Effect of Welding Variables on Aluminum Alloy Weldments

BY R. J. BRUNGRABER AND F. G. NELSON

Rate of heat input influences strength of welds in heat treatable alloys but is not a factor for strain hardenable alloys

Introduction

When welds are made in cold-worked or heat-treated aluminum alloys, the heat of welding reduces the mechanical properties in a narrow zone, known as the heat-affected zone, surrounding the welds. It is generally recognized that the amount of heat introduced into the metal during the welding operation and the rate of removal of this heat have an effect on the extent of this heat-affected zone. The rates of heat input and removal also affect the strength of the weld, particularly in panels of the heat-treatable alloys if they are not reheat-treated after welding.

The object of the investigation described in this paper was to study the relationship between the variables that determine the rate of heat input and the resulting strength and extent of heat-affected zone.

Test Specimens

The welded panels that were studied in this investigation are described in Table 1. The table contains data on the conditions of welding as well as the dimensions of the panels. The mechanical properties of these welded panels, which are not shown, exceeded the requirements of applicable qualification specifications (AWS, ASME).

Welding Variables

A quantity that serves as a measure of the heat input to a weld is the ratio $E/Vt$, where $E =$ potential difference (V), $I =$ current (amp), $V =$ velocity of the heat source (ipm), and $t =$ plate thickness (in.).

The quantity $E/Vt$ is expressed in units of watt-minutes per sq in. and can be thought of as the electrical...
energy per unit of longitudinal cross-sectional area of the weld. The theoretical significance of this quantity is demonstrated by the work of Adams, \(^2\) discussed in the next section. If an a-c source was used, as in the case of gas tungsten-arc welding, the power factor, \(\cos \phi\), would have to be introduced. Thus, the quantity \(\frac{E_l}{Vt}\) would become \(E_l \cos \phi / Vt\). In the equations that follow, the parameter \(d\) will be considered as \(E_l / Vt\) since all panels used in this investigation were welded with d-c power, with the gas metal-arc method.

**Peak Temperature Distributions**

Based on a heat-flow analysis, Adams\(^2\) has developed the following expression for the distance from the edge of the fusion zone of a weld to the point at which a given temperature rise, \(T_p - T_0\), takes place:

\[
d = C_1 \left( \frac{E_l}{Vt} \right) \left( \frac{1}{T_p - T_0} \right) - \left( \frac{1}{T_m - T_0} \right)
\]

(1)

where \(d\) = distance from edge of the fusion zone to the point where \(T_p\) is measured (in.), \(T_p\) = peak temperature at a distance, \(d\), from the weld (F), \(T_m\) = initial temperature of the plate (F), \(T_0\) = melting point of the material (F), and \(C_1\) = a constant which depends upon the thermal conductivity of the material. \(V\), \(E\), \(I\) and \(t\) are as previously defined.

In the development of eq (1), it was assumed that the plates were insulated on the faces; this is reasonably representative of the usual welding operations where the plates being welded are either surrounded by air or clamped to a steel backing plate. The heat transfer through air is small in comparison with that through the aluminum plate, and the steel backing plates generally retain enough heat from previous welding passes to make their effectiveness as heat sinks very small. The above is not true, however, when water-cooled backing plates are used and, as discussed later, the data published by Burch\(^3\) demonstrate that the use of a water-cooled backing plate very definitely affects the heat flow so that eq (1) does not apply.

In order to apply eq (1) to aluminum weldments, it is necessary to establish values for \(C_1\) and \(T_m\). The values of \(t\) and \(T_0\) will be known for a given welding operation, and with modern

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**Table 1 — Gas Metal-Arc Welding Variables and Extent of Heat-Affected Zone (The Variables Shown are for the Particular Pass Which Resulted in the Maximum Value of \(E_l/Vt\))**

<table>
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<tr>
<th>Alloy and temper</th>
<th>Welding Method</th>
<th>Filler wire</th>
<th>Dimen. of panel, in.</th>
<th>Number of passes</th>
<th>I, current amp</th>
<th>E, voltage, v</th>
<th>V, speed, ipm</th>
<th>El/Vt, watt-min/in.</th>
<th>Extent HAZ, b in.</th>
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(a) All panels were made by joining two plates of equal size with a groove weld parallel to the last dimension.
(b) Distance from center of weld to edge of heat-affected zone, determined by hardness surveys.
welding methods, particularly automatic welding, the values of V, E and I can be closely controlled and measured. In order to compare eq (1) with measured peak-temperature distributions, it is also necessary to establish the extent of the fusion zone.

A value of C, that gives satisfactory agreement with the results of this investigation is 0.45. Approximate values of T₀ and Tₘ are 100 and 1200 °F, respectively.

The extent of the fusion zone may depend somewhat on the parameter El/Vt, but it is governed primarily by the thickness of the plate and the geometry of the edge preparation. For plate thicknesses up to and including 1 in., the edge preparation often consists of a 60 deg vee (included angle) with a 1/16 in. abutting root face. In this case, the extent of the fusion zone (measured from the center line of the weld) is approximately 0.6t, where t is the plate thickness. For thicknesses greater than 1 in., a "J" type of edge preparation is often used and, in this case, the extent of fusion zone can be closely approximated by (0.4 + 0.2t/).

The above values for C₁, T₀, and Tₘ, and the values of d from eq (1) give the following expressions for r, the distance from the weld center line to the point where a given peak temperature, Tₚ, is measured.

For t ≤ 1 in.:

\[ r = 0.6t + 0.45 \left( \frac{El}{Vt} \right) \left( \frac{1.090 - 0.0009 T_p}{T_p - 100} \right) \]  

(2)

For t ≥ 1 in.:

\[ r = 0.4 + 0.2t + 0.45 \left( \frac{El}{Vt} \right) \left( \frac{1.090 - 0.0009 T_p}{T_p - 100} \right) \]  

(3)

Equation 2 is compared with measured peak temperature distributions.
with good agreement, in Fig. 1. The peak-temperature values in Fig. 1 were measured both with thermocouples (using a continuous reading oscillograph) and with temperature-sensitive lacquers. The good agreement between the readings made with the two methods demonstrates that such lacquers are satisfactory for measuring peak temperatures during welding — Fig. 2.

The temperature-sensitive lacquers can conveniently be used in two ways for measuring thermal distributions caused by welding. First, a single set of stripes can be painted on before any welding is done and then all passes made. These stripes will establish the most extensive thermal distribution occurring at any time during the welding sequence. This could be used to predict the resulting extent of heat-affected zone; that region, adjacent to a weld, in which the properties have been affected by the heat of welding. A second approach and the one that was used to check the thermocouple measurements is to put a fresh set of stripes on before each pass.

Figure 2 shows stripes of temperature-sensitive lacquers, with critical temperatures ranging from 300 through 800 F. The stripes were applied to the plate before welding. The stripes in Fig. 2 (bottom right) were on the side away from the heat source and indicate a maximum temperature of about 500 F. Measurements of the amount of each stripe that turned color were made with a scale. In Fig. 2 (top — a two-pass weld) fresh stripes were placed prior to pass no. 2. Figure 2 (top left) indicates that a greater heat input was developed in the first pass because it was the penetration pass and therefore yielded a high El/Vt value; the second pass when applied was backed up by the first pass, yielding a lower El/Vt value. Figure 2 (bottom) shows the results at similar measurements for an 11-pass weld and demonstrates that the heat input for passes 1 through 7 changed the temperature distribution pattern greatly. The 11th pass was on the back of the panel and demonstrated that for the low value of El/Vt employed in that pass, the panel remained at a fairly low temperature.

In order to use eqs 2 and 3 to calculate the extent of the heat-affected zone, it is necessary to establish the highest temperature, Tc, at which a given aluminum alloy can be heated during welding without appreciably affecting the mechanical properties. With Tc substituted for Tp, eqs 2 and 3 give values of distance, bh, from the center of the weld to the edge of the heat-affected zone. On the basis of a

![Fig. 4 — Variation of extent of heat-affected zone with El/Vt](image)

![Fig. 5 — Variation of extent of heat-affected zone bh with thickness, for recommended welding procedures](image)
Fig. 6 — Variation of groove-weld strength with $E_l/V_t$ for 6061-T6 weldments prepared with 5556 filler metal.

Fig. 7 — Variation of tensile strength of groove welds with $E_l \cos \phi/V_t$.
preliminary study of test data, the value of \( T_c \) is about 550 F for Group I alloys and about 700 F for Group II alloys. The alloys were divided into these two groups on the basis of the data in Fig. 3. Based on the lowest values of the melting range, the alloys under consideration can be separated into two distinct groups. Subsequent data will show that this type of separation is not reasonable.

Using the above values for \( T_c \), eqs. 2 and 3 can be rewritten in terms of \( b_h \) as follows.

1. Alloy 6061-T6 or 6063-T6:
   - For \( t \leq 1 \text{ in.} \): 
     \[
     b_h = 0.6t + 0.00035 \frac{E_l}{V_t} \quad (4)
     \]
   - For \( t > 1 \text{ in.} \):
     \[
     b_h = 0.4 + 0.2t + 0.00035 \frac{E_l}{V_t} \quad (5)
     \]

2. Alloys 5356 and 5456 and other nonheat-treatable alloys:
   - For \( t \leq 1 \text{ in.} \):
     \[
     b_h = 0.6t + 0.00035 \frac{E_l}{V_t} \quad (6)
     \]
   - For \( t > 1 \text{ in.} \):
     \[
     b_h = 0.4 + 0.2t + 0.00035 \frac{E_l}{V_t} \quad (7)
     \]

In Fig. 4, eqs 4 and 6 are compared with some experimentally determined values of \( b_h \), and demonstrate satisfactory agreement. Figure 5 shows the variation of \( b_h \), with thickness, as calculated by eqs 4, 5, 6 and 7, in which the values of \( E, I, \) and \( V \) are those recommended for consumable electrode welding in the handbook, "Welding Alcoa Aluminum." It should be noted that, if the recommended procedures are followed, \( b_h \) should never exceed 1.5 in. according to Fig. 5.

Effect of \( E_l/V_t \) on Weld Strength

Not only does the extent of the heat-affected zone depend upon the parameter \( E_l/V_t \) but, at least for some alloys, the strength of the weld is also a function of \( E_l/V_t \). This is demonstrated in Figs. 6 and 7. The variation of transverse groove-weld tensile strength with \( E_l/V_t \) for 3/8 in. thick 6061-T6 plate welded with 5556 filler metal is shown in Fig. 6. The plates were gas metal-arc welded using a d-c power source so that the power factor did not enter the problem. The specimens were tested in the as-welded condition. Figure 6 demonstrates that by using a large number of passes, each resulting in a low value of \( E_l/V_t \), the strength of 6061-T6 weldments can approach that of unaffected base metal. The strength decreases nearly linearly with increasing values of \( E_l/V_t \).

In Fig. 7 are plotted data on strength of welds reported by Burch. These data were obtained from tensile tests on butt-welds in 6061 sheet, welded in the -T4 temper and artificially aged to the -T6 temper after welding. The welds were made with 4043 filler metal using a tungsten electrode and, in some cases, a water-cooled backing. In plotting the data, the value of \( E_l/V_t \) was multiplied by the power factor, \( \cos \phi \), since an a-c power source was used.
The data in Fig. 7 demonstrate that increased strength can be obtained by increasing the rate of heat removal with a water-cooled backing as well as by reducing the rate of heat input through control of the welding variables. Comparison of the strengths obtained from the 1/8 and 1/4 in. sheet welded with a water-cooled backing with the strengths of the 1/8 in. sheet welded with an insulated backing demonstrates that the water-cooled backing had about the same effect on strength as reducing the value of $E \cos \phi /Vt$ by 50%. The strength of the 1/16 in. material welded with a water-cooled backing was essentially equal to the strength of the base metal for values of $E \cos \phi /Vt$ up to about 2600.

In Fig. 8, the transverse tensile strength and 10 in. gage length yield strength of some butt welds in 3/8 in. thick 5456-H321, one of the Group I alloys, are plotted vs. the corresponding values of the parameter $E/Vt$. The welds were made by gas metal-arc process with argon shielding using a d-c power source, so that the power factor was not involved. Values in Fig. 8 do not appear to be greatly affected by $E/Vt$ up to about 2000.

Conclusions

The effect of welding variables on the strength of welds and the extent of the heat-affected zone in aluminum alloys was investigated. The following conclusions were reached on the basis of this investigation:

1. The effect of the heat of welding on strength and on the extent of the heat-affected zone is a function of the parameters $E/Vt$, where $E$ and $I$ are the welding voltage and current, respectively, and where $V$ is the velocity at which the weld is made, and $t$ is the thickness of the material. When welds are made with an a-c power source, this parameter should be multiplied by the power factor, $\cos \phi$.

2. The relationship between the peak temperature reached at a point in a plate during the welding operation and the distance between that point and the center line of the weld is given approximately by eqs 2 and 3.

3. The relationship between the extent of the heat-affected zone and the parameter $E/Vt$ is given approximately by eqs 4 and 5 for 6061-T6 and 6063-T6 and by eqs 6 and 7 for non-heat-treatable alloys.

4. The extent of the heat-affected zone should not exceed 1.5 in. from the center line of the weld if the procedures recommended are followed.

5. The tensile strengths of groove welds in 6061-T6 made with 5556 filler, not heat-treated after welding, can approach the strength of the unaffected parent metal for small values of $E/Vt$. The strength decreases almost linearly with increasing values of $E/Vt$ up to about 2000.

6. Use of a water-cooled backing in welding heat-treatable aluminum alloy sheet has an effect on weld strength similar to that of a reduction in the value of $E/Vt$ (based on published data).

Bibliography


Residual Stresses and Distortion in Welded Aluminum Structures and Their Effects on Service Performance

by K. Masubuchi

This interpretive report, sponsored by the Aluminum Alloys Committee of the Welding Research Council consists of eight sections. It discusses residual stresses and distortion in welded aluminum structures and their effects on service performance. After a brief introduction, Section 2 discusses thermal stresses during welding, residual stresses and distortion in weldments in aluminum alloys. Section 3 cites allowable distortion specified in several standards including (1) AWS codes for buildings and highway and railway bridges, (2) ASME boiler and pressure vessel code, and (3) U.S. Navy standard for ship hulls. Section 4, which serves as an introduction to Section 5, discusses changes of residual stresses in weldments due to external loading. Section 5 discusses effects of residual stresses on fracture strength of welded structures. Section 6 covers effects of residual stresses and distortion on buckling strength of welded aluminum structures. Section 7 discusses reduction of residual stresses and distortion. Section 8 points out areas where future research is needed. It is concluded that research is needed on the following subjects:

1. Assessment of information on distortion in aluminum structures
2. Rational standards on allowable distortion
3. Effects of residual stresses and distortion on buckling strength
4. Effects of residual stresses on fracture characteristics
5. Reduction of residual stresses and distortion

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