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**ALBUQUERQUE DIVISION**

APPLIED RESEARCH AND DEVELOPMENT



# METALLURGICAL CHARACTERISTICS OF WELDMENTS IN 0.750–INCH–THICK 6061 ALUMINUM

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# 1. INTRODUCTION

1.1 One of the most widely used alloys of aluminum is the alloy designated 6061. This heat-treatable alloy contains relatively small amounts of silicon and magnesium and produces strengths, after heat-treatment, that are of intermediate level, i.e., 35 ksi yield strength.

1.2 Weldability of this alloy, even though heat-treatable, is considered excellent and where section sizes are thin and full post-weld treatments can be conducted, weld efficiencies approach 100%. The normal filler material is alloy 4043 which is a high silicon aluminum alloy and is not, in itself, heat-treatable. Strength levels of weldments utilizing 4043 are dependent upon the degree of base metal dilution achieved in the joint. In thicker sections where little or no dilution is obtained, strength levels are a function of the lower non-heat-treatable 4043 filler unless fillers such as 4643 are used. Alloy 4643 is very similar to 4043 but advantage is taken of the heat-treat response due to small amounts of magnesium, silicon, and copper contained in 4643 (Figure 1). Improvements in thick weldment strength levels utilizing 4643 have been noted in the as-welded, aged-only or fully post-weld heat-treated conditions.

1.3 Heat-treatment of this alloy is of major interest in fabricated weldments. The normal cycle consists of solution-heat-treatment at 990°F, followed by immediate and rapid, cold water quenching (-T4), and with a subsequent eight-hour, 350°F aging treatment (-T6 condition). This treatment produces maximum strength levels on both base metal or fabricated weldments. There are, however, instances where full heat-treatment after welding is impractical if not impossible. The most applicable pre-weld and post-weld material conditions and heat-treatment can be defined as follows:

(a) -T6 material, weld and leave as-welded.

(b) -T6 material, weld and slight age only.

(c) -T4 material, weld and age only.

(d) -T6 material, weld and fully heat-treat.

The final weld characteristics, of course, depend on which of these conditions is used.

# 2. OBJECTIVE

2.1 The objectives of this investigation can be stated as follows:

(a) To weld 3/4-inch-thick 6061 aluminum in various conditions and to evaluate and select the most promising heat-treatment.

(b) To compare this heat-treatment with as-welded properties of 3/4-inch 6061 welded by the MIG manual back pass, automatic back pass, and automatic copper backup techniques.

(c) To determine the effects of various heat-treating cycles on welded plates.

(d) To determine the effects of weld groove configuration and weld procedure.

(e) To establish techniques and data directly applicable to production processing of welded 6061 aluminum.

# 3. PROCEDURE

3.1 Four weld plates were fabricated under each of the following conditions:

| Condition | Original Material | Post-weld Heat-Treatment |
|---|---|---|
| 1 | -T6 | None — As-welded |
| 2 | -T6 | Aged 4 hrs @ 350°F |
| 3 | -T4 | Aged 8 hrs @ 350°F |
| 4 | -T4 | Solution Treat @ 990°F, Water Quench, Age 8 hrs @ 350°F |

3.2 Two additional weld plates were fabricated under Conditions 1 and 2 with the following welding procedures as defined in Figure 2.

| Procedure | Welding Technique |
|---|---|
| A | Hand MIG weld, chip, and back pass |
| B | Automatic MIG weld, chip, and back pass |
| C | Automatic MIG weld, copper backup |

3.3 Welding parameters and groove configuration were monitored and recorded for each weld series. Data recorded included wire alloy, gas cover, current, voltage, wire feed speed, welding speed, number of weld passes, and interpass temperature. This data is included in Figures 3 and 4.

3.4 Testing of plates was conducted with the same pattern layout for specimens in all plates evaluated. Specimen included full-thickness cross-weld, 0.252" diameter all-weld, 0.352" diameter base-metal and cross-weld, guided bends, and macro/micro specimens. The layout plan is shown in Figure 5.

3.5 Further tests were conducted for 30T Rockwell hardness and microprobe chemistry in certain areas of interest.

| Element | % of Element Alloy 6061 | Alloy 4043 | Alloy 4643 |
|---|---|---|---|
| Magnesium | 0.8 - 1.2 | 0.05 max. | 0.10 - 0.30 |
| Silicon | 0.40 - 0.8 | 4.5 - 6.0 | 3.6 - 4.6 |
| Copper | 0.15 - 0.40 | 0.30 max. | 0.10 max. |
| Iron | 0.7 max. | 0.8 max. | 0.8 max. |
| Manganese | 0.15 max. | 0.05 max. | 0.05 max. |
| Chromium | 0.15 - 0.35 | --- | --- |
| Zinc | 0.10 max. | 0.10 max. | 0.10 max. |
| Titanium | 0.15 max. | 0.20 max. | 0.15 max. |
| Aluminum | Balance | Balance | Balance |

Figure 1. CHEMICAL COMPOSITION OF 6061, 4043, AND 4643 ALUMINUM ALLOYS

| Category | Processing |
|---|---|
| Condition 1 | Welded in -T6 temper and left as-welded. |
| Condition 2 | Welded in -T6 temper and aged only, 4 hours at 350° F. |
| Condition 3 | Welded in -T4 temper and aged only, 8 hours at 350° F. |
| Condition 4 | Welded in -T4 temper, solutioned at 990° F, water quenched, and aged 8 hours at 350° F. |
| Procedure A | Same as Conditions 1 and 2, but welded by the Manual MIG process with back pass. |
| Procedure B | Same as Conditions 1 and 2, but welded by Automatic MIG process with back pass. |
| Procedure C | Same as Conditions 1 and 2, but welded by the Automatic MIG process against a copper back-up bar. |

Figure 2. DEFINITION OF WELD PLATE MATERIAL CONDITIONS AND PROCEDURES

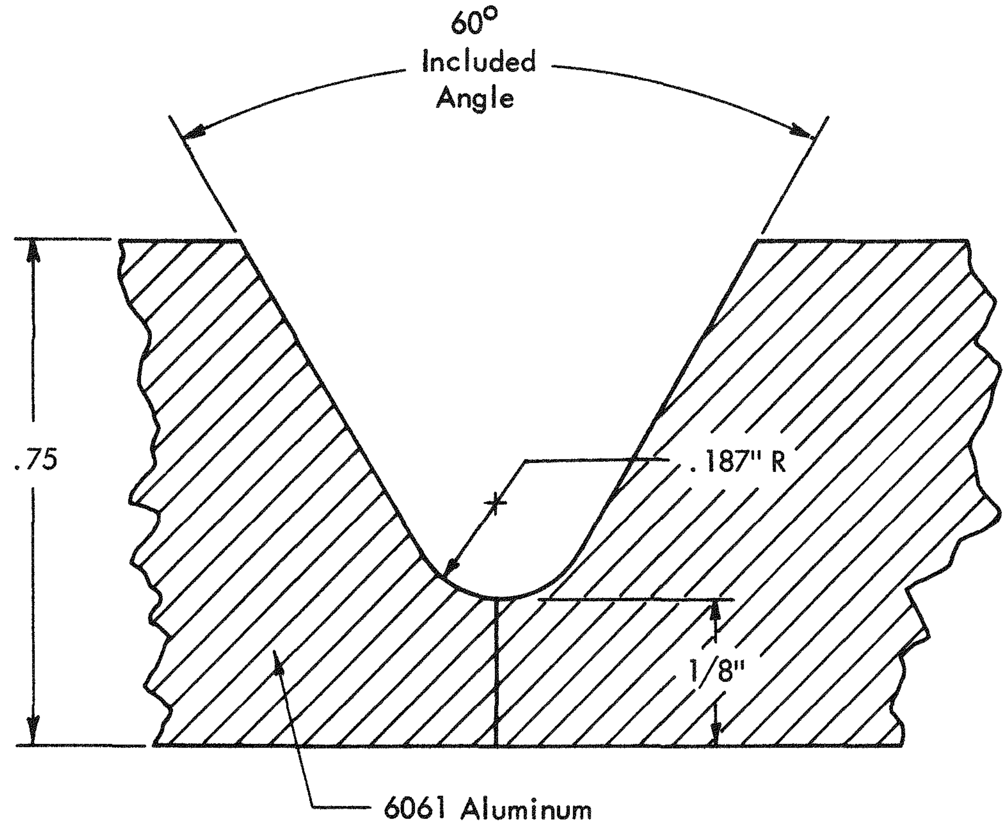



Figure 3. GROOVE CONFIGURATION FOR CONDITIONS 1, 2, 3, and 4 and FOR PROCEDURES A, B, and C

| Weld Parameter | Conditions 1, 2, 3, and 4 | Procedure A | Procedure B | Procedure C |
|---|---|---|---|---|
| Filler Alloy | 1/16" 4643 | 1/16" 4643 | 1/16" 4643 | 1/16" 4643 |
| Gas Helium | 100 CFH | 75 CFH | 100 CFH | 100 CFH |
| Cover Argon | 5 CFH | 10 CFH | 5 CFH | 5 CFH |
| Current-Root | 200-220 amps | 200-220 amps | 220-240 amps | 220-240 amps |
| Current-Filler | 260-290 amps | 240-260 amps | 250-270 amps | 260-290 amps |
| Voltage-Root | 28-30 V | 31-33 V | 29-30 V | 29-32 V |
| Voltage-Filler | 32-33 V | 33-34 V | 32-33 V | 29-32 V |
| Wire Feed | 265-285 IPM | 250-260 IPM | 260-270 IPM | 260-270 IPM |
| Speed | 18-20 IPM | Manual | 18-20 IPM | 16-18 IPM |
| No. Passes | 7-8 | 8 | 8 | 7 |
| Interpass Temp. | 150° F max. | 150° F max. | 150° F max. | 150° F max. |

NOTE: Plates welded per Procedure A received an initial TIG fusion pass conducted at 150 - 190 amps, 14 volts, 26-35 IPM wire feed and 11-13 IPM traverse.

Figure 4. WELD PARAMETERS USED FOR JOINING OF 6061 ALUMINUM WELDMENTS

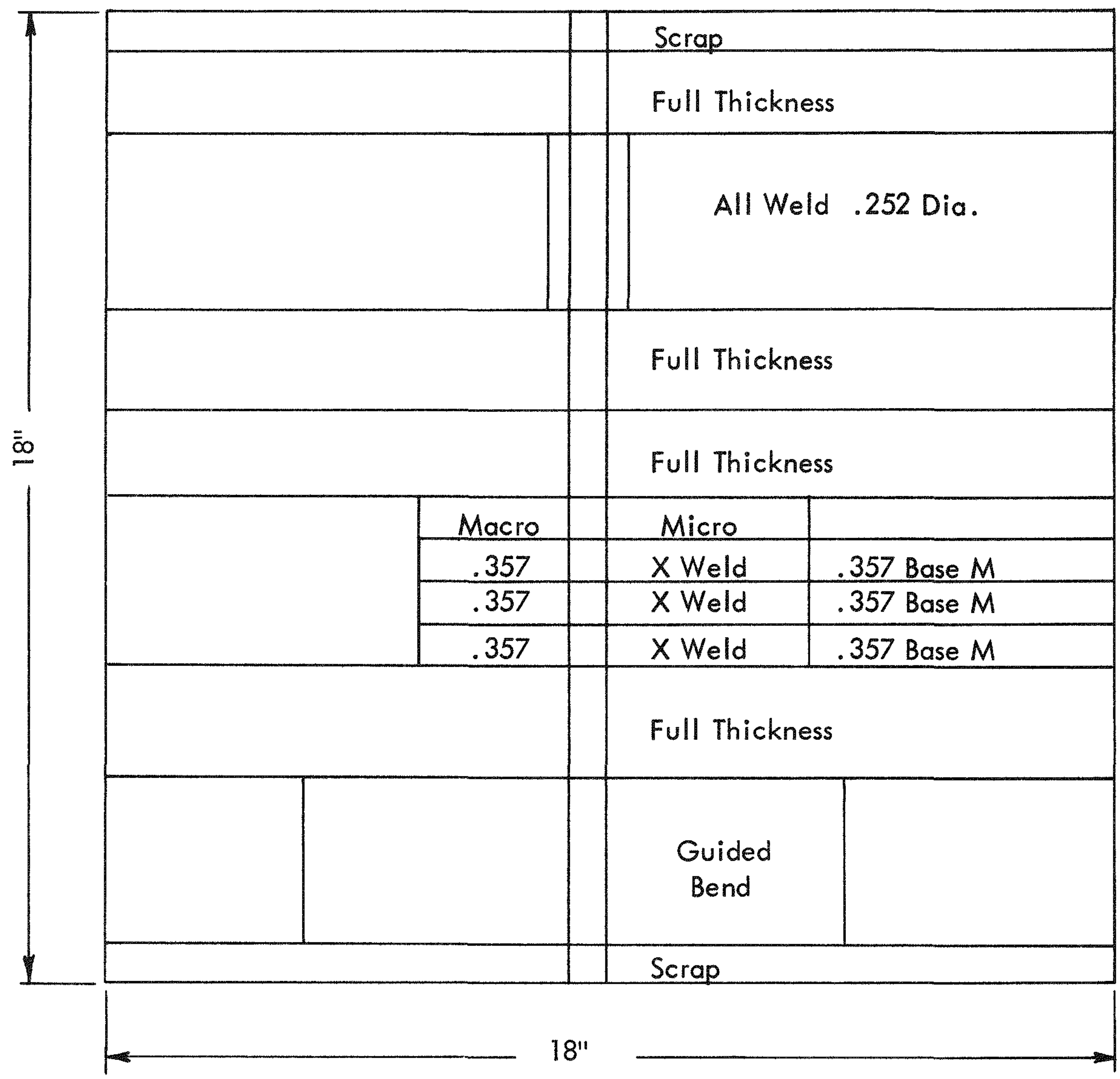



Figure 5. SPECIMEN LAYOUT FOR ALL WELDMENTS OF 6061 ALUMINUM, CONDITION 1-4, PROCEDURES A, B, and C

# 4. RESULTS AND DISCUSSION

## 4.1 Effects of the Welding Heat on the Metallurgical Structure of 6061 Aluminum

4.1.1 In order to fully appreciate the variations and effects of high temperature and short duration heat input on 6061 aluminum, it is necessary to discuss some of the metallurgical aspects of the alloy.

4.1.2 At temperatures of 990°F optimum solution of the hardening elements, chiefly magnesium and silicon in 6061, is obtained, and by water quenching, the potential for hardening under artificial aging cycles is retained. Aging treatments for extended times (8 hours to 20 hours) at temperatures of 320°F to 350°F result in hardness and strength increases. Optimum properties of -T6 material are 45 ksi ultimate, 40 ksi yield, and 12% elongation with 95 Brinell hardness. Hardening to less than optimum levels can be obtained by shorter aging times and/or higher aging temperatures. Excessive temperatures or times result in lowered hardness with strengths approaching those typical of an annealed structure. Full annealing of 6061 is obtained under conditions of heating to 775°F, holding for two to three hours and furnace cooling at 50°F per hour to 500°F. This condition is the softest structure of 6061 aluminum. Typical annealed properties are 18 ksi ultimate, 8 ksi yield, and 25% elongation with 30 Brinell hardness.

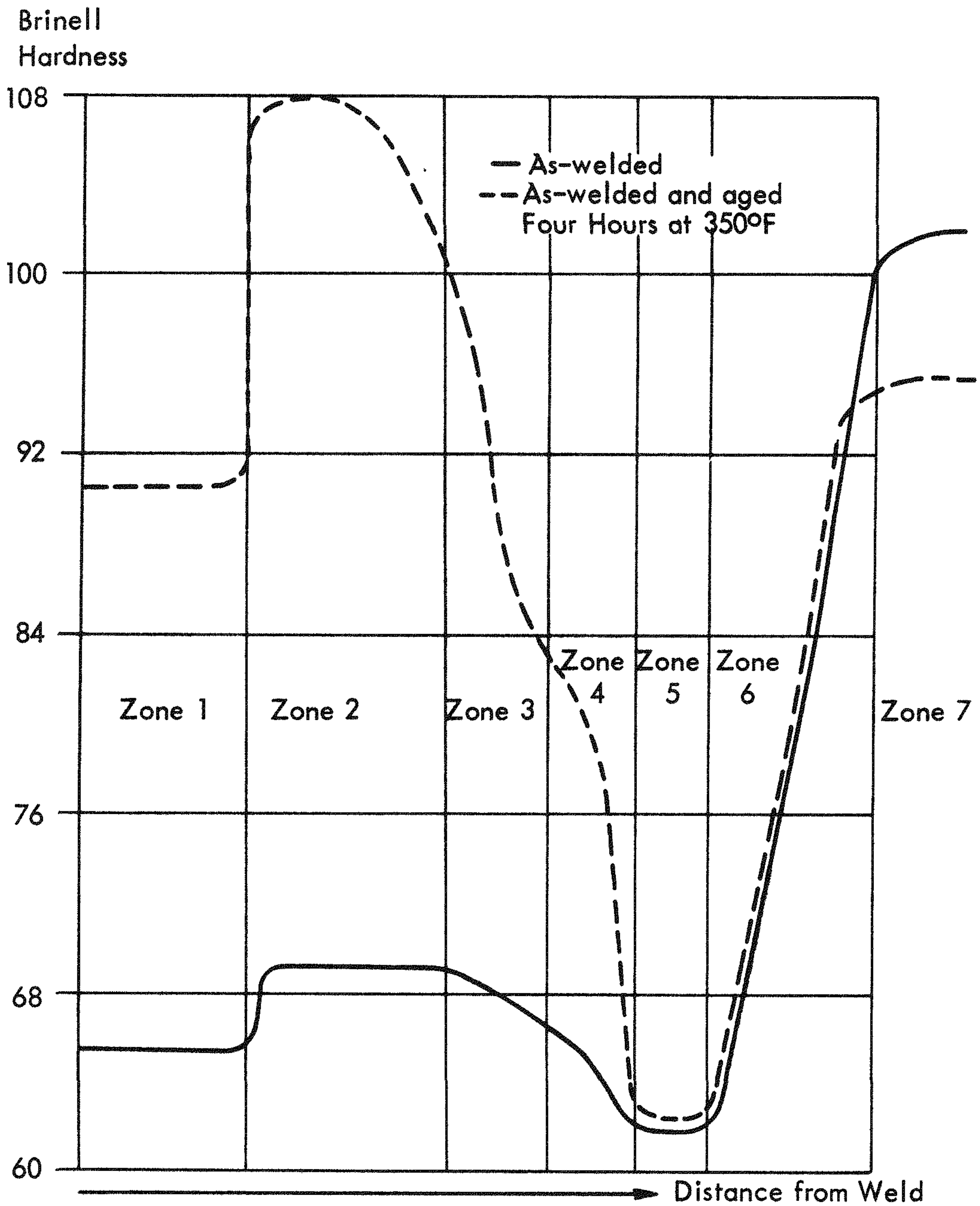
4.1.3 Since welding heat input causes temperatures that can be higher than the melting point of 6061 aluminum and the weld heat is localized and of short duration, variations between the optimum -T6 condition and the soft annealed condition can be expected in a weld heat-affected zone. In a weld heat-affected zone, maximum -T6 properties are not expected since quenching is not normally conducted after welding. Fully annealed structures are not expected either, since the times are not sufficiently long and furnace cooling is not normally conducted after welding.

4.1.4 Figure 6 shows the various zones that can be expected in as-welded or as-welded aged-only weldments. Multi-pass welding naturally complicates the location, widths, and degree of the affected zones.

## 4.2 Determination of Properties Versus Heat-treat Cycle

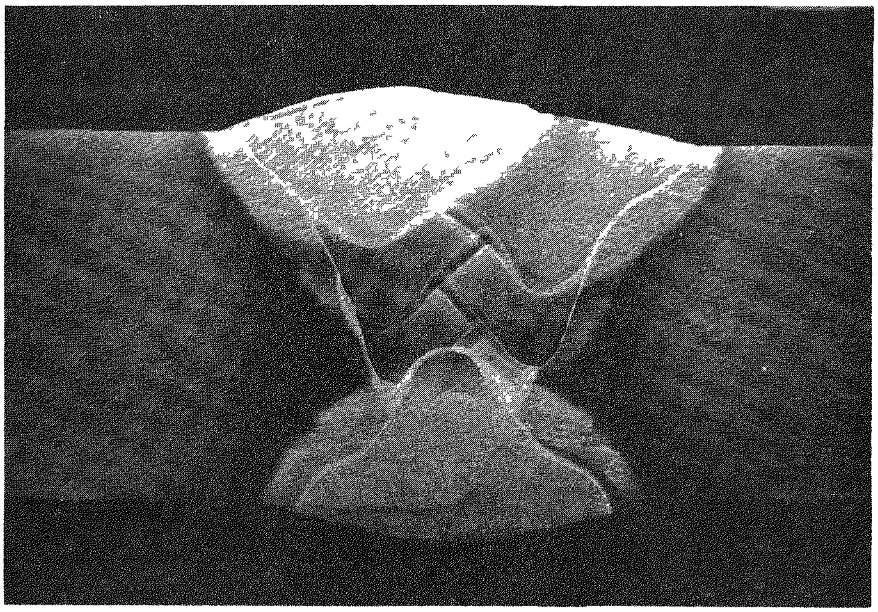
4.2.1 This portion of the evaluation was concerned with weldments processed per Conditions 1 through 4. Of major interest was the macrostructure and mechanical properties of each condition. These macrostructures are shown at a magnification of 2.5 X in Figures 7 and 8.

4.2.2 The macrostructures of the as-welded, and the as-welded and aged conditions are essentially identical. The only noticeable effect is one of a darker etching of weld metal in the aged condition. Some darkening is also present in the mid-passes of the as-welded condition due to aging from weld heat. A dark zone of maximum overaging is visible in each macro. The fully heat-treated macro exhibits complete elimination of heat-affected zones and a general weld homogenization effect.

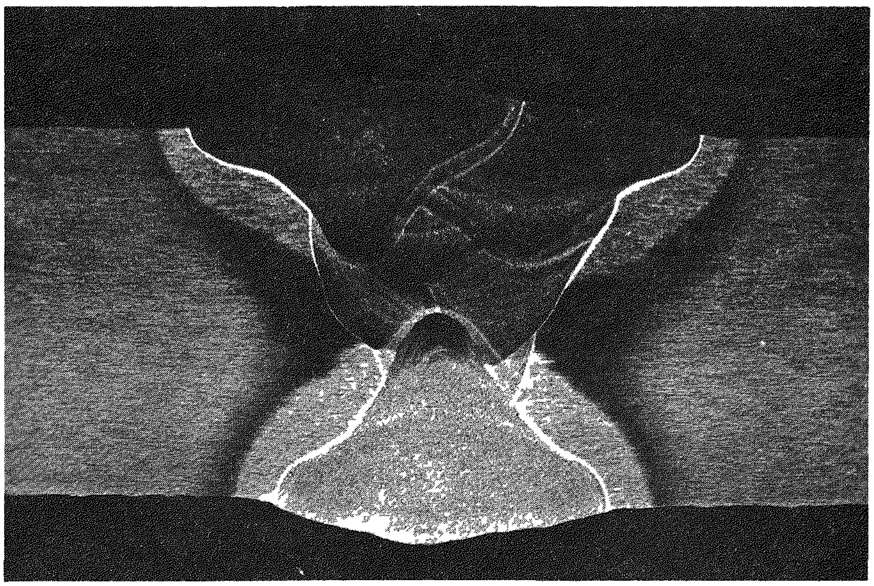



Zone 1 Deposited Weld Metal
Zone 2 Maximum Solution Effect
Zone 3 Decreasing Solution Effect
Zone 4 Increasing Overage - Decreasing Solution Effect
Zone 5 Maximum Overaging
Zone 6 Decreasing Overage
Zone 7 Unaffected Base Metal

Figure 6. TYPICAL AREAS AND HARDNESS OF HEAT-AFFECTED ZONES IN THICK WELDMENTS OF 6061 -T6 ALUMINUM DUE TO WELD HEAT

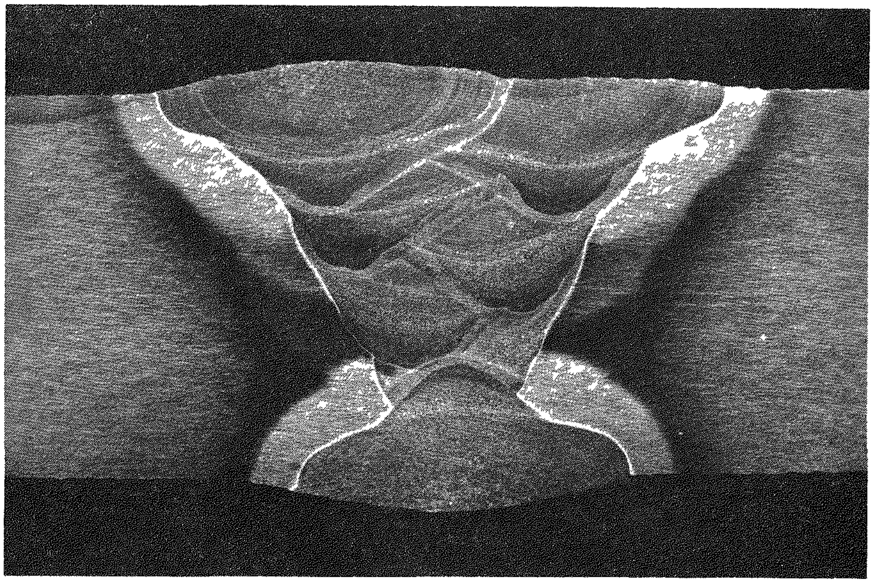


Condition 1. Welded in -T6 Temper, As-welded

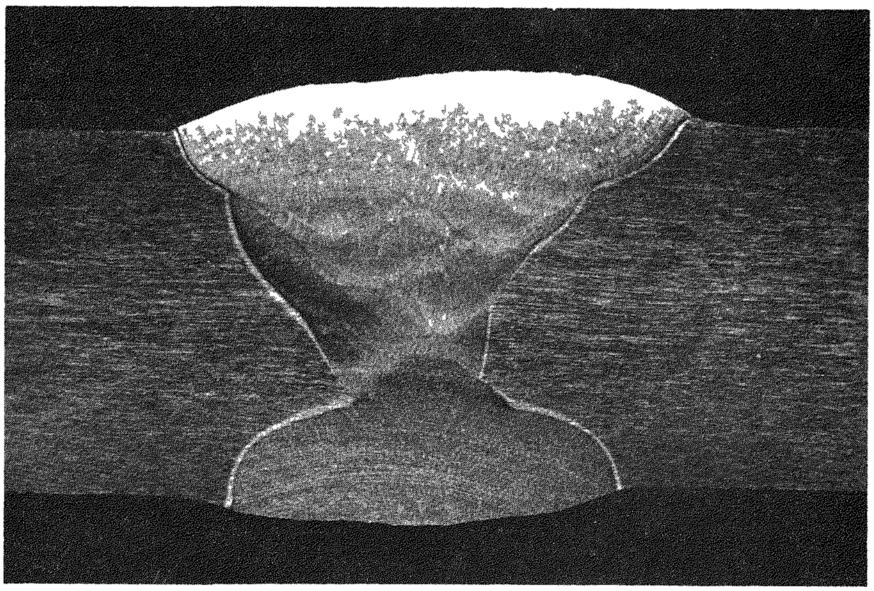


Condition 2. Welded in -T6 Temper, Aged Four Hours at 350°F

Figure 7. MACROSTRUCTURE OF CONDITIONS 1 AND 2 2.5X



Condition 3. Welded in -T4 Temper, Aged 8 Hours at 350°F



Condition 4. Welded in -T4 Temper, Solution Treated at 990°F, Water Quenched, Aged 8 Hours at 350°F

Figure 8. MACROSTRUCTURE OF CONDITIONS 3 and 4     2.5 X

4.2.3 Average mechanical properties of specimens from each condition are shown in Figure 9. Pertinent results can be summarized as follows:

(a) As-deposited weld metal exhibits the lowest strength levels, but highest elongations (yield - 14 ksi, ultimate - 30 ksi, elongation - 18%).

(b) Aging of as-deposited weld metal (4643 filler) results in increases by a factor of two in yield strength, one-quarter in ultimate strength and a reduction to one-half of the as-deposited elongation.

(c) Full heat-treatment of deposited weld metal (4643 filler) produces strength levels equivalent to base metal, but because of the cast structure and type of aging, a reduction in elongation to one-quarter of that of the base-metal level is experienced.

(d) The effects of aging on the cross-weld $R_2$ and full-thickness specimens essentially parallel those experienced on all-weld material. Full heat-treatment results in approximate 100% weld strength efficiency but with lowered elongations.

## 4.3 Selection of Condition and Heat-treat Cycle

4.3.1 A summary of tensile data obtained by welding in -T4 and -T6 conditions and conducting various post heat-treat cycles is shown in Figure 10. The data shows that the as-welded condition is the most ductile, but through use of a simple four-hour, 350°F age cycle, strength levels can be significantly increased without serious reduction in weld elongation or -T6 base-metal properties.

4.3.2 Further examination of the minimum value obtained in all tests for each condition (Figure 11) shows again that a significant increase in weld yield strengths can be obtained by a relatively simple aging cycle of four-hours at 350°F. Comparison of the minimum values with the average properties (Figures 10 and 11) shows that there is little variation between the average properties and minimum specimen values.

4.3.3 Welding of -T6 material, both as-welded and aged, was selected for further evaluation. These conditions were believed to be most interesting from the standpoint of weldment fabrication and processing involving 0.750-inch-thick 6061 welded, complicated shapes. Further weld studies were made on weldments fabricated by the manual MIG, automatic MIG, and automatic MIG, copper back-up processes.

## 4.4 Determination of Properties Utilizing Weld Procedures A, B, and C

4.4.1 This portion of the evaluation was concerned with weldments fabricated by manual MIG, automatic MIG, and automatic MIG with copper back-up. Each of these weldments was given the heat-treatment considered best from previous data (weld in -T6, age four hours at 350°F). Each procedure was also evaluated in the as-welded condition.

| Type | No. Spec. | Yield (ksi) | Ultimate (ksi) | Elong. % |
|---|---|---|---|---|
| **Condition 1, Weld in -T6, As-welded** | | | | |
| All-weld, $R_3$ | 4 | 14.4 | 29.7 | 18.0 |
| X-weld, $R_2$ | 12 | 15.2 | 27.8 | 13.2 |
| Base Metal-L, $R_2$ | 12 | 45.2 | 47.7 | 12.2 |
| Full Thick. XW | 16 | 17.7 | 31.8 | 10.4 |
| Guided Bend-XW | 1 | 33° angle - 11.6% elongation at failure. | | |
| **Condition 2, Weld in -T6, AgedOnly - 4 hrs @ 350° F** | | | | |
| All-weld | 4 | 28.0 | 36.5 | 7.7 |
| X-weld | 12 | 21.6 | 30.5 | 9.2 |
| Base Metal-L, $R_2$ | 12 | 41.7 | 45.7 | 14.5 |
| Full Thick. XW | 16 | 26.1 | 34.0 | 5.8 |
| Guided Bend-XW | 1 | 26° angle - 8.7% elongation at failure. | | |
| **Condition 3, Weld in -T4, Aged Only - 8 hrs @ 350° F** | | | | |
| All-weld | 4 | 28.0 | 36.4 | 7.5 |
| X-weld | 12 | 22.5 | 31.7 | 7.5 |
| Base Metal-L, $R_2$ | 12 | 41.8 | 44.9 | 16.0 |
| Full Thick. XW | 16 | 26.8 | 35.8 | 4.8 |
| Guided Bend-XW | 1 | 25° angle - 8.2% elongation at failure. | | |
| **Condition 4, Weld in -T4, Full Heat-treat** | | | | |
| All-weld | 3 | 42.0 | 46.5 | 4.0 |
| X-weld | 9 | 42.3 | 47.8 | 10.0 |
| Base Metal-L, $R_2$ | 9 | 43.7 | 48.2 | 18.0 |
| Full Thick, XW | 11 | 40.8 | 46.2 | 5.4 |
| Guided Bend-XW | 1 | 16° angle - 5.6% elongation at failure. | | |

Figure 9. AVERAGE MECHANICAL PROPERTIES FROM FOUR WELDMENTS, EACH OF CONDITIONS 1, 2, 3, AND 4, 0.750" 6061 ALUMINUM

| TYPE SPECIMEN | CONDITION | YIELD (ksi) | ULTIMATE (ksi) | ELONG. (%) |
|---|---|---|---|---|
| All-weld, $R_3$ | (1) -T6, as-welded | 14.4 | 29.7 | 18.0 |
| | (2) -T6, 4 hrs @ 350°F | 28.0 | 36.4 | 7.5 |
| | (3) -T4, 8 hrs @ 350°F | 28.0 | 36.5 | 7.7 |
| | (4) -T4, Full heat-treat | 42.0 | 46.5 | 4.0 |
| X-weld, $R_2$ | (1) -T6, as-welded | 15.2 | 27.8 | 13.2 |
| | (3) -T4, 8 hrs @ 350°F | 21.6 | 30.5 | 9.2 |
| | (2) -T6, 4 hrs @ 350°F | 22.5 | 31.7 | 7.5 |
| | (4) -T4, Full heat-treat | 42.3 | 47.8 | 10.0 |
| Full Thickness X-weld | (1) -T6, as-welded | 17.7 | 31.8 | 10.4 |
| | (3) -T4, 8 hrs @ 350°F | 26.1 | 34.0 | 5.8 |
| | (2) -T6, 4 hrs @ 350°F | 26.8 | 35.8 | 4.8 |
| | (4) -T4, Full heat-treat | 40.8 | 46.2 | 5.4 |
| Base Metal, Longitudinal | (1) -T6, as welded* | 45.2 | 47.7 | 12.2 |
| | (2) -T6, 4 hrs @ 350°F | 41.8 | 44.9 | 16.0 |
| | (3) -T4, 8 hrs @ 350°F | 41.7 | 45.4 | 14.5 |
| | (4) -T4, Full heat-treat | 43.7 | 48.2 | 18.0 |

*Base metal tempers were: Full -T6, -T6 and slight over age, optimum ACFI age, and optimum solution and age, respectively.

Figure 10. SUMMARY OF AVERAGE MECHANICAL PROPERTIES OF CONDITIONS 1, 2, 3, AND 4 ARRANGED BY SPECIMEN TYPE

| Type | Minimum Yield (ksi) | Minimum Ultimate (ksi) | Minimum Elongation (%) | Failure Location |
|---|---|---|---|---|
| Condition 1 (weld in -T6, as-welded) | | | | |
| All-weld - $R_3$ | 13.8 | 28.6 | 14.0 | Predominant heat-affected zone failures |
| X-weld - $R_2$ | 12.9 | 24.9 | 9.0 | |
| Base metal L $R_2$ | 42.0 | 44.7 | 9.0 | |
| Full thick. XW | 14.3 | 29.7 | 6.0 | |
| Condition 2 (weld in -T6, aged 4 hrs 350°F) | | | | |
| All-weld - $R_3$ | 25.9 | 34.5 | 6.0 | Predominant weld metal failures some heat-affected zone failures |
| X-weld - $R_2$ | 20.9 | 29.3 | 6.0 | |
| Base metal - L $R_2$ | 39.6 | 43.9 | 11.0 | |
| Full thick. XW | 23.6 | 30.4 | 3.0 | |
| Condition 3 (weld in -T4, aged 8 hrs 350°F) | | | | |
| All-weld - $R_3$ | 25.7 | 35.0 | 3.0 | Borderline weld metal heat-affected zone failure |
| X-weld - $R_2$ | 21.5 | 31.2 | 5.0 | |
| Base metal - L $R_2$ | 39.9 | 42.9 | 14.0 | |
| Full thick. XW | 22.3 | 30.1 | 3.5 | |
| Condition 4 (weld in -T4, full heat-treat) | | | | |
| All-weld - $R_3$ | 40.4 | 44.7 | 2.0 | Practically all weld metal failures |
| X-weld - $R_2$ | 40.5 | 46.6 | 4.0 | |
| Base metal - L $R_2$ | 42.3 | 47.4 | 16.0 | |
| Full thick. XW | 38.3 | 41.6 | 4.0 | |

Figure 11. MINIMUM MECHANICAL PROPERTY VALUES OBTAINED IN TESTING OF CONDITIONS 1,2,3, AND 4, .750" 6061 WELDMENTS

4.4.2 The macrostructures of these weldments are shown in Figures 12, 13, and 14. These structures are typical of those observed previously.

4.4.3 Mechanical properties of weldments from each procedure are shown in Figures 15 and 16. These data show that regardless of weld procedure, properties are acceptable and improved significantly by aging four-hours at 350°F. Examination of minimum levels experienced (Figure 17) again shows little variation between the average and minimum values.

## 4.5 Measurements of Weld Metal, Heat Zone, and Base Metal Hardness

4.5.1 Each series of weldments was evaluated for variation in hardness resulting from the welding heat input. Measurements were made on the Rockwell 30T scale and results are listed in Figures 18, 19, and 20. These values can be summarized as follows:

Rockwell Superficial 30T Hardness

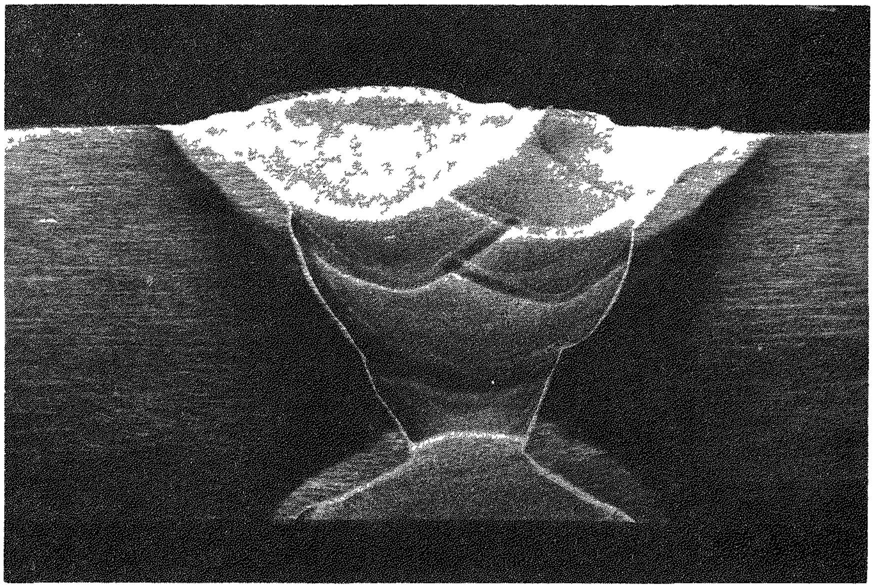
| Area | As-welded | Aged |
|---|---|---|
| Weld Metal | 21 - 34 | 38 - 54 |
| Inner Heat-affected Zone | 23 - 42 | 28 - 65 |
| Outer Heat-affected Zone | 29 - 52 | 32 - 56 |
| Base Metal | 60 - 62 | 55 - 62 |

The manual technique appeared to produce slightly lower hardness than the other procedures, possibly due to longer dwell times.

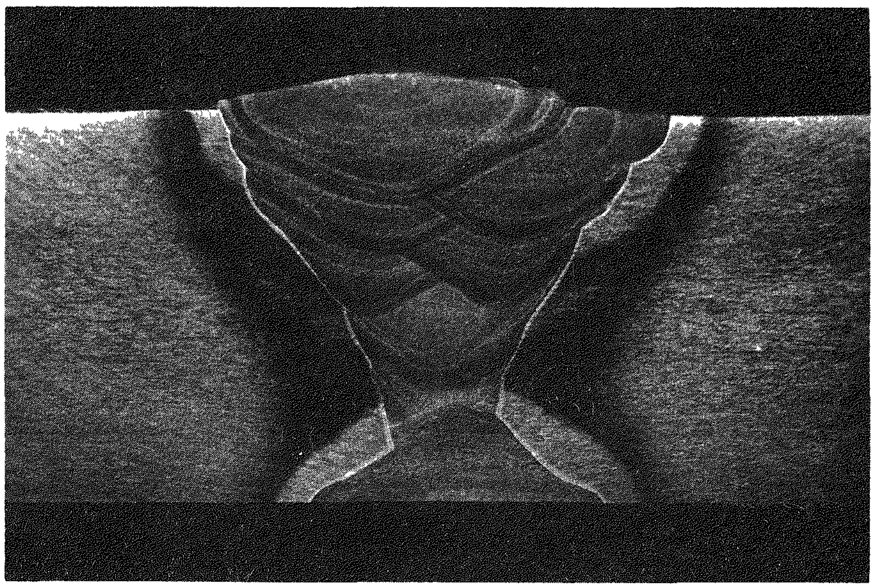
## 4.6 Microprobe Analysis of Weld Metal, Base Metal and Areas in Contact with Copper Back-up

4.6.1 This evaluation was conducted to insure that detrimental effects were not occurring due to melting or diffusion of copper into the aluminum. An analysis was first conducted on areas immediately in contact with the copper. Results, shown in Figure 21, reveal that copper pickup is not a problem.

4.6.2 Figures 22 and 23 show an analysis of filler pass areas and a typical base metal structure. Again, no abnormalities are observed.

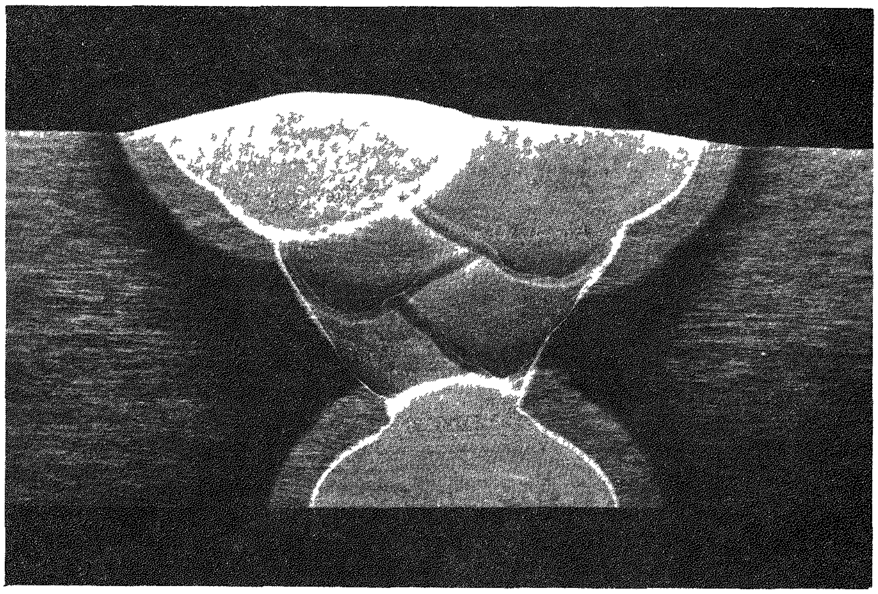


A. Welded in -T6 Temper - As-welded

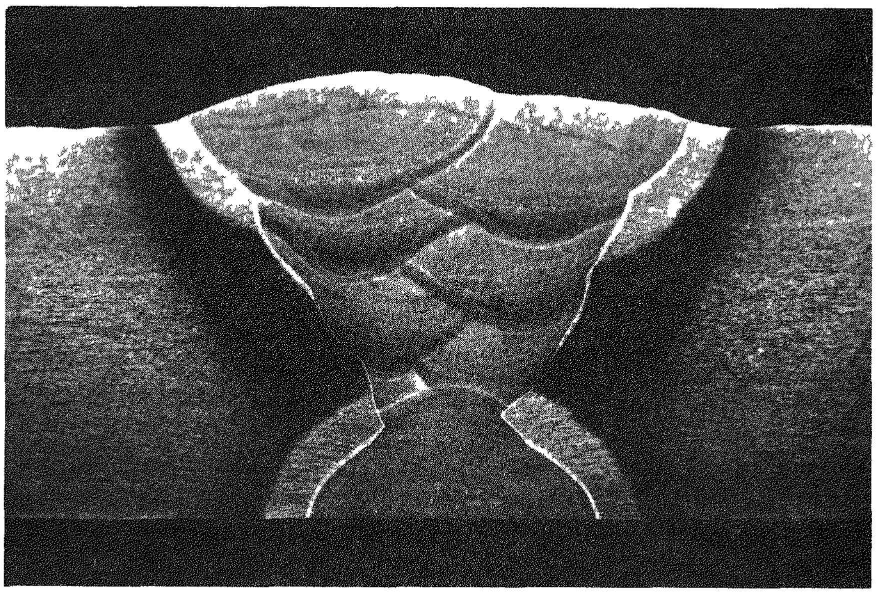


B. Welded in -T6 Temper and Aged 4 Hours at 350°F

Figure 12. MACROSTRUCTURE OF 6061 WELDMENTS FABRICATED BY THE MANUAL MIG PROCESS WITH BACK PASS-PROCEDURE A 2.5 X

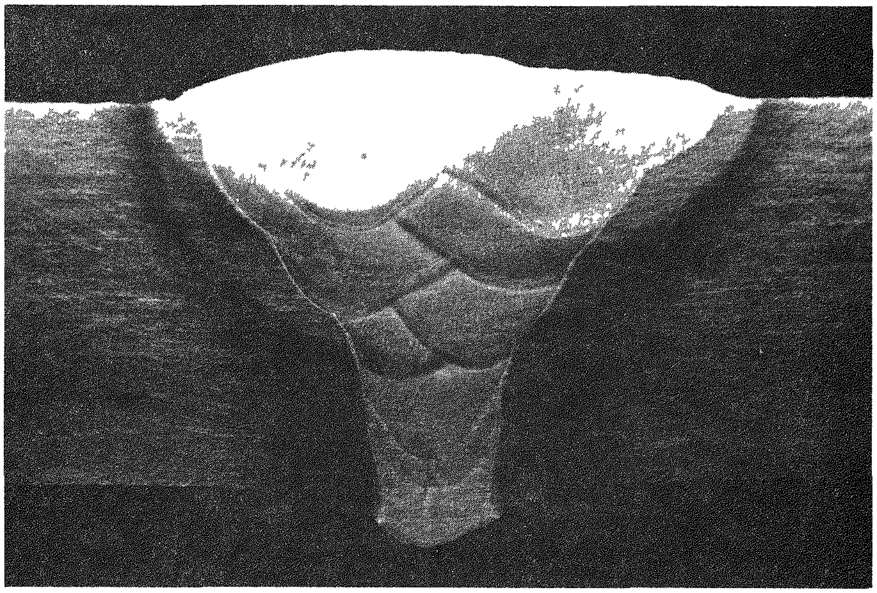


A. Welded in -T6 Temper - As-welded

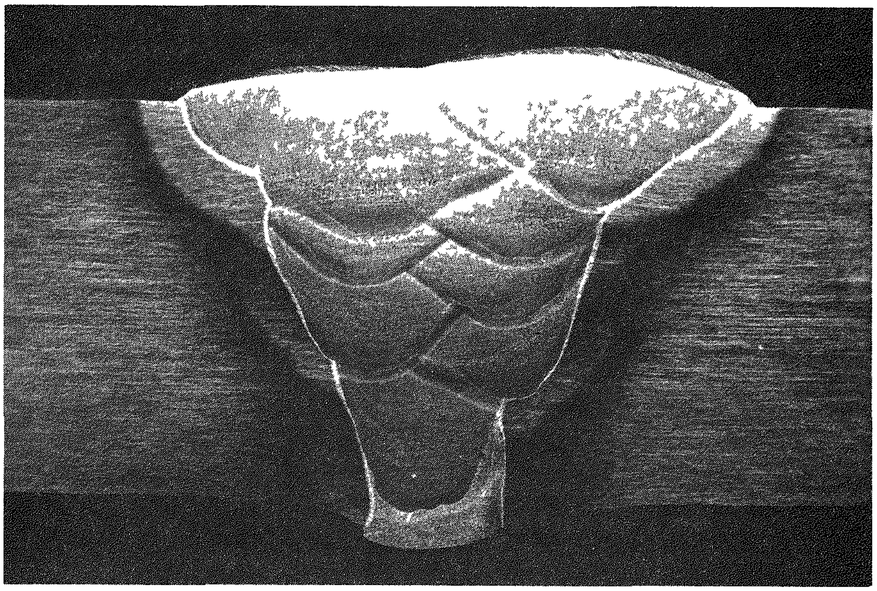


B. Welded in -T6 temper and Aged Four Hours at 350°F

Figure 13. MACROSTRUCTURE OF 6061 WELDMENTS FABRICATED BY THE AUTOMATIC MIG PROCESS WITH BACK PASS-PROCEDURE B 2.5X



A. Welded in -T6 Temper - As-welded



B. Welded in -T6 and Aged Four Hours at 350°F

Figure 14. MACROSTRUCTURE OF 6061 WELDMENTS FABRICATED BY THE AUTOMATIC MIG PROCESS AGAINST A COPPER BACK-UP 2.5 X

| Type | No. Spec. | Yield (ksi) | Ultimate (ksi) | Elong. (%) |
|---|---|---|---|---|
| Procedure A - Manual MIG Back Pass | | | | |
| All - weld, $R_3$ | 2 | 13.9 | 28.2 | 19.0 |
| X-weld, $R_2$ | 6 | 15.5 | 28.0 | 10.5 |
| Base Metal L, $R_2$ | 6 | 44.5 | 47.6 | 14.0 |
| Full Thick. XW | 8 | 18.0 | 29.1 | 8.5 |
| Procedure B - Automatic MIG Back Pass | | | | |
| All - weld, $R_3$ | 3 | 14.5 | 28.6 | 19.0 |
| X-weld $R_2$ | 9 | 15.7 | 28.0 | 13.0 |
| Base Metal L, $R_2$ | 9 | 45.0 | 47.3 | 15.0 |
| Full Thick. XW | 12 | 16.7 | 26.4 | 8.7 |
| Procedure C - Automatic MIG - Copper Back-up | | | | |
| All - weld, $R_3$ | 1 | 13.9 | 28.8 | 18.0 |
| X-weld, $R_2$ | 3 | 15.7 | 28.5 | 9.5 |
| Base Metal L, $R_2$ | 3 | 44.7 | 47.0 | 14.5 |
| Full Thick. XW | 4 | 17.7 | 32.3 | 10.0 |

Figure 15. AVERAGE MECHANICAL PROPERTIES OF .750 INCH 6061 WELDMENTS JOINED IN THE -T6 TEMPER, AS-WELDED BY PROCEDURES A, B, AND C

| Type | No. Spec. | Yield (ksi) | Ultimate (ksi) | Elong. (%) |
|---|---|---|---|---|
| **Procedure A - Manual MIG Back Pass** | | | | |
| All - weld, $R_3$ | 2 | 23.5 | 33.6 | 12.0 |
| X-weld, $R_2$ | 6 | 22.4 | 31.6 | 6.5 |
| Base Metal L, $R_2$ | 6 | 43.0 | 47.8 | 13.7 |
| Full Thick. XW | 8 | 23.8 | 32.1 | 4.1 |
| **Procedure B - Automatic MIG Back Pass** | | | | |
| All - weld, $R_3$ | 1 | 23.7 | 34.1 | 10.0 |
| X-weld, $R_2$ | 3 | 22.3 | 31.7 | 6.0 |
| Base Metal L, $R_2$ | 3 | 43.8 | 47.9 | 14.0 |
| Full Thick. XW | 4 | 26.1 | 33.2 | 4.0 |
| **Procedure C - Automatic MIG Copper Back up** | | | | |
| All - weld, $R_3$ | 3 | 24.9 | 35.9 | 12.0 |
| X-weld, $R_2$ | 9 | 24.3 | 33.6 | 6.5 |
| Base Metal L, $R_2$ | 9 | 45.5 | 47.1 | 14.0 |
| Full Thick. XW | 12 | 26.6 | 37.1 | 5.5 |

Figure 16. AVERAGE MECHANICAL PROPERTIES OF .750 INCH 6061 WELDMENTS JOINED IN THE -T6 TEMPER, AS-WELDED AND AGED FOUR-HOURS AT 350°F

| Condition | Weld Procedure | Type Specimen | Min. Yield (ksi) | Min. Ultimate (ksi) | Min. Elong. (%) |
|---|---|---|---|---|---|
| As-welded | A | All-weld | 13.5 | 28.2 | 18.0 |
| As-welded | B | All-weld | 14.0 | 28.3 | 18.0 |
| As-welded | C | All-weld | 13.9 | 28.8 | 18.0 |
| Aged | A | All-weld | 22.8 | 33.1 | 12.0 |
| Aged | B | All-weld | 23.7 | 34.1 | 10.0 |
| Aged | C | All-weld | 23.4 | 34.8 | 10.0 |
| As-welded | A | X-weld | 15.0 | 27.9 | 6.0 |
| As-welded | B | X-weld | 15.4 | 27.7 | 10.0 |
| As-welded | C | X-weld | 15.5 | 28.0 | 9.0 |
| Aged | A | X-weld | 21.8 | 31.1 | 5.0 |
| Aged | B | X-weld | 22.2 | 31.7 | 6.0 |
| Aged | C | X-weld | 23.2 | 32.6 | 5.0 |
| As-welded | A | Full Thick. XW | 16.9 | 27.9 | 7.0 |
| As-welded | B | Full Thick. XW | 13.9 | 27.3 | 8.0 |
| As-welded | C | Full Thick. XW | 17.4 | 31.6 | 9.0 |
| Aged | A | Full Thick XW | 23.1 | 30.5 | 3.0 |
| Aged | B | Full Thick XW | 25.9 | 32.6 | 3.0 |
| Aged | C | Full Thick XW | 25.8 | 37.0 | 4.0 |

Figure 17. MINIMUM MECHANICAL PROPERTY VALUES OBSERVED IN WELDMENTS JOINED PER PROCEDURE A, B, AND C

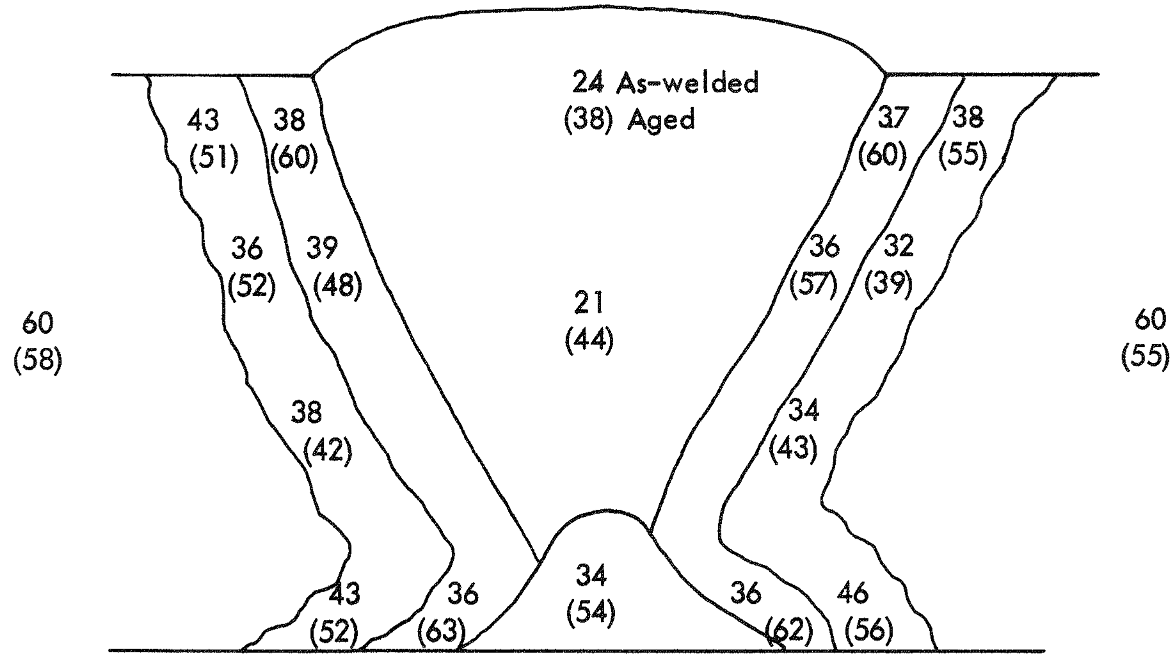



Figure 18. ROCKWELL 30T HARDNESS OF 6061 WELDMENT JOINED BY THE MANUAL MIG PROCESS WITH BACK PASS

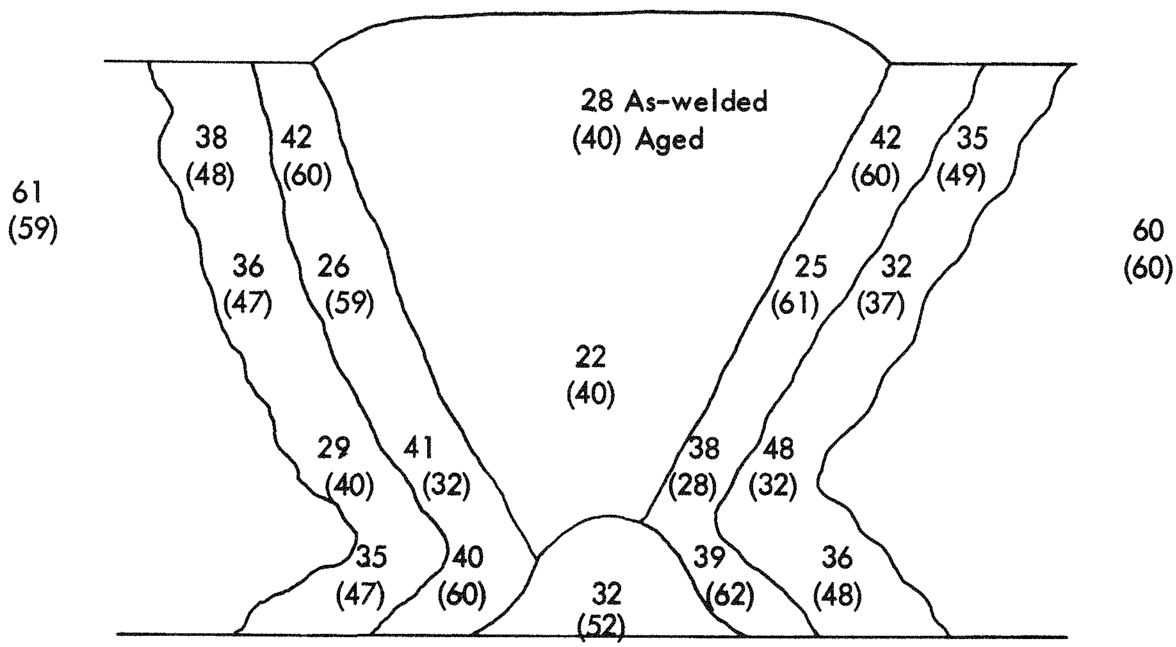



Figure 19. ROCKWELL 30T HARDNESS OF 6061 WELDMENT JOINED BY THE AUTOMATIC MIG PROCESS WITH BACK PASS

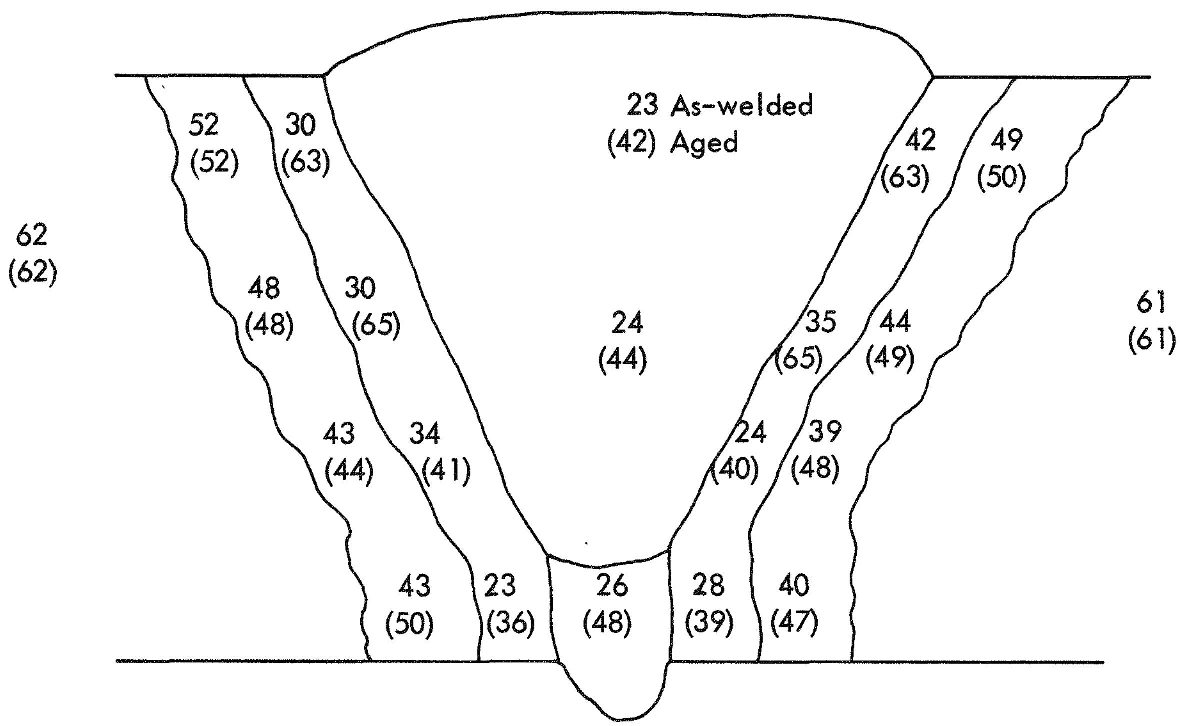
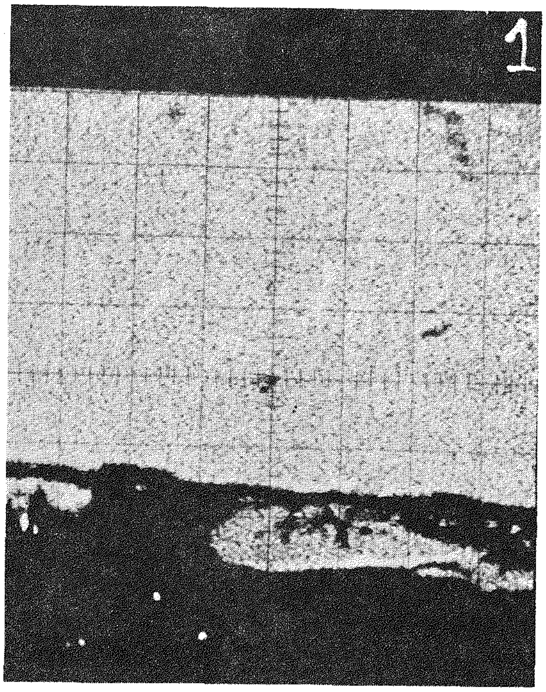
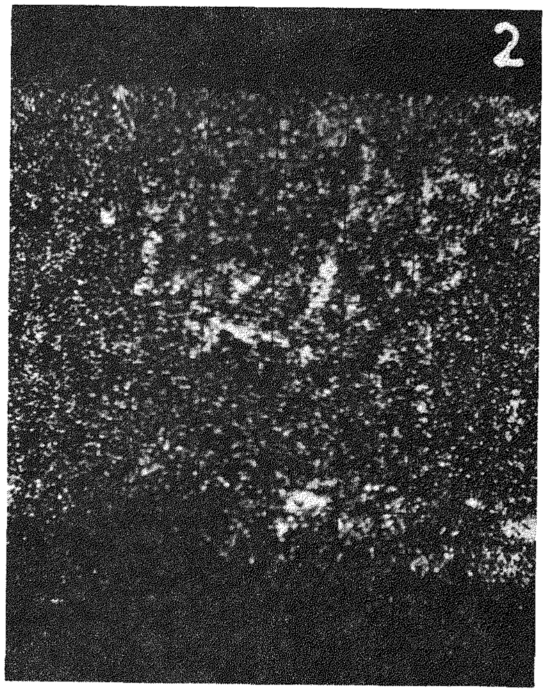


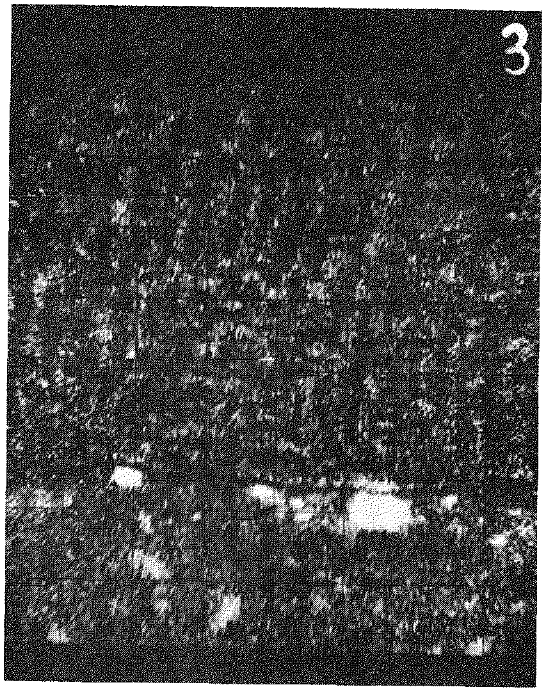

Figure 20. ROCKWELL 30T HARDNESS OF 6061 WELDMENT JOINED BY THE AUTOMATIC MIG PROCESS WITH COPPER BACK-UP



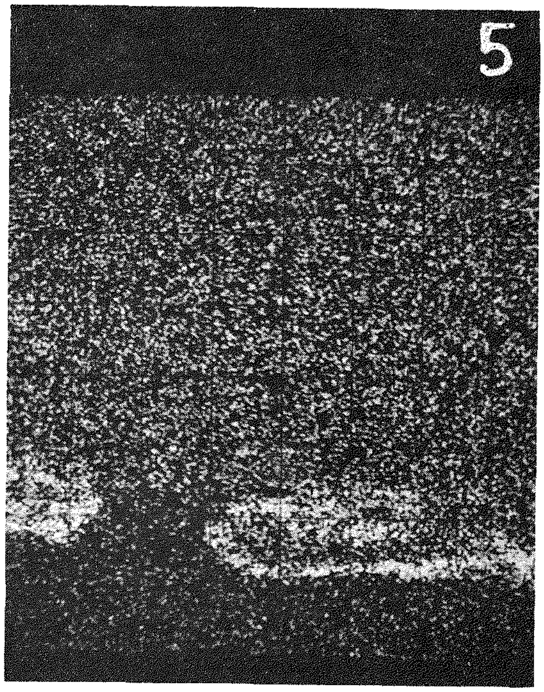

A. Electron Back Scatter
Actual Scan Area - .014" x .014"




B. Iron X-ray

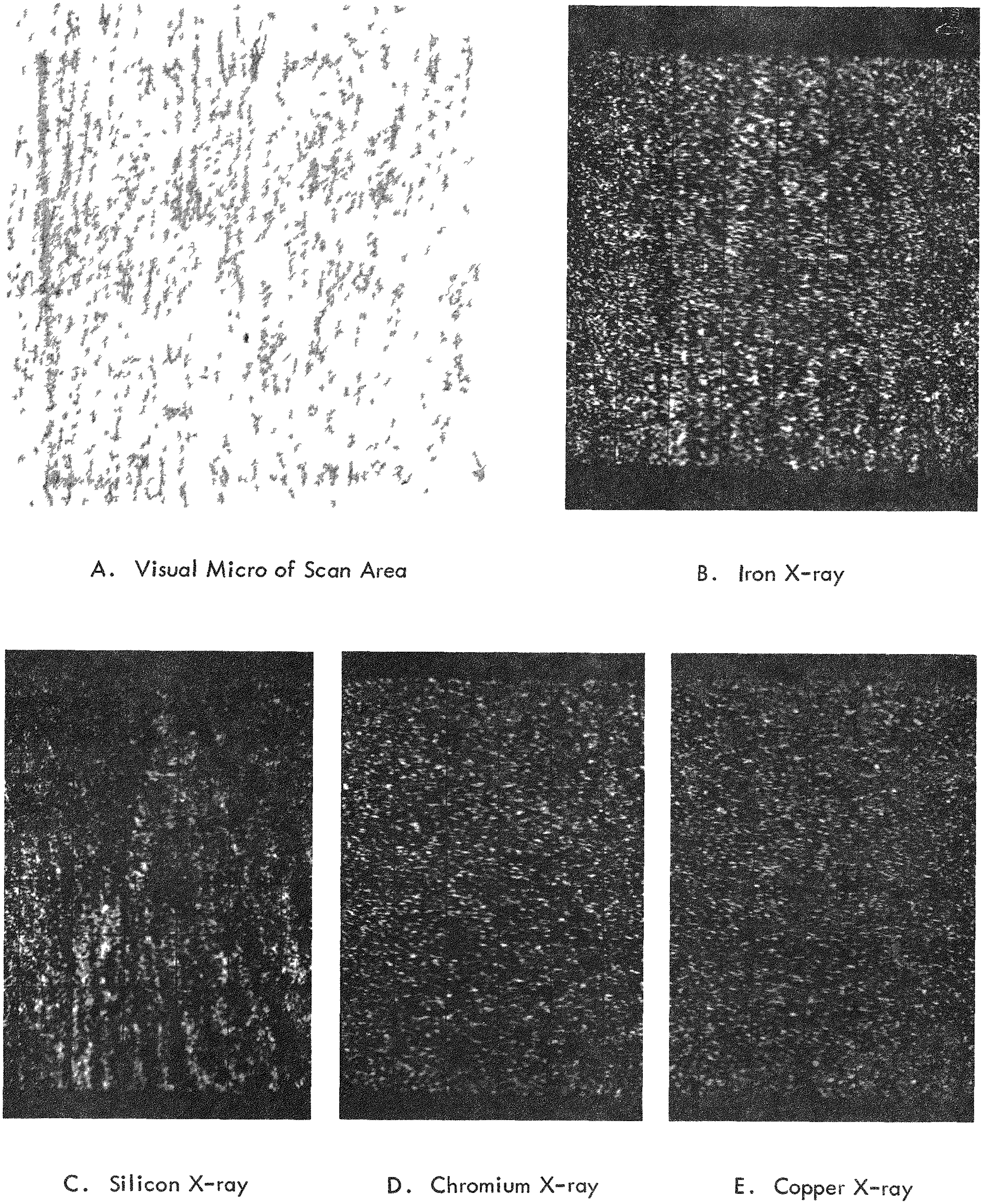



C. Silicon X-ray




D. Copper X-ray

Figure 21. MICROPROBE ANALYSIS FOR IRON, SILICON, AND COPPER ON A SURFACE IN CONTACT WITH COPPER BACK-UP 220 X



A. Visual Micro of Scan Area

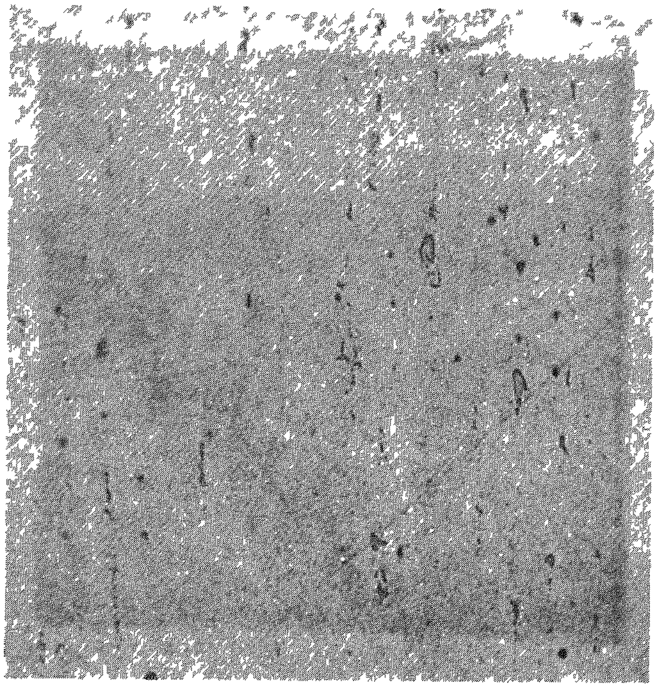
B. Iron X-ray

C. Silicon X-ray

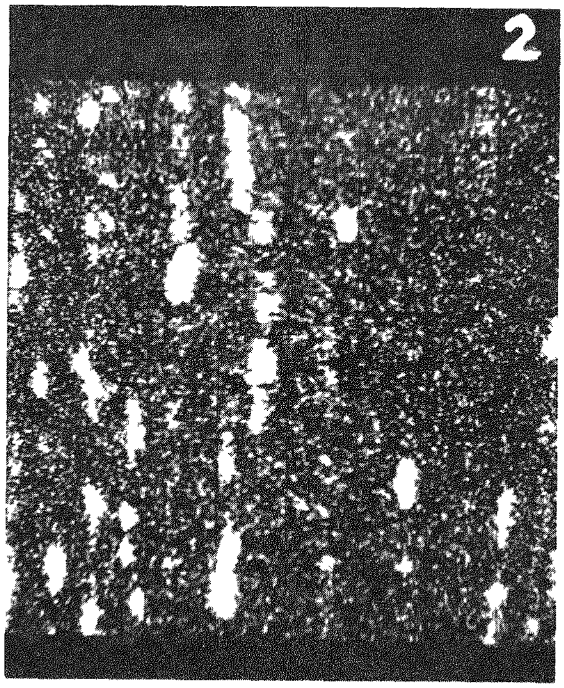
D. Chromium X-ray

E. Copper X-ray

Figure 22. MICROPROBE ANALYSIS FOR IRON, SILICON, CHROMIUM AND COPPER IN THE FILLER PASS AREA OF A 6061 WELDMENT WITH 4643 FILLER ADDITION 250 X

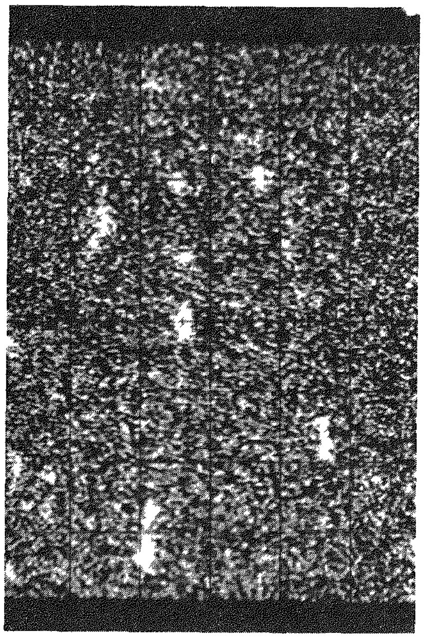


A. Visual Micro of Scan Area

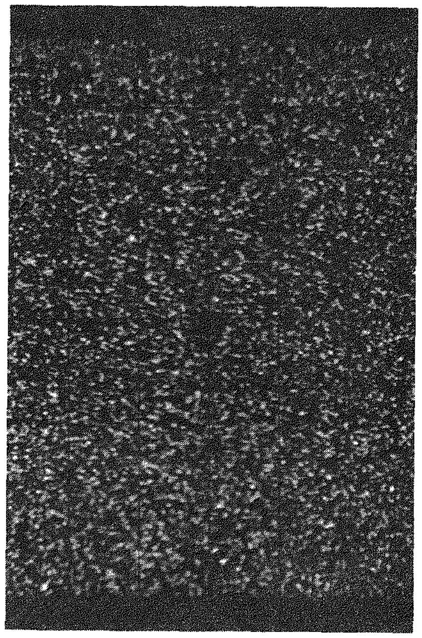



B. Iron X-ray

C. Silicon X-ray



D. Chromium X-ray



E. Copper X-ray

Figure 23. MICROPROBE ANALYSIS OF BASE METAL 6061 ALUMINUM FOR ELEMENTS IRON, SILICON, CHROMIUM, AND COPPER 250 X

## 5. CONCLUSIONS

5.1 The techniques and weld procedures used in this investigation produce acceptable weldments in 3/4-inch-thick 6061 aluminum.

5.2 Strength levels (cross-weld) of 15 ksi yield and 27 ksi ultimate are typical in the as-welded condition (welded in -T6 temper).

5.3 Weld metal elongations as-deposited are typically 18% in one inch.

5.4 Aging-only of weldments for four-hours at 350°F increases cross-weld strength to typical levels of 22 ksi yield and 31 ksi ultimate.

5.5 Weld metal elongations are reduced to 7-10% by the four-hour age at 350°F.

5.6 The effect of the four-hour, 350°F age on base metal -T6 temper strength levels is insignificant.