Effect of Heat Input on Welds in Aluminum Alloy 7039

Metal heated to 600F and above showed greatest reduction in hardness after welding, but this loss can be almost fully restored by post-weld aging.

BY R. A. KELSEY

ABSTRACT. This investigation evaluated the effect of varying number of passes, interpass temperature and panel width on the properties of double-vee GMA butt-welds (5356 electrode) in 1¼ in. aluminum alloy 7039-T63 plate.

Parent material properties appeared to be unaffected in locations where the heat of welding did not exceed 400F. Metal heated in the 400-600F temperature range underwent hardness reductions which were not restored by natural or artificial post-weld aging. Metal heated to 600F and above showed the greatest reduction in hardness immediately after welding, but its hardness was almost fully restored by post-weld aging.

Weld joint tensile yield strength decreased and elongation increased when the number of passes was decreased from 16 to 4, with interpass cooling to 150F. Tensile failures occurred in the weld metal and the tensile strengths were unaffected by the varying heat input.

Interpass cooling had little effect on the magnitude of the residual stresses generally associated with welding. On the surface of the parent material immediately adjacent to the weld bead, the tensile residual stresses parallel to the weld decreased with increasing number of passes; while the tensile residual stresses normal to the weld increased with increasing number of passes.

The high resistance to stress-corrosion cracking of these 7039 welds was not affected by the range of welding variables used in this investigation. Increased heat input per pass increased the width of the HAZ susceptible to corrosion but resulted in a shallower penetration of the corrosive attack.

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Introduction

Heat of welding produces changes in the properties of the parent metal adjacent to a weld in heat treatable aluminum alloys. These changes are a function of the thermal history accompanying welding, which may be influenced by factors such as preheating, joint configuration, type of backup and hold-down, welding process, heat input per pass, time interval between passes, cooling during and after each pass, welding sequence and dimensions of the parts being welded.

Post weld solution heat treatment and aging will generally restore the metal in the heat-affected zone (HAZ) to nearly its original strength. However, reheat-treatment after welding is not always practical. For this reason the Al-Zn-Mg alloys are of interest because they appear to be less affected by the thermal history of welding than some other types of heat treatable alloys and they naturally age after welding to provide increased strength.

This paper gives the results of an investigation to determine the effect of varying heat input during welding on the following properties of butt welds in $1^1/_4$ in. aluminum alloy 7039-T63 plate:

1. Time-temperature relationships in HAZ
2. Extent and variation of strength level in HAZ as determined by hardness surveys made at natural aging intervals ranging from one day to 33 months after welding, as well as after artificially aging
3. Microstructure
4. Full-section cross-weld tensile strength
5. Residual stresses
6. Corrosion and stress-corrosion performance
7. Resistance to penetration by .30 caliber armor-piercing projectiles.

Materials

Aluminum alloy 7039 has 4% Zn and 2.8% Mg as major alloying elements.[1, 2] Other elements, such as Mn, Cr and Ti, are added in lesser amounts to enhance mechanical properties and corrosion resistance and for grain refinement. Alloy 7039 was originally developed for use as an armor material and is currently being employed in several armored vehicles.

Two filler alloys, 5039 and 5356, are generally used in welding 7039. Alloy 5039 is a 3.8% Mg-2.8% Zn alloy which produces higher weld strengths than 5356, which has 5% Mg. Alloy 5356, which was used in this investigation, has the advantage of ease of welding and less tendency to develop cracking when welding thick sections and therefore is widely used in armor applications.

Specimens and Test Procedures

Panels were welded in 4, 8 or 16 passes by the Alcoa Process Development Laboratories following procedures given in Table 1. No hold-down or backup fixtures were used during welding and the panels were supported in such a way that heat loss to the work table was negligible. Start and stop tabs were welded to the

Table 1—Welding Procedures

Panel no.	5356 Electrode diam, in.	Type of joint (see below)	No. of passes	Interpass cooling*	W, in.	Heat input, kilojoules/in. Total	Avg	max and min with pass no.		Time to complete 1 ft of weld, min/ft Arc time	Total time**
1A	3/32	A	4	CW	6	240	60	70(1)	50(2)	4	6
1	3/32	B	4	CW	18	330	83	104(1)	55(2)	6	8
2	3/32	B	4	to 150F	18	340	85	113(4)	58(2)	5	30
3	1/16	B	4	to 150F	18	350	88	107(1)	74(2)	5	27
4	1/16	B	8	CW	18	340	42	68(1)	27(8)	6	11
5	1/16	B	8	to 150F	18	370	46	77(1)	35(6)	7	30
6	1/16	B	8	to 250F	18	340	43	73(1)	29(6)	6	14
7	.046	B	16	CW	18	350	22	34(1)	17(15)	8	15
8	.046	B	16	to 150F	18	350	22	49(1)	13(16)	8	37

* CW indicates continuous welding with no deliberate attempt to cool panel between passes.
** Based on total time elapsed from striking arc for first pass to completion of last pass, including time required for interpass cooling

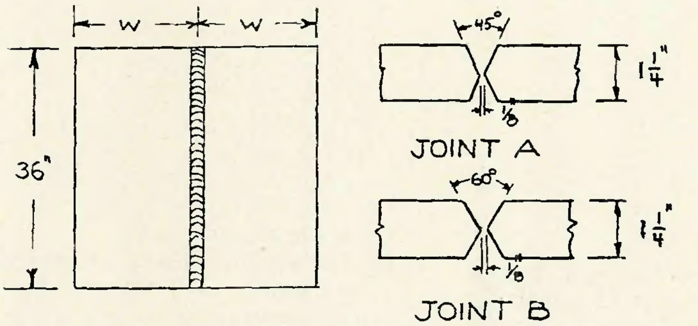
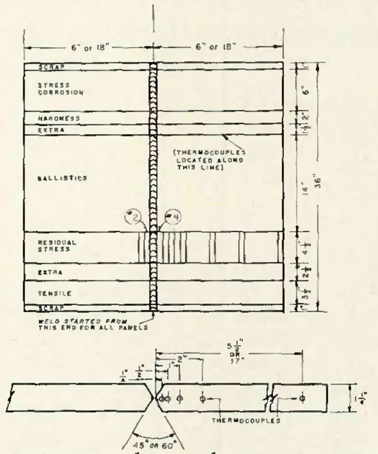


Fig. 1—Test specimen location in welded panels (right)



panel at each end of the groove and a 2-in. long tack weld was applied at the midlength of the joint to maintain surface alignment and edge spacing during welding. Panels were either welded continuously or allowed to cool naturally between passes, to either 150 or 250F.

Welds were made by the manual gas metal-arc (GMA) process with a 20 cfh argon-40 cfh helium gas mixture and 5356 electrode. A $^{7}/_{16}$-in. diameter steel rod supported the weld metal during application of the root pass. Root passes were applied with the torch tip pointed backward, towards the weld that had been deposited, to avoid contact of the welding arc with the steel backup rod. The second passes in Panels No. 1A, 1, 2 and 3 were also applied in this manner. None of the root passes were back chipped. Subsequent passes were applied with the torch tip pointed forward, in the direction of travel. All weld passes were started from the same end of the panel.

Temperatures were measured in the parent material adjacent to the joint during welding by thermocouples located at the bottom of holes drilled from the surface to the mid-thickness of the plate. A recording oscillograph was used to obtain a continuous record of temperature, voltage and current versus time. Arc time was also recorded.

Figure 1 shows the location of test specimens in the welded panels. Each welded panel was examined by X-ray. Panels No. 1A and 1 showed evidence of incomplete root fusion. The other panels showed no discontinuities.

Hardness surveys were made on $^{1}/_{4}$-in. full thickness cross-weld slices. A series of adjacent slices was used to obtain hardnesses for various periods of natural aging after welding. Hardness readings were also made on two sets of slices artificially aged 12 hr at 300F (one set was artificially aged after 2 months and the other set after 33 months of natural aging) and on another set of slices artificially aged 24 hr at 250F (after 33 months of natural aging).

Metallographic examinations were made on the same slices used in the hardness survey. The slices were first radiographed to determine weld soundness, and then etched in a caustic solution to reveal the macrostructure and the extent of the HAZ. After examination of the macrostructure, the slices were polished, etched with Keller's etch and examined at 500X to determine soundness of the welds and the extent of any abnormalities, such as microporosity, unusual grain structures and extent of precipitation through the HAZ.

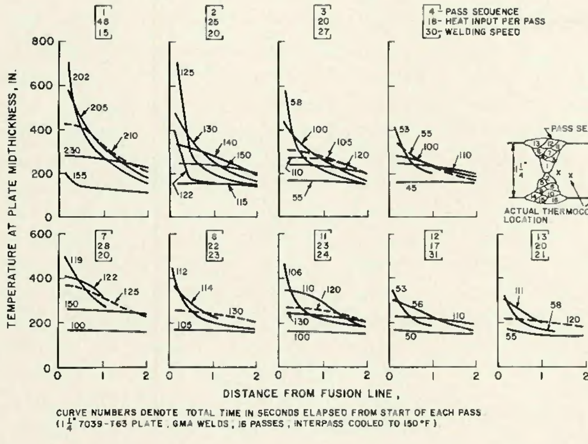
Cross-weld tensile tests were made after one month of natural aging on 1-in. wide, full-section specimens. Tensile tests were also made on parent material unaffected by heat of welding.

Residual stresses parallel to the weld were determined from the relaxed strains measured by isolating strip-type specimens at various locations across the width of the welded panels, as shown in Fig. 1. In addition, biaxial residual stresses on the surface, immediately adjacent to the weld bead, were calculated from strains measured using electrical resistance strain gages bonded to the top and bottom surfaces of the strips on either side of the center weld metal strip (shown as Strips No. 2 and 4 in Fig. 1).

Solution potential measurements were made in the weld metal, in the HAZ, and in the parent material unaffected by heat of welding.

General resistance to corrosion was evaluated by immersing 1-in. wide full-section cross-weld strips in a sodium chloride-hydrogen peroxide solution (53 g NaCl + 3 g H_2O_2 per liter) for a period of one month. The edges of the specimens were coated to eliminate unrealistic edge effects, especially at the weld bead and in the HAZ.

Stress-corrosion tests were made using $^{1}/_{4}$-in. thick by 1-in. wide by $8^{3}/_{8}$-in. long specimens, centered across the weld and removed from each surface of the panel. Matching specimens from each 1-in. weld seg-



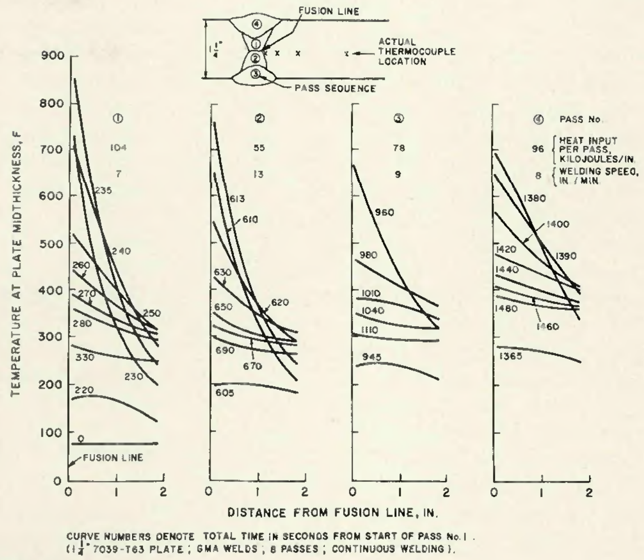
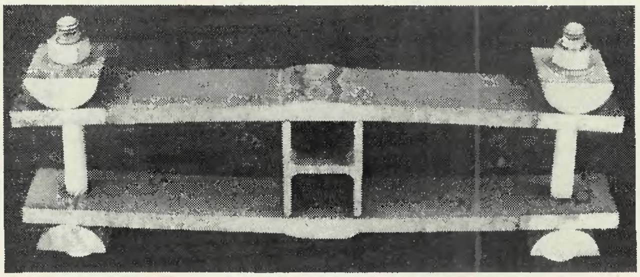


Fig 3—Temperature variations in HAZ of panel No. 1 (left) and panel No. 8 (right)

Fig. 2—Beam assembly for stress corrosion test (right)



ment were stressed as beam assemblies, as shown in Fig. 2 (Ref. 3). The specimens were bent so that the as-welded surface was stressed in tension of 75% of the 10-in. gage length yield strength in a tension test. (Yield strengths for a 10-in. gage length were estimated to be 10% higher than those determined for the 6-in. gage length used in the full-section tensile tests.) The stressed beam assemblies were exposed in the industrial atmosphere at New Kensington, Pa., and a 3.5% NaCl alternate immersion bath.

Ballistic tests were made one month after welding by impacting the panels in the weld, in the lowest hardness region of the HAZ and in the unaffected parent material with .30 cal armor-piercing (M2) projectiles, with the line of fire normal to the plate. Protection Ballistic Limits (V_{50} PBL) were determined from the average velocity of six impacts, having a velocity spread of 100 ft per sec or less, and consisting of three impacts resulting in partial penetration and three which resulted in complete penetration. (Test method specified by Military Specification MIL-A-46063.) A complete penetration is defined as the perforation of a 0.002-in. aluminum witness sheet, located parallel to and 6-in. behind the target, by either the projectile, projectile fragments or target fragments.

Results and Discussion

Thermal Relationships

The rate of heat input per inch of weld in gas metal-arc welding is proportional to the welding voltage and current and inversely proportional to the welding speed.[4] Most of the heat of welding will be dissipated by conduction through the adjacent metal, although a small amount will be lost by radiation and convection to the surrounding environment. For a given material, the rate of heat conduction from the weld puddle will depend on the geometry of the parts being welded and the temperature differential between the weld metal and the adjacent parent material.

Table 1 summarizes heat input data for the weld panels. These data show that the total heat input required to complete the weld joints in the wide panels did not vary appreciably. However, Panel No. 1A required a heat input of only 240 kilojoules per in. as compared to an average input of 350 kilojoules per in. for the wider panels. This difference can be attributed to the difference in panel width and to the fact that the joint in Panel No. 1A had a 45 deg groove as compared to a 60 deg groove for the wider panels.

In planning this investigation, the total number of passes was specified for each panel but the actual heat input per pass was left up to the judgment of the welding engineer. Table 1 shows that there were marked differences between the maximum and minimum heat input used in the various passes for a given joint. Also the location of the pass (pass number) associated with either the maximum or minimum heat input varied. As will be discussed later, some weld properties are adversely affected by increasing heat input per pass. Thus, whenever feasible, it would generally appear to be desirable to maintain a more uniform heat input per pass.

Table 1 shows that for the wide panels the actual welding time (arc time) to complete one foot of weld increased with increasing number of passes. The total time of welding varied widely because of delays between passes necessitated by interpass cooling and handling of the samples. Circumstances might be quite different in actual production welds. Such welds would generally be longer than those used in the test panels and might be completed by two or more welders working simultaneously. Also, a welder could shift from one area or part to another. For these reasons, total time for welds made with interpass cooling could be considerably shorter than those shown in Table 1. In the case of continuous welding it might actually be necessary to place some restrictions on the welding schedules to avoid excessive heat build-up.

Figure 3 shows the variation of temperature with time adjacent to the weld in Panel No. 1, which was welded continuously in four passes, and Panel No. 8, which was welded in 16 passes with interpass cooling to 150F. In general, these data, which are typical of those for all of the test panels, reflect the effect of heat input per pass, pass location and interpass temperature control on the temperature distribution in the vicinity of the weld along the midplane of the plate.

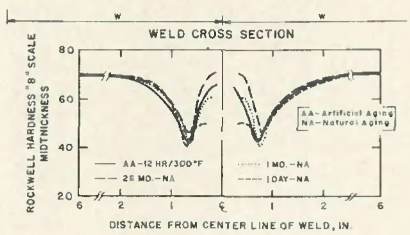
In both panels the temperatures immediately adjacent to the fusion zone reached 800-900F for the first two passes, even though the heat input for the first two passes in Panel No. 1 was about twice that for Panel No. 8. However, 2 in. from the weld the temperature in Panel No. 1 during the first pass reached 330F while in Panel No. 8 the maximum temperature at this point was 230F.

In Panel No. 1 continuous welding resulted in a build-up in the plate temperature so that, just prior to making the fourth pass, the temperature in the weld vicinity was about 275F. It is interesting that the temperature was also around 275F just prior to making the 16th pass in Panel No. 7, which was also welded continuously. Similar temperature build-up did not occur with successive passes where interpass temperature control was maintained between passes, since the plate was allowed to cool naturally to a selected temperature before starting the next pass. A comparison of the temperature distributions in the various panels show that increasing number of passes and interpass cooling results in generally lower temperature and time at temperature at a given location in the vicinity of the weld. For example, at a distance 2 in. from the weld, the temperature reached 400F after the fourth pass in Panel No. 1, while in Panel No. 8, the temperature at this location never exceeded 230F (first pass).

Hardness Surveys

There is a general correlation between hardness and tensile strength for aluminum alloys having similar chemical composition. Therefore, hardness surveys in the HAZ provided a convenient and simple means of studying the effect of heat input during welding on strength. Figure 4 shows hardness measurements at the midthickness of slices removed from some of the panels. Hardness variations adjacent to the top and bottom surfaces of the slices were similar to those at the midthickness. The initial plate hardness was around R_B80.

Hardness variations across the welded panels followed the same pattern for all of the weld joints and, with the exception of Panel No. 1A, may be classified by three regions as shown in Fig. 4b. In Region I the properties of the parent material are unaffected by heat of welding. The temperature at (A,) which is at the outer edge of the HAZ, (interface between Regions I and II), never exceeded 400F during welding, Regions II and III comprise the HAZ in the parent material. Region II does not recover strength by aging and because of this the HAZ width was unaffected by aging. Temperature measurements show that the maximum temperatures in this region ranged from 400 to 600F during



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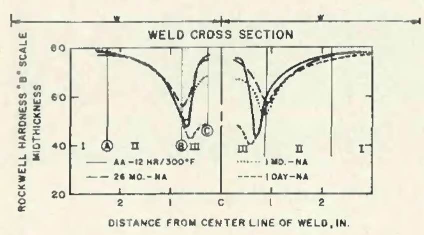

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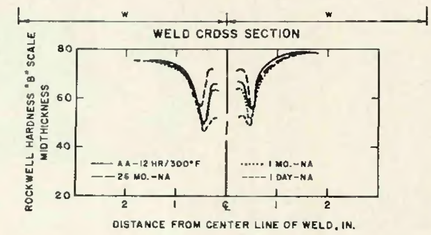

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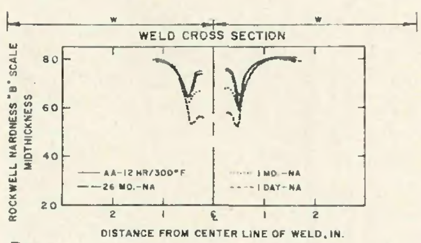

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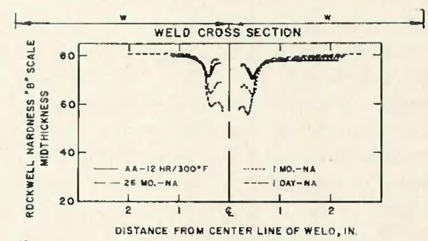
Fig. 4—Hardness surveys: (a) Panel no. 1A (4 passes, continuous welding, 45° double vee, W = 6″); (b) Panel no. 1 (4 passes, continuous welding, 60° double vee, W = 18″); (c) Panel no. 4 (8 passes, continuous welding, 60° double vee, W = 18″); (d) Panel no. 5 (8 passes, interpass cooled to 150F, 60° double vee, W = 18″); (e) Panel no. 8 (16 passes, interpass cooled to 150F, 60° double vee, W = 18″)



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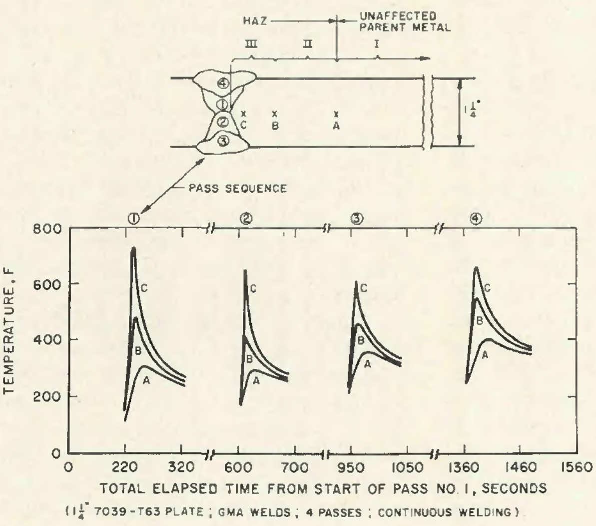
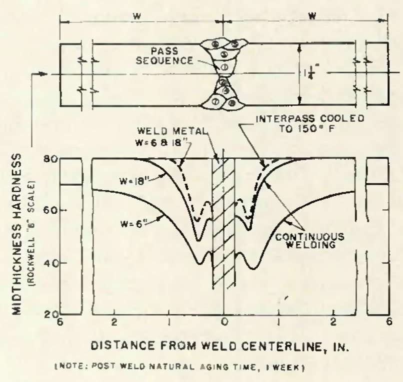


Fig. 5—Time-temperature relationships in HAZ of panel no. 1 (left)

Fig. 6—Effect of interpass temperature and plate width of HAZ hardness—Ref. 5 (below)



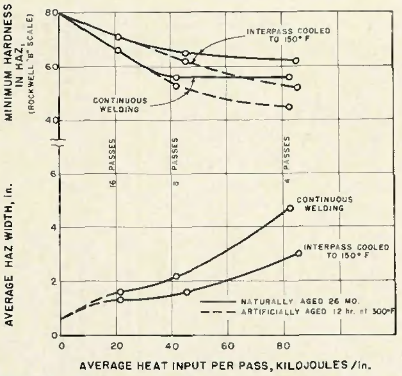


Fig. 7—Effect of interpass temperature and heat input on hardness and width of HAZ

Table 2—Minimum Hardness in HAZ at Plate Midthickness

			Rockwell hardness, B-scale							
			Naturally aged						Art. aged	HAZ
Panel no.	No. of passes	Interpass cooling	1 day	1 mo	6 mo	17 mo	26 mo	33 mo	12 hr/ 300F[a]	width,[b] in.
1A	4	CW	41	41	42	44	46	—	42	>12
1	4	CW	42	51	49	57	56	—	45	4.7
2	4	to 150F	46	56	56	61	62	—	52	3.0
3	4	to 150F	45	52	52	62	62	61	51	2.8
4	8	CW	48	50	55	59	56	58	53	2.2[c]
5	8	to 150F	53	61	—	65	65	—	62	1.6
6	8	to 250F	48	—	57	62	62	—	60	2.1
7	16	CW	56	62	63	65	66	66	67	1.6
8	16	to 150F	57	64	68	71	71	—	71	1.3

[a] Naturally aged two months prior to artificial aging
[b] Region having R_B77 or less. HAZ width unaffected by aging
[c] Estimated. One of plates used in panel had hardness less than R_B77

welding. Although Region III shows the greatest reduction in hardness immediately after welding, it regains hardness upon aging. This can be attributed to the fact that this region was heated to 600F or higher during welding and therefore underwent solution heat treatment. Typical time-temperature curves in the three regions are shown in Fig. 5.

Panel No. 1A differed from Panel No. 1 in that the width of plate on either side of the weld was 6 in. instead of 18 in. Panel No. 1A was welded continuously in four passes and temperature measurements during welding showed that the entire panel reached a temperature slightly above 400F after the last pass. Hardness readings, Fig. 4a, showed that continuous welding reduced hardness of the entire plate from the original value of R_B80 to R_B70 or less. These data demonstrate that proportions of the parts being welded may have a significant effect on weld joint properties.

Of further interest in connection with the effect of geometry on properties of weldments are tests reported in Ref. 5 and summarized in Fig. 6. These data show that butt welds made continuously in eight passes between 18-in. wide 7039-T63 plates resulted in only slightly wider, lower strength HAZ than that observed in a similar weld interpass cooled to 150F. However, when similar welds were made between narrow (6-in.) plates, continuous welding resulted in a HAZ that extended to the edge of the plate, while interpass cooling to 150F produced a joint having HAZ hardness and width similar to that obtained in the wider plates. Thermocouples at the midthickness of the plates, 2 in. from the weld centerline, showed a peak temperature of 250F when both narrow and wide plates were interpass cooled to 150 F. For welds made continuously, a peak temperature of 375F was observed in the wide plate while the peak temperature in the narrow plate was 550 F.

Figure 7 and Table 2 show that both the HAZ width and the minimum hardness in the HAZ were significantly affected by heat input per pass. Increasing heat input per pass resulted in increasing HAZ width and lower hardness. Also, continuous welding resulted in wider, lower hardness HAZ than did interpass cooling to 150F. HAZ hardness increased with natural aging up to about 17 months.

Samples were artificially aged for 12 hr at 300F after 2 months and 33 months of natural aging. The only noticeable effect of the different natural aging period was that hardnesses were slightly higher in Region III for samples having the longer natural aging period. For samples naturally aged for 33 months, artificial aging for 24 hr at 250F resulted in similar HAZ hardness to that of samples artificially aged for 12 hr at 300F. For welds made in 4 and 8 passes, artificial aging was not as effective as natural aging in restoring HAZ hardness.

Hardness of the weld metal was generally unaffected by varying heat input. Weld metal hardness in all weldments responded to natural aging, increasing from about R_B30 after welding to about R_B45 after 17 months natural aging.

Microstructures

Welds in heat treatable alloys generally exhibit four microstructural zones.[6] In this investigation, the width of these zones varied with welding procedure, but the microstructural changes within a particular zone were similar for all panels. The weld metal zone was a mixture consisting of melted base plate and 5356 filler metal with an as-cast dendritic cell structure. The cell size in the cast metal did not vary significantly in the various weldments.

The fusion zone, an area in which intergranular melting occurred, abutted the weld metal and contained portions of the original parent structure with partially melted and resolidified eutectic at the grain boundaries resulting from heating to temperatures between the liquidus and solidus.

The resolution heat treated zone is the area where temperatures were below the solidus of the alloy but high enough to redissolve the precipitates that were originally present in the parent plate. Temperatures in this area during welding were 600F or higher, resulting in partial or complete solution heat treatment. The microstructure varied from fine precipitates, associated principally with the grain boundaries, to coarse precipitates dispersed throughout the grain matrix. The latter structure is generally associated with low solution heat treating temperatures or slow cooling rates from a solution heat treatment. Within the overaged zone the alloy had been heated in the range of temperatures from 400 to 600F. Alloy 7039 begins to overage at temperatures above 320F; and the precipitate agglomerates and coarsens. This is accompanied by a reduction in mechanical properties which is usually attributed to loss of coherency between the precipitate and its matrix. Beyond the overaged zone the parent material structure was unaffected by the heat of welding.

Tensile Tests

Table 3 summarizes the results of the cross-weld tensile tests made one month after welding. These data show that, generally, yield strength increased and elongation decreased with increasing number of passes or decreasing heat input per pass. Weld metal hardness was less than that in the HAZ and thus failures occurred partly through or at the edge of the weld metal. Weld metal hardness, and therefore tensile strength, was not greatly affected by varying weld parameters. The cross-weld average tensile strength for the nine test panels was 47 ksi or about 67% of the parent material strength. For welds made in a given number of passes, yield strength appeared to be independent of interpass temperature. However, welds made continuously had higher elongations than those interpass cooled to 150 F.

Residual Stresses

Temperature gradients developed during welding result in longitudinal residual stresses (stress parallel to weld) which are tensile in and adjacent to the weld zone, with balancing compressive stresses away from the weld.[7] Maximum tensile stresses can be produced which approach the yield strength of the material in the HAZ.[8] Figure 8 shows that the peak longitudinal tensile stresses in the 36-in. wide panels did not vary greatly, ranging from 15 to 19 ksi. The somewhat lower stress in the 12-in. wide panel (No. 1A) probably reflects a reduction in restraint to weld contraction, as compared to the wider panels.

Figure 9 indicates the residual stresses adjacent to the weld determined from the relaxed strains measured with electrical resistance strain gages. These stresses represent the stresses on the plate surface, while those shown in Fig. 8 represent the average stress through the plate thickness.

Figure 9 shows the longitudinal surface stress decreased slightly with increasing number of passes. However, the particularly significant finding indicated by these residual stress determinations was the considerable increase of the surface stress normal to the weld with increasing number of passes. These latter stresses ranged from negligible values in welds made in 4 passes to tensile values of around 22 ksi for welds made in 16 passes. Interpass cooling did not show a marked influence on residual stresses introduced by welding.

The higher residual stresses normal to the weld for the welds made with the greater number of passes are attributed to the effect expected from a more localized heating, such as would be induced by the final passes in a weld made of a great number of passes. The material in the region of the last passes would be upset upon heating by virtue of the restraint to both lateral and longitudinal expansion offered by the cooler, stronger adjacent material.

As a result of this permanent shortening, elastic tensile stresses would then be developed both normal and parallel to the weld upon final cooling. The evidence of such a residual stress state, as provided by these measurements, is considered quite significant in regard to the influence that surface tensile stresses might have on fatigue performance or on stress-corrosion cracking when the short transverse edge of a plate is exposed adjacent to a weld.[3, 9]

Table 3—Full-Section Cross-Weld Tensile Properties (1-in. Wide Specimens)

Panel no.	No. of passes	Interpass cooling	Yield strength, 0.2% offset 6 in. G.L. ksi	Tensile strength* ksi	Elongation, % in 6 in. G.L. ksi
1A	4	CW	31	49	4.8
1	4	CW	31	45	3.8
2	4	to 150F	32	46	3.5
3	4	to 150F	32	46	3.3
4	8	CW	33	49	3.2
5	8	to 150F	35	47	2.6
6	8	to 250F	34	48	2.7
7	16	CW	36	46	2.7
8	16	to 150F	38	44	2.5

* Failures occurred through and at edge of weld

Parent Material Tensile Properties (1¼-in. 7039-T63 Plate)

Direction	Yield strength (0.2% offset), ksi	Tensile strength, ksi	Elongation, % in 0.5 in., G.L.
Longitudinal	60	69	14
Long transverse	60	70	13

Specimens were ⅛-in. diameter

Corrosion and Stress Corrosion

Solution Potential Measurements

Solution potential curves for various weldments are shown in Fig. 10. These data show that the area affected by the heat of welding was greatest for the weldment which had been prepared by the four-pass, high energy input technique. The use of a greater number of passes with the attendant lower energy input per pass decreased the width of the heat-affected zone. For welds made in a given number of passes, interpass cooling had no significant effect on the resultant solution potential curves of these weldments.

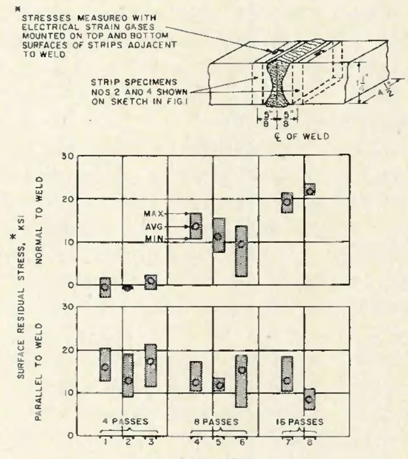


Fig. 9—Surface residual stresses parallel and normal to weld

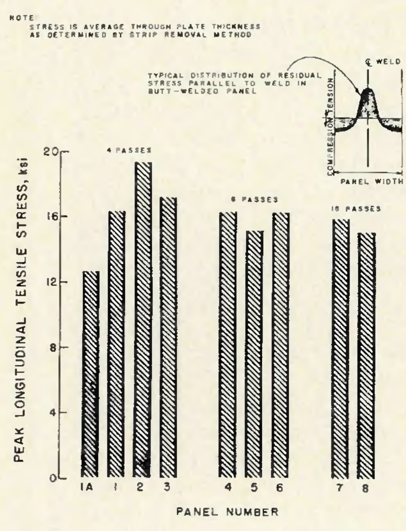


Fig. 8—Peak tensile residual stresses parallel to weld (left)

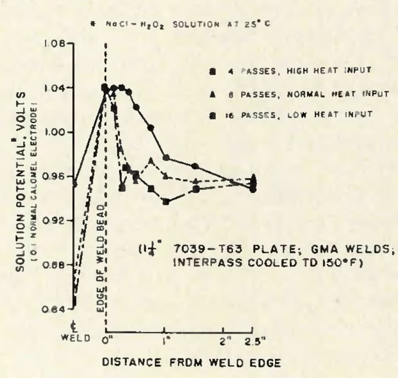


Fig. 10—Solution potential measurements (below)

Resistance to Corrosion

The condition of welded test samples after a one-month immersion in a $NaCl-H_2O_2$ solution is illustrated in Figs. 11 and 12. It should be noted that the sodium chloride-hydrogen peroxide solution is a very aggressive electrolyte which was chosen to accentuate the local galvanic effects in the 7039-T63 alloy weldments.

Severe attack of the HAZ, typical for Al-Zn-Mg alloy weldments exposed in a strong chloride electrolyte, was encountered with all the weldments. As shown in Fig. 11, reductions in the number of welding passes from 16 to 8 to 4 markedly increased the width that was susceptible to selective corrosion as predicted by the potential measurements. However, this does not imply more severe damage in weldments prepared by the four pass sequence, since the increased width of the HAZ reduced the cathode-anode ratio, thereby resulting in more shallow penetration of the corrosive attack. Interpass cooling to 150 F or 250F did not significantly affect the corrosion pattern in these weldments.

Selective corrosion of the HAZ in 7039 alloy weldments is related to the re-solution of zinc and magnesium in the metal heated to above 600F, which causes this region to become anodic to both the parent plate and the weld metal. Post-weld aging under suitable time and temperature conditions will nearly eliminate this tendency for selective corrosion of the HAZ but may cause susceptibility to stress-corrosion cracking.[10, 11]

Aging studies at Alcoa Research Laboratories have shown that post-weld aging for 10-16 hr at 300F will largely prevent accelerated corrosion of the heat-affected zones of 7039-T6 weldments, and will not significantly alter the strengths of the parent metal. It should be noted, however, that such aging treatments may cause susceptibility to stress-corrosion cracking along the fusion line. More drastic aging at 325 or 350F will appreciably lower the tensile properties of the parent plate, and will also develop a marked sensitivity to stress-corrosion cracking in Al-Mg filler alloys.

Selective corrosion in the HAZ region of naturally aged 7039 alloy weldments has been observed only in aggressive chloride environments such as sea water or salt water immersion tests. This type of HAZ corrosion has not occurred in exposures of 4 to 5 years in industrial and seacoast atmospheres.

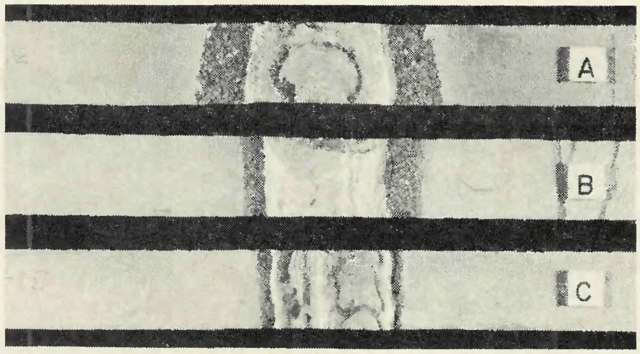


Fig. 11—Effect of passes on selective corrosion in HAZ: $NaCl-H_2O_2$ solution (A-4 passes; B-8 passes; C-16 passes. Interpass cooled to 150F)

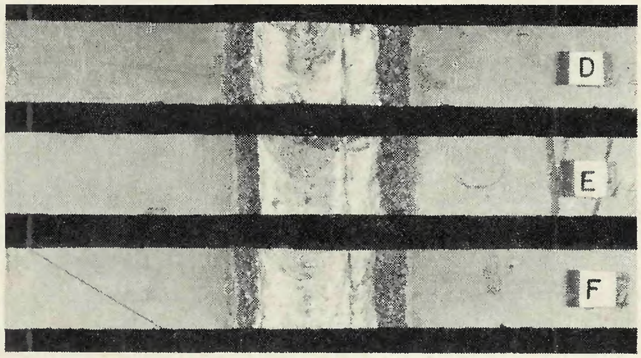


Fig. 12—Effect of interpass cooling on selective corrosion in HAZ: $NaCl-H_2O_2$ solution (D-continuous welding; E-interpass colled to 150F; F-interpass cooled to 250F. 8 passes)

Resistance to Stress-Corrosion Cracking

Beam assemblies of all weldments, stressed at 75% of the joint yield strength (10-in. gage length), exhibited no stress-corrosion cracking after exposure to the 3.5% NaCl alternate immersion for a period of one year, and the New Kensington atmosphere for a period of 29 months.*

Ballistic Tests

The results of the .30 cal AP-M2 ballistic tests on the 36-in. wide panels showed that welding created a ballistic window in which the V_{50} PBL was about 8% lower than that of the parent material. Although the test results do not completely confirm this, the PBL in the HAZ would be expected to decrease with decreasing number of passes since, as shown in Ref. 1, PBL for aluminum alloys against armor-piercing projectiles is proportional to tensile strength (and therefore hardness). The PBL in the weaker weld metal was about equal to that in the HAZ. This can be attributed to the additional thickness provided by the weld bead. The PBL of Panel No. 1A was about 5% lower than that of Panel No. 1, in both the parent material and in the HAZ.

*Removal of ¼-in. thick slices from the panel surface for stress-corrosion specimens relieved the tensile residual welding stresses normal to the weld. If beam tests were conducted on full-thickness sections, these stresses would be additive to the imposed stresses (assuming elastic action) and could affect the resistance to stress-corrosion cracking.

Conclusions

This investigation evaluated the effect of varying number of passes, interpass temperature and panel width on the properties of double-vee gas metal-arc butt-welds (5356 electrode) in $1^1/_4$-in. aluminum alloy 7039-T63 plate. In general, the investigation shows that the decision of whether welds should be made with either large or small heat input per pass and with or without interpass temperature control will depend on the application involved. The following conclusions should provide general guidelines for selecting welding parameters for multipass welds in thick plate of Al-Zn-Mg alloys:

1. Weld joint properties are affected by the dimensions of the plates being welded. Narrow plates provide less metal to act as a heat sink and therefore generally have a wider HAZ and lower strength than do wider plates.

2. Widely varying number of passes and interpass temperatures do not have a significant effect on total amount of heat input required to complete a weld joint.

3. Parent material properties appear to be unaffected in locations where temperature during welding does not exceed 400F. Metal heated in the 400-600F temperature range undergoes hardness reductions which are not restored by natural or artificial post-weld aging. Metal heated to 600F and above shows the greatest reduction in hardness immediately after welding, but its hardness is almost fully restored by post-weld natural or artificial aging.

4. HAZ width increases with decreasing number of passes and conditions which allow heat build-up during welding. Continuous welding in four passes of a joint between 6-in. wide plates resulted in a HAZ extending to the edge of the plate.

5. Based on measurements over a 6-in. gage length across the weld, joint yield strength decreased from 38 to 32 ksi and elongation increased from 2.5 to 3.5% when the number of passes was decreased from 16 to 4, with interpass cooling to 150F. Tensile failures occurred in the weld metal. Since the weld metal does not strengthen with aging except where mixing occurs with the 7039 parent metal, weld strengths were unaffected by varying heat input. Tensile strengths averaged 47 ksi.

6. Interpass cooling between passes has little effect on the magnitude of residual welding stresses. The surface tensile residual stresses parallel, and immediately adjacent, to the weld decrease slightly with increasing number of passes. The surface tensile residual stresses normal, and immediately adjacent, to the weld increase significantly with increasing number of passes.

7. The HAZ acts as a "ballistic window" where the velocity required for projectile penetration is lower than that required to penetrate the parent material. Decreasing number of passes increases the width of this window. Ballistic resistance of the weld with bead intact was comparable to that of the HAZ.

8. The high resistance to stress-corrosion cracking of these 7039 welds was not affected by the range of welding variables used in this investigation. Increased heat input per pass increased the width of the HAZ susceptible to corrosion but resulted in a shallower penetration of the corrosive attack.

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References

1. Baysinger, F. R., "Investigation of Welding and Fabricability of Kaiser Experimental Alloy MR39A," Final Project Report No. MS PR 64-12 (May 21, 1964) of Contract No. NAS8-5065 sponsored by George C. Marshall Space Flight Center, Huntsville, Ala.

2. "Aluminum Standards & Data," The Aluminum Association, New York, December, 1969.

3. Shumaker, M. B., Kelsey, R. A., Sprowls, D. O., and Williamson, J. G., "Evaluation of Various Techniques for Stress Corrosion Testing Welded Aluminum Alloys," ASTM Special Technical Publication No. 425, Stress Corrosion Testing (December, 1967), pp. 317-341.

4. Adams, Clyde M., Jr., "Cooling Rates and Peak Temperatures in Fusion Welding," The Welding Journal, Vol. 37, No. 5, May, 1958, Research Supplement, pp. 210s-215s.

5. Demmler, A. W., Kelsey, R. A., Lyle, J. P., and Shumaker, M. B., "Aluminum Armor(U)," Proceeding of American Ordnance Association Conference on Fabrication and Utilization of Materials for Light Armor, U. S. Army Tank-Automotive Command, Warren, Michigan, December 13-14, 1966. SECRET.

6. Brooks, Carson, "The Effect of Weld Heat in Arc Welding Aluminum," Light Metal Age, Vol. 24, Nos. 5-6, June, 1966, pp. 10-12.

7. Barker, R. S., and Sutton, J. G., "Stress Relieving and Stress Control," Chapter 10, Vol. III, "Aluminum-Fabrication and Finishing," American Society for Metals, edited by K. R. Van Horn, 1967, pp. 355-382.

8. Hill, H. N., "Residual Welding Stresses in Aluminum Alloys," Metal Progress, Vol. 80, No. 2, August, 1961, pp. 92-96.

9. Phillip, F., Pritchard, H. R., and Rosenthal, H., "Stress Corrosion Tests on Welded Cruciforms of 7039-Type Aluminum Alloy," AGARD Conference Proceedings No. 53 of Conference on Engineering Practice to Avoid Stress-Corrosion Cracking, 30 Sept.-1 Oct., 1969.

10. Young, John G., "BWRA Experience in the Welding of Aluminum-Zinc-Magnesium Alloys," The Welding Journal, Vol. 47, No. 10, October, 1968, Research Supplement, pp. 451s-461s.

11. Sprowls, D. O., et al., "Investigation of the Stress-Corrosion Cracking of High Strength Aluminum Alloys," Final Report for the Period May 6, 1963 to Oct. 6, 1966, of Contract No. NAS8-5340, sponsored by George C. Marshall Space Flight Center, Huntsville, Ala.