3, 190	2. 565	147	25
4950B2	14, 901	3, 350	2. 478	142	29
4950B3	15, 123	3, 400	2. 495	143	25
4950B4	14, 500	3, 260	2. 600	149	21
Average	14, 678	3, 300	2. 535	145	25
5152B1	14, 589	3, 280	2. 443	140	28
5152B2	13, 566	3, 050	2. 635	151	24
5152B3	14, 589	3, 280	2. 338	134	30
5152B4	14, 234	3, 200	2. 495	143	30
Average	14, 245	3, 203	2. 478	142	28
5354B1	14, 545	3, 270	2. 565	147	24
5354B2	14, 545	3, 270	2. 548	146	24
5354B3	14, 234	3, 200	2. 565	147	16
5354B4	14, 234	3, 200	2. 600	149	18
Average	14, 390	3, 235	2. 570	147	21
5556B1	13, 300	2, 990	2. 670	153	21
5556B2	15, 123	3, 400	2. 426	139	30
5556B3	15, 012	3, 375	2. 408	138	34
5556B4	14, 412	3, 240	2. 530	145	25
Average	14, 462	3, 251	2. 509	144	28

Table A-11

INDIVIDUAL SPECIMEN BEND DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

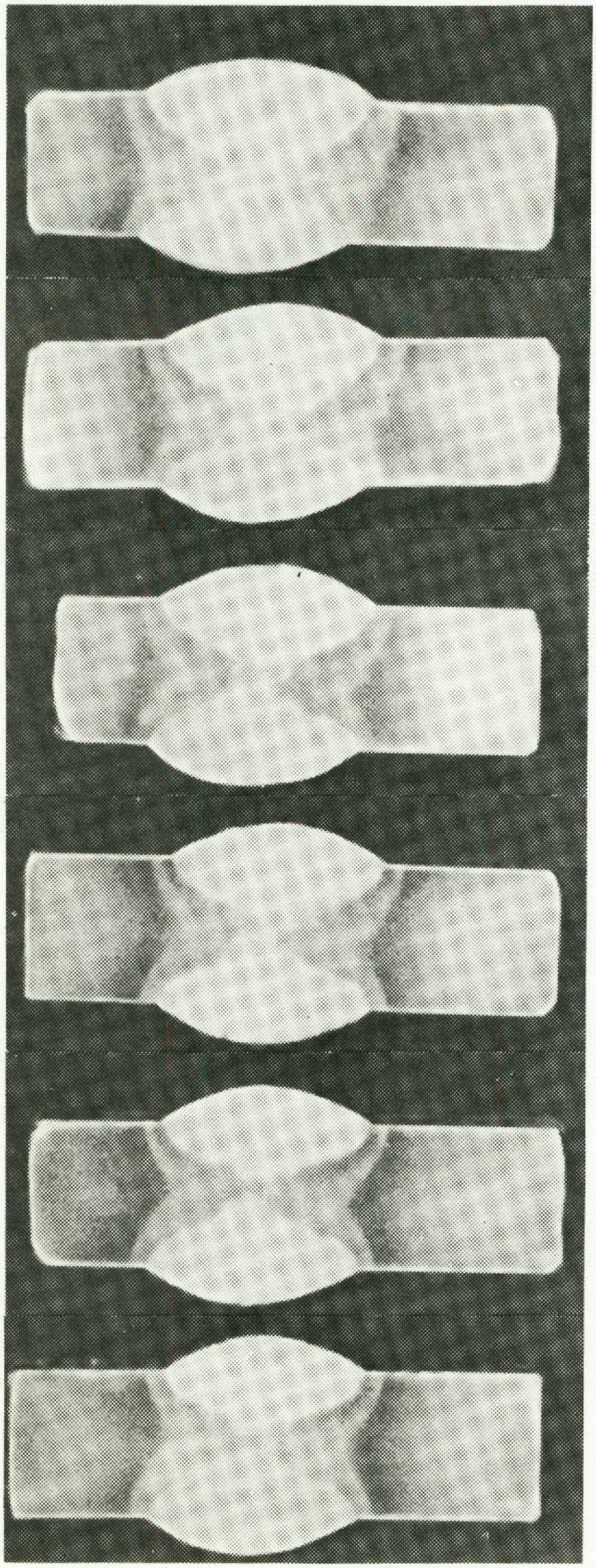
Specimen Code	Failure Load		Included Angle		% Elongation 0.0127 m (1/2 in.)
	Newtons	lb	Radians	Degrees	
99100B1	11,231	2,525	2.687	154	22
99100B2	14,011	3,150	2.513	144	20
99100B3	13,878	3,120	2.530	145	24
99100B4	13,300	2,990	2.583	148	24
Average	13,105	2,946	2.578	148	23
101102B1	13,967	3,140	2.460	141	24
101102B2	14,056	3,160	2.443	140	22
101102B3	13,344	3,000	2.530	145	20
101102B4	13,477	3,030	2.583	148	20
Average	13,711	3,083	2.504	144	22
103104B1	12,410	2,790	2.583	148	21
103104B2	13,811	3,105	2.600	149	20
103104B3	13,811	3,105	2.513	144	26
103104B4	13,122	2,950	2.635	151	24
Average	13,289	2,988	2.583	148	23
105106B1	14,478	3,255	2.356	135	30
105106B2	14,367	3,230	2.408	138	30
105106B3	14,234	3,200	2.443	140	28
105106B4	14,100	3,170	2.495	143	26
Average	14,295	3,214	2.426	139	29
107108B1	12,810	2,880	2.722	156	15
107108B2	14,678	3,300	2.356	135	34
107108B3	14,234	3,200	2.530	145	18
107108B4	14,345	3,225	2.513	144	25
Average	14,017	3,151	2.530	145	23

Table A-11

INDIVIDUAL SPECIMEN BEND DATA, PANELS WITH COPPER ADDED—PHASE II (Continued)

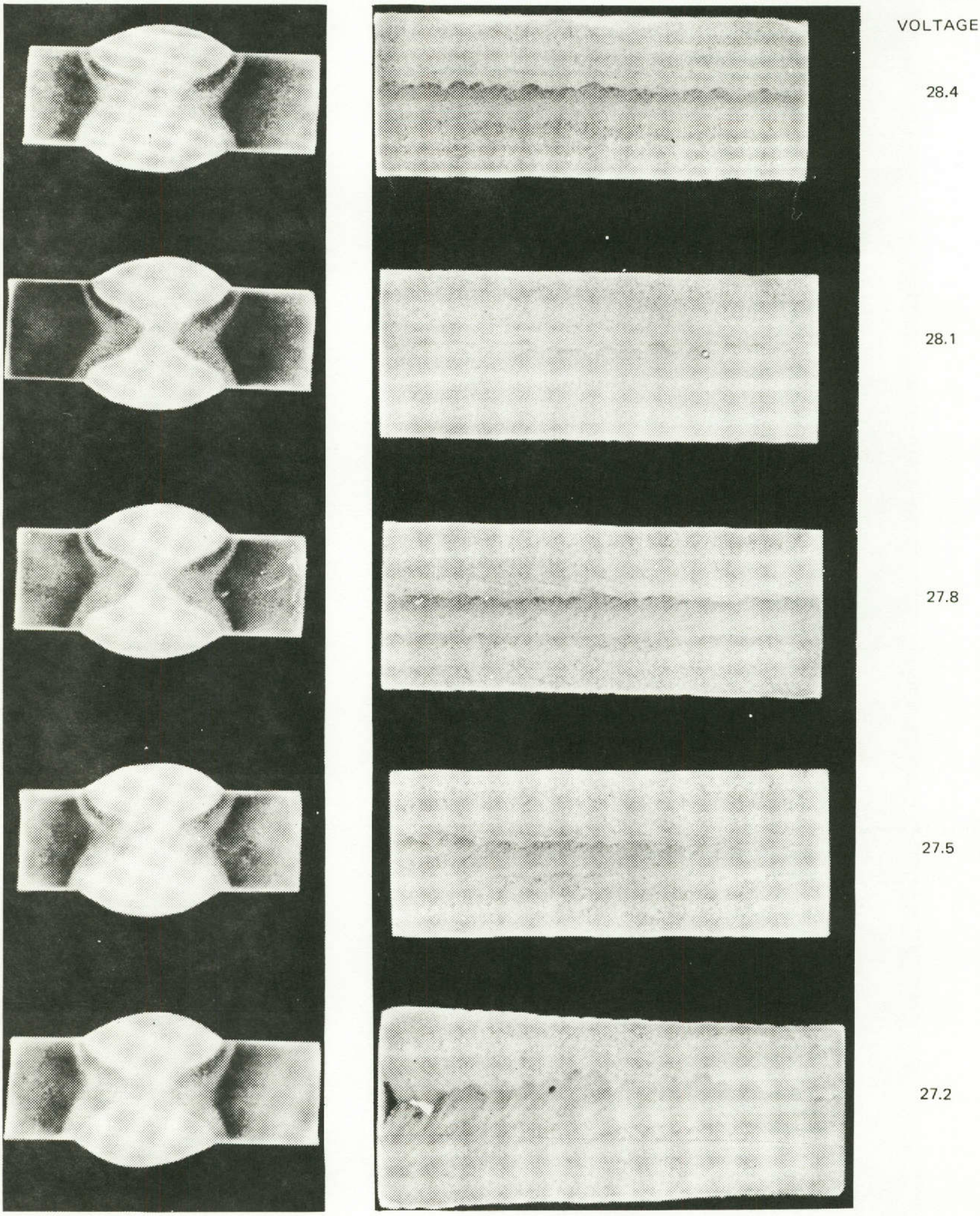
Specimen Code	Failure Load		Included Angle		% Elongation 0.0127 m (1/2 in.)
	Newtons	lb	Radians	Degrees	
109110B1	13, 122	2, 950	2. 600	149	21
109110B2	14, 790	3, 325	2. 373	136	30
109110B3	13, 166	2, 960	2. 670	153	15
109110B4	14, 145	3, 180	2. 513	144	25
Average	13, 806	3, 104	2. 539	146	23
111112B1	14, 189	3, 190	2. 443	140	28
111112B2	13, 967	3, 140	2. 495	143	28
111112B3	13, 900	3, 125	2. 443	140	30
111112B4	13, 967	3, 140	2. 548	146	26
Average	14, 006	3, 149	2. 482	142	28
113114B1	14, 011	3, 150	2. 565	147	21
113114B2	14, 500	3, 260	2. 460	141	30
113114B3	14, 456	3, 250	2. 426	139	29
113114B4	14, 122	3, 175	2. 600	149	21
Average	14, 272	3, 209	2. 513	144	25
115116B1	12, 010	2, 700	2. 600	149	24
115116B2	14, 456	3, 250	2. 478	142	26
115116B3	14, 011	3, 150	2. 530	145	24
115116B4	13, 900	3, 125	2. 530	145	26
Average	13, 594	3, 056	2. 535	145	25
117118B1	13, 789	3, 100	2. 443	140	24
117118B2	15, 368	3, 455	2. 460	141	26
117118B3	14, 234	3, 200	2. 600	149	26
117118B4	14, 456	3, 250	2. 530	145	28
Average	14, 462	3, 251	2. 508	144	26

CR82



WF	VOLTAGE
360	29.7
340	26.7
350	29.7
340	27.3
340	29.7
340	27.9
330	29.7
340	28.7
320	29.7
340	29.1
310	29.7
340	29.7

Figure A-1. Variable Wire Feed and Arc Voltage Test with 5-Mil Copper Implant



NOTE: WIRE FEED SPEED { 350 IPM FOR FIRST SIDE WELD
345 IPM FOR SECOND SIDE WELD

Figure A-2. Variable Voltage Test (Constant Wire Feed) with 5-Mil Copper Implant