ABSTRACT. Cracking is a major concern in welding aluminum alloys. Although weld solidification cracks can be eliminated through the addition of filler metal, the additives modify the alloy or base metal constituents and may not always be desirable. High-energy beam processes, such as electron beam welding, that result in minimal heat input reduce crack sensitivity, but their high cost limits their applications. In this study, the conventional gas tungsten arc welding process is modified by disconnecting the workpiece from the power supply and placing a second torch on the opposite side of the workpiece. Such a modification changes the direction of the current flow, improves the weld penetration and reduces the heat input. Using this modified process, 6061-T651 alloy was welded without filler metals. Analysis suggested the reduced heat input, the changed direction of the current flow and the symmetric heating were responsible for the observed reduction of the cracking sensitivity.

Introduction

Cracking is a major concern in welding aluminum alloys. This is due to the relatively high thermal expansion of aluminum, the large change in volume upon solidification and the wide solidification-temperature range (Ref. 1). High heat inputs, resulting from high currents and slow welding speeds, increase the thermal stress, solidification shrinkage and partially melted region, thus contributing to both the weld solidification cracking and HAZ liquation cracking. Although weld solidification cracks can be effectively controlled using selected filler metal (Refs. 2–5), the additives modify the alloy or base metal constituents and may not always be desirable (Ref. 2).

High-energy beam processes reduce the overall heat input. The high thermal gradient from the weld into the base metal creates limited metallurgical modifications and is least likely to cause intergranular cracking in butt joints when no filler metal is added (Ref. 1). The electron beam welding process can weld aluminum alloys without the addition of filler metal (Refs. 1, 6, 7). However, due to the strong reflection, laser welding of aluminum alloys is less effective (Refs. 8–10).

The authors developed a new GTA welding process that can increase the weld penetration by using two torches on the opposite sides of the workpiece and connecting them to the power supply in series (Refs. 11, 12). The connection between the power supply and the workpiece in a conventional arc welding system is removed. As a result, the welding current flows from the power supply to a torch, then through the work more or less normally, then to another torch and finally returns to the power supply. Such a current flow concentrates the arcs and improves the weld penetration, thus resulting in a reduction in the heat input. This process may provide a method to weld aluminum alloys without filler metal and to generate positive effects on productivity, cost and weld quality. In this study, the dual-torch gas tungsten arc welding (GTAW) process will be used for welding aluminum.

Experimental Procedure

Figure 1 illustrates the configuration of the experimental system used to perform the proposed arc welding method, referred to as opposing dual-torch gas tungsten arc welding (ODT-GTAW). The two terminals of the square wave, constant current, AC power supply were connected to two regular GTAW torches. The polarity ratio and the flow rate of the shielding gas (argon) were 15 ms to 15 ms and 12 L/min, respectively.

Y. M. ZHANG and S. B. ZHANG are with Welding Research and Development Laboratory, Center for Robotics and Manufacturing Systems, University of Kentucky, Lexington, Ky.
Experimental Results

Experimental results showed, although no filler metal was added, ODT-GTAW made no cracks — Figs. 2 and 3. However, regular AC GTAW made cracks. Figure 4 shows the weld face appearance of the welds made using the two different methods.

Experiments also showed that the ODT-GTAW process improved the weld penetration. It is known that in order to weld 3.2-mm-thick aluminum plates, regular AC GTAW needs one to two passes with 110–140 A current and 4 mm/s welding speed (Ref. 1). For 6.4-mm-thick plates, two passes are needed at 200–240 A current and 3–4 mm/s welding speed (Ref. 1). As can be seen in Fig. 2, ODT-GTAW significantly penetrates 6.4-mm-thick plates in a single pass with 145 A current and 7.5 mm/s welding speed. For 9.5-mm-thick plates, with preheating to 177°C (350°F), regular AC GTAW needs three passes at 260–300 A current and 3–4 mm/s welding speed. For the ODT-GTAW, 9.5-mm-thick plates can be sufficiently penetrated in a single pass with 150 A current at a welding speed of 2 mm/s, without preheating. The improvement in the weld penetration is quite significant. Due to the improvement in the weld penetration capability, the heat input and fusion zone are reduced. Lower heat input and no preheat decrease the width of the HAZ (Ref. 1). Such decreases should help increase the weld strengths for 6061 alloys and other aluminum alloys (Ref. 1).

Table 1 gives the test results for the mechanical properties of the welds made using ODT-GTAW. The samples were tested as welded. The results are average readings from three samples for each condition. It can be seen that when the welding speed is 4.2 or 6 mm/s, the ultimate strength of the ODT-GTA welds is 199 MPa or higher, slightly better than that of the regular gas shielded arc welds (186 MPa or higher, Ref. 1). Also, the joint ductility measured over a 50.8-mm gauge length (12.4% or higher) is better than that of the regular gas shielded arc welds (8% or higher, Ref. 1). Furthermore, the mechanical properties of the ODT-GTA welds are independent of filler metals. Hence, when the welding speed is appropriate — 4.2 or 6 mm/s in the experiments — the ODT-GTAW process demonstrates some characteristics that may better meet some particular requirements. When the welding speed is 7.5 mm/s, porosity is increased and the resultant weld strength is reduced.

Test results reveal that ODT-GTAW can achieve acceptable mechanical strengths if the welding speed is 4 to 6 mm/s. When the welding speed increases, porosity in the weld will increase and the resultant strength degrades (Table 1). For aluminum welding, the recommended maximum welding speed is 5 mm/s (Ref. 1). Hence, the welding speed associated with ODT-GTAW is acceptable.

Discussion

Experimental results reveal that the proposed ODT-GTAW method is a potential arc welding process to weld 6061 alloy, and possibly other aluminum alloys, without filler metal. To understand
the principle of the proposed approach, the process and its mechanism in reducing the crack sensitivity should be discussed.

**Process**

The majority of the welding current in regular arc welding, such as in plasma arc welding (Ref. 13), grounds through the top surface of the base metal. In the proposed method, the welding current is through the workpiece — Fig. 5. Such a difference in the direction of the welding current generates a difference in the resultant forces.

It is known that the current is subjected to electric field force $F_e$ caused by the difference of the electric potential between the electrode and work and electromagnetic force $F_m$ (Fig. 5A) in the arc length area. These two forces can be calculated using the following equations (Refs. 14, 15):

$$\begin{align*}
F_e &= qE \\
F_m &= J \times B
\end{align*}$$

(1)

where $q$ is the charge of the particle considered, $E$ is electric field strength vector, $J$ is current density vector and $B$ is magnetic flux density vector. $F_e$ has two components, $f_e(x)$ and $f_e(y)$. Component $f_e(x)$, along the $x$ direction, diverges the current and increases when the current approaches the work. Component $f_e(y)$ along the $y$ direction, accelerates the particles in the plasma toward the work.

For $F_m$, its component $f_m(x)$ along the $x$ direction concentrates the current, but diminishes as the current reaches the work. The component along the $y$ direction, $f_m(y)$, also accelerates the particles in the plasma toward the work.

In ODT-GTAW (Fig. 5B), the current directly flows through the work. $f_e(x)$ and $f_m(y)$ are zero or negligible. This results in $f_m(x)$, which converges the current being increased to its maximum, while the divergent force $f_e(x)$ is zero. Hence, the current and the arc become much more concentrated than in regular arc welding.

For ODT-GTAW, the current in metal is subjected to the same forces as in the electrode-to-work distance due to its direction — Fig. 5B. The electromagnetic force will tend to converge the current, thus driving the fluid flow toward the axis of the current flow — Fig. 5B. Such flow tends to deepen the penetration. Due to the varying polarity, the direction of such fluid flow is subjected to periodical change. Such change may tend to generate a stirring effect in the weld pool. However, in regular arc welding, such a flow exists on the surface of the workpiece, but not inside the base metal.

In the proposed approach, the two arcs symmetrically heat the workpiece. The symmetric heating decreases the thermal distortion of the workpiece during the welding. The reduced thermal distortion should tend to decrease the thermal stress.

**Crack Sensitivity**

Weld cracking in aluminum alloys may be classified into two primary categories based on the mechanism responsible for the cracking and the crack location (Ref. 1). Solidification cracking occurs within the weld zone and typi-
cally appears along the center of the weld or at the termination craters (Ref. 1). Liquation cracks take place adjacent to the fusion zone and may or may not be readily apparent.

Solidification cracking occurs when high levels of thermal stress and solidification shrinkage are present when the weld pool is undergoing solidification (Ref. 1). Due to the high coefficient of thermal expansion, the solidification shrinkage of aluminum alloys is almost twice that of ferrous alloys (Ref. 1). High heat inputs melt large amounts of base metal, thus intensifying the shrinkage. It is the increase in penetration for a given current that allows lower current and therefore lower heat inputs to be used with ODT-GTAW. For example, to weld a 6.4-mm-thick aluminum workpiece, the heat input into the workpiece in a unit length along the weld joint W/U should be less than $145 \times 2U / \left( {7.5 \text{ mm} / \sec} \right) = 38.7U_{0}$. Here $U_{0}$ is the welding current, $v$ is the welding speed, and $U$ is the arc voltage of the two arcs that is approximately twice $U_{0}$, the arc voltage in regular AC GTAW measured by volts. For regular AC GTAW, the heat input into the workpiece in a single pass is $200U_{0} / 3 = 66.7U_{0}$ (Two passes are needed to weld a 6.4-mm-thick aluminum workpiece by regular AC GTAW.) Hence, the ODT-GTAW reduces the shrinkage, thus positively contributing to the reduction of solidification cracking sensitivity.

Due to the reduced heat input, the thermal stress may decrease. Also, the symmetrical heating associated with the ODT-GTAW, which lowers the thermal distortion, may help decrease the thermal stress. The reduction in the thermal stress can decrease the solidification cracking sensitivity.

An important cause of the solidification cracking is the wide range of the solidification temperatures. The partial melted state of the metals during solidification blocks the flow of the melted metals. If the solidifying metals can be shaken, the flow of the unsolidified metals and the heat transfer may be improved. (We notice that magnetic stirring has been generated to reduce cracking sensitivity, Refs. 16–18.) In the proposed approach, the electromagnetic force-driven flow acts in the neighborhood of the central line of the weld and changes its direction according to the polarity of the AC welding current. Such a flow may tend to shake the solidifying metals at a frequency of the AC current. In our experiments, the frequency of the AC current is $33.3 \text{ Hz}$ and is relatively high in comparison with the thermal process. Hence, the location and direction of the AC current flow in the ODT-GTAW may also be a factor that reduces the crack sensitivity. However, further studies will be needed in order to confirm this assumption.

Conclusions

The proposed ODT-GTAW appears capable of welding 6061 alloys without addition of filler metals under conditions used in this study. In addition to the reduction in the cracking sensitivity, the ODT-GTAW process also provides some other advantages, such as the reduction in the number of the passes. However, to actually apply the proposed ODT-GTAW method, both sides of the workpiece must be accessible.

Three possible causes have been assumed to explain how the ODT-GTAW reduces the cracking sensitivity. It is evident further studies must be conducted to verify these causes.

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References


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