Improved Microstructure and Properties of 6061 Aluminum Alloy Weldments Using a Double-Sided Arc Welding Process

Y.M. ZHANG, C. PAN, and A.T. MALE

Due to its popularity and high crack sensitivity, 6061 aluminum alloy was selected as a test material for the newly developed double-sided arc welding (DSAW) process. The microstructure, crack sensitivity, and porosity of DSAW weldments were studied systematically. The percentage of fine equiaxed grains in the fully penetrated welds is greatly increased. Residual stresses are reduced. Porosity in the welds is reduced and individual pores are smaller. It was also found that the shape and size of porosity is related to solidification substructure. In particular, a weld metal zone with equiaxed grains tends to form small and dispersed porosity, whereas elongated porosity tends to occur in columnar grains.

I. INTRODUCTION

AS one of the most commonly used heat-treatable aluminum alloys, 6061 is available in a wide range of structural shapes, as well as sheet and plate products. Typically, it is used in autobody sheet, structural members, architectural panels, piping, marine applications, screw machine stock, and many other applications.[1] Generally, this alloy is easily welded by conventional arc welding processes (gas metal arc welding and gas tungsten arc welding (GTAW)) and high-energy processes (laser-beam and electron-beam welding). However, certain characteristics, such as solidification cracking, porosity, heat-affected zone (HAZ) degradation, *etc.*, must be considered during welding, due to the greater amount of alloying additions used in this alloy.[2–5] Because of high-energy density and low overall heat input, laser beam and electron beam welding processes possess the advantage of minimizing the fusing zone and HAZ[5] and producing much deeper penetration than arc welding processes.[6] However, their high cost limits their usage in industry.

Currently, the authors have developed a new welding process called "double-sided arc welding" (DSAW).[7–9] In this process, as shown in Figure 1, two torches (such as plasma arc torch and gas tungsten arc (GTA) torch, or dual GTA torches) are placed on the opposite sides of a base metal plate to increase penetration. They are directly connected to two terminals of a single power supply. The welding current loop becomes negative terminal - anode torch - workpiece - cathode torch - positive terminal instead of the conventional negative terminal - anode torch - cathode workpiece - positive terminal. As a result, current flow concentrates the arc and improves weld penetration, resulting in a reduction in heat input. For example, in order to penetrate 6.5-mm-thick Al plate, regular AC GTAW needs two passes, but AC double - sided GTAW requires only one pass.[8] In addition, the heat input in each pass for regular AC GTAW is approximately twice the heat input needed by the later.[8] The heat input is reduced to 25 percent. This process may provide a method to weld aluminum alloys without filler metal addition and to generate positive effects on productivity, cost, and weld quality. Extensive experiments have been performed on different metals and alloys using the DSAW process. Some unique characteristics and advantages have been obtained. For example,[7] on 6.4-mm-thick aluminum plates, the DSAW achieves 5.2-mm depth with 6-mm width, while regular variable polarity plasma arc welding (VPPAW) penetrates 3 mm with 8-mm width. The depth-to-width ratio is nearly doubled.

In the present work, the microstructures, solidification behavior, and cracking sensitivity of the 6061 aluminum alloy welded joints were studied systematically by comparison between normal arc welding process and the present DSAW process.

II. EXPERIMENTAL PROCEDURE

The 6061 aluminum alloy studied in the present experiment was the commercial plate 6061-T651 (wt pct: 0.28Cu, 0.6Si, 1.0Mg, 0.20Cr, and bal Al) in thickness of 4.76, 6.4, and 9.5 mm.

The DSAW with dual GTA torches was performed without filler metal addition. The two terminals of the square wave constant current AC power supply were connected to two regular GTA torches. The polarity ratio was 15 to 15 ms. The maximum current of the power supply was 150 A at arc voltage of 50 V. Uphill (vertical) welds were made in the butt joints from both sides with a shielding gas of pure argon at the flow rate of 12 L/min. In addition to DSAW, VPPAW was also used to make comparative welds with 1.5 L/min plasma gas flow rate and a 2.57-mm (0.093-in.) diameter orifice. Table I lists major welding parameters and conditions for both DSAW and VPPAW. Because of the difference in penetration capability and process characteristics, different parameters and conditions were used for DSAW and VPPAW.

Samples were mechanically polished and electrolytically etched with a solution of 20 pct hydrofluoric acid + 80 pct

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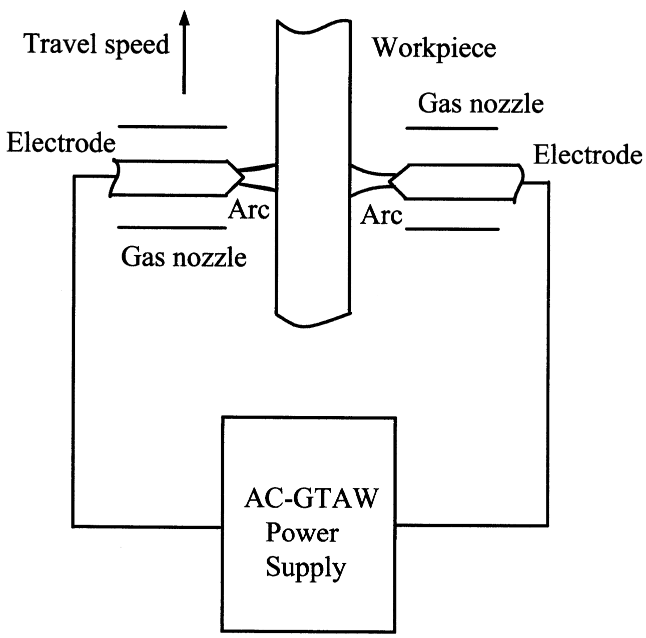


Fig. 1—The principle of double-sided GTA welding process.

water. The microstructures, fracture surfaces, and porosity were examined using a Nikon Epiphot 300 optical metallurgical microscope and a Hitachi S-3200 scanning electron microscope (SEM), operated at 20 kV.

III. RESULTS AND DISCUSSION

A. *Solidification Behavior*

Generally, solidification behavior in the weld pool is determined by several factors, such as thermal gradient in the liquid, G_L, solidification growth rate, R, chemical composition, pool shape, *etc.*[10,11] However, all of these depend upon the welding process. Different processes produce different solidification structures, thus different mechanical properties of joints. Among existing arc welding processes for aluminum, the VPPAW welding process achieves the deepest penetration. Hence, it was selected for comparative studies with the unique solidification characteristics of DSAW.

Figure 2 illustrates the solidification structures around the fusion boundary with different welding processes and different welding conditions. In the bead-on-plate VPPAW joint and partially penetrated double-sided GTAW joint, the microstructures of the welds consisted of well-developed cast columnar structures, which nucleated and grew epitaxially from the solid-liquid boundary or partially melted grains toward the upper surface, as shown in Figures 2(a) and (b). Observation indicated that the columnar grains typically comprised over 80 pct of the whole weld metal zone. Equiaxed grains only formed in a small area around the center. In addition, the size of the columnar grains increased toward the fusion boundary. This is the result of epitaxial solidification, which grows toward the center in a direction along the maximum thermal gradient.[10,11] The growth rate increases from zero at the fusion boundary to a maximum value at the weld center.[11]

As observed in Figure 2(c), in the fully penetrated DSGTAW joint, only a very narrow columnar structure exists

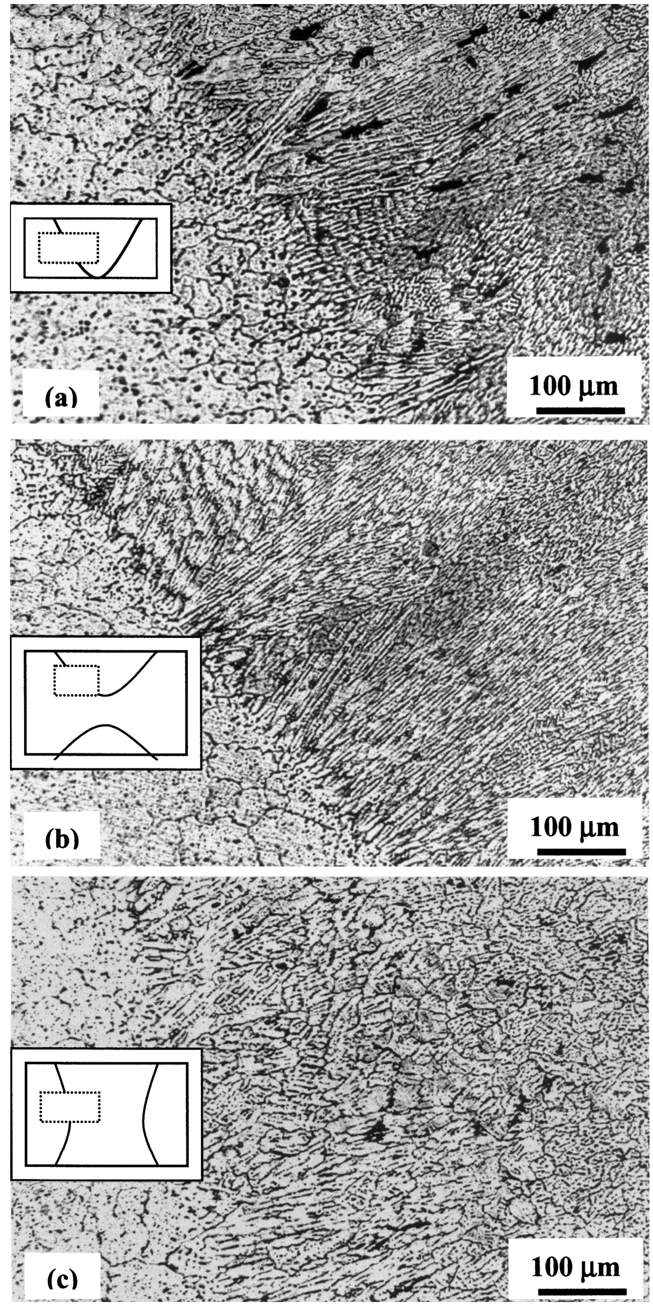


Fig. 2—Microstructures around the fusion boundary: (*a*) sample S-5, VPPAW; (*b*) sample S-3, DSGTAW, partial penetration; and (*c*) sample S-1, DSGTAW, full penetration.

along the fusion boundary. In most of the weld metal zone (typically over 70 pct), fine equiaxed grains become the major solidification structure. Figure 3 shows a typical morphology of the fine equiaxed grain in the center of the weld metal zone.

Generally, fine equiaxed grains tend to reduce solidification cracking and improve mechanical properties of the welded joint. This is due to the fact that, in fine-grained materials, low melting point segregates tend to be distributed over a larger grain boundary area, and equiaxed grains accommodate strains more uniformly or permit easier transport of liquid between grains.[12] However, unlike in casting, the natural occurrence of columnar-to-equiaxed transition in

Table I. **Welding Conditions**

Sample	Welding Method	Thickness (mm)	Arc Voltage (V)	Welding Current (A)	Welding Speed (mm/s)	Joint Type	Penetration
S-1	DSGTAW	6.4	47	145	4.2	butt	full
S-2	DSGTAW	6.4	47	145	6	butt	full
S-3	DSGTAW	6.4	47	145	7.5	butt	partial
S-4	DSGTAW	9.5	48	150	2	butt	full
S-5	VPPAW	4.76	36	EP = 100 EN = 80	4.7	bead-on-plate	full

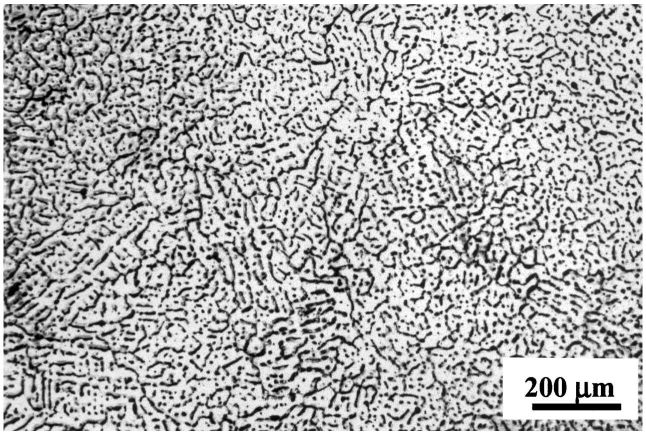


Fig. 3—Morphology of equiaxed grains in the weld metal zone of sample S-1.

the grain structure of weld is not very common.[10,13] It is well known that the Ti and Zr[14–18] and Cu, Cr, and Mn[19,20] alloying additions have an effect on grain refinement in Al-base casting and welding. Pearce and Kerr[21] used magnetic stir to increase the fraction of fine equiaxed grain in aluminum alloys. Clark *et al.*'s[22] research demonstrated that a columnar-to-equiaxed transition is favored in GTA welding in Al-Cu alloy by using high current and welding speed combination, increasing copper content, and increasing the weight percent of the nucleating agent for equiaxed grains. Brooks[11] found that a large equiaxed zone existed in the 6061 Al weld because of a high degree of constitutional supercooling.

For a given alloy system, the morphology of the solidification structure is controlled by the solidification parameters—the solidification growth rate R and the thermal gradient in the liquid G_L. That is to say, the ratio of the two parameters G_L/R changes from a maximum value at the fusion boundary to a minimum along the center of the weld. These changing solidification conditions result in a weld solidification structure changing from planar at the weld boundary to columnar dendrite and then to equiaxed dendrite grain along the weld center.[13]

For the present DSGTAW process, extensive experimental work has revealed that the fraction and width of the fine equiaxed grain region also gradually increased in the weld metal zone along with the increase in depth of penetration. It is known that when the penetration increases, the amount of the melted metal increases. Such an increase in the amount of the melted metal helps heat the workpiece before cooling. Hence, the thermal gradient during cooling is reduced. This tends to increase the amount of fine equiaxed grains. However, equiaxed grains are observed throughout nearly the whole weld metal zone. This cannot be explained by the reduced thermal gradient alone. The authors believe that the alternative fluid flow in the weld pool may be the major cause of such a formation of the equiaxed grain zone. In fact, in conventional arc welding, the welding current is largely grounded through the surface of the workpiece and little current flows through the depth of the weld pool. In the DSAW process, the welding current must directly flow through the weld pool from one side to the other side of the workpiece. The presence of the welding current inside the weld pool must cause an electromagnetic force driven fluid flow in the weld pool. Due to the varying polarity of the current, the direction of such fluid flow must change periodically. Such change may tend to generate a stirring effect in the weld pool.[8] Then the nucleation and growth of the grains during solidification becomes isotropic and forms the fine equiaxed grains in the greater part of the weld metal zone. This solidification characteristic will benefit the properties of the 6061 aluminum alloy welded joint, as will be discussed in Section B.

B. *Solidification Cracking Sensitivity*

The popularity and higher solidification cracking sensitivity of 6061 aluminum alloy weldments are other factors that attract many researchers.[2,3,5,8,23] Generally, solidification cracking occurs when higher levels of thermal stress and solidification shrinkage are present during welding.[1] It is influenced by a combination of mechanical, thermal, and metallurgical factors. In practice, the solidification cracking sensitivity of aluminum alloy weldments is determined by the chemical composition and weld conditions. For 6061 alloy, the greater amount of alloying additions of Mg and Si increases its cracking sensitivity. The primary methods for eliminating cracking in aluminum welds are to control weld metal composition through filler alloy additions and to use low heat input by using a special welding process, such as electron-beam or laser-beam welding.[1,3,5] In practice, some other methods, such as arc oscillations,[24–26] electromagnetic stirring,[21,27] external local heating,[28] and mechanical vibration,[29] are also used.

Figures 4 and 5 illustrate the weld surface and cross-sectional appearance of welds made using different processes. It is clear that the DSAW process has the higher cracking resistance. The cracking in the bead-on-plate VPPAW joint is typical of solidification cracking, which appears along the center of the weld metal zone. As discussed previously, the cracking is mainly produced by two factors, stress conditions and metallurgical factors.

In general, the stress concentration in the welded joint of aluminum alloy is induced in two ways: thermal stress,

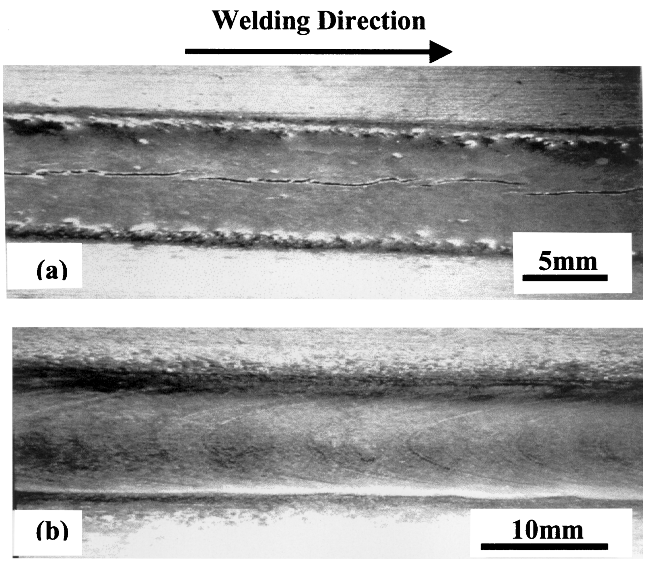
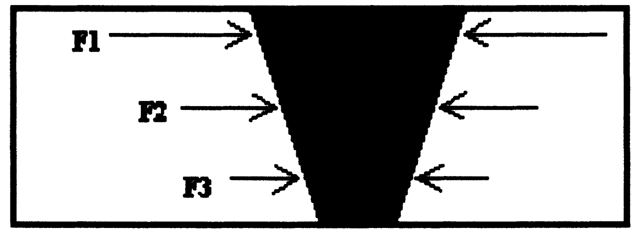
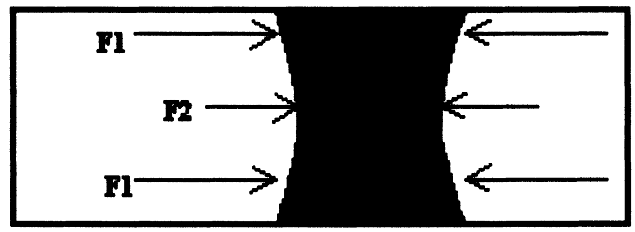


Fig. 4—Morphologies of the weld surfaces: (*a*) sample S-5, VPPAW; and (*b*) sample S-1, DSGTAW.



(*a*)



(*b*)

Fig. 6—Sketch map of the shrinkage force in the welds: (*a*) VPPAW, bead-on-plate; and (*b*) DSGTAW, butt, no filler.

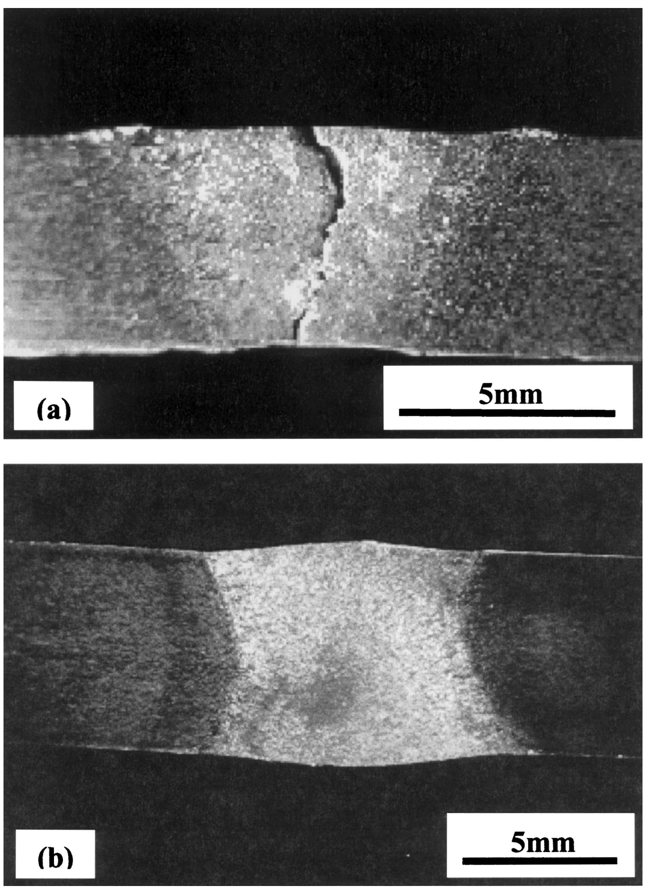


Fig. 5—Morphologies of the cross section of the welds: (*a*) sample S-5, VPPAW; and (*b*) sample S-1, DSGTAW.

due to the high coefficient of thermal expansion and large solidification shrinkage, almost twice that of steel. When an aluminum alloy plate is welded using a normal arc welding process, the molten pool typically is V-shaped, as shown in Figure 5(a). Shrinkage forces within the V-shaped zone cause the plate to have an angular distortion. The shrinkage induced stresses increase from bottom to top surface,[30,31] as shown in Figure 6(a). If the plate is constrained during welding, the distortion will decrease; however, the residual stress in the weld zone will greatly increase.[30] However, in the case of the DSAW process, two GTAW torches act upon the aluminum plate simultaneously and symmetrically. This means that shrinkage forces are symmetrical in the weld zone during cooling, as illustrated by Figure 6(b). This unique phenomenon associated with DSAW minimizes the transverse distortion and the residual stress in the weld pool. It helps reduce cracking sensitivity.

The solidification microstructure is another critical factor influencing cracking sensitivity in aluminum alloy weldments.[2,3,10,11] The DSAW process produces fine equiaxed grains in the weld metal zone, as shown in Figures 2 and 3. This microstructure is known to improve solidification cracking resistance. Observation of fracture surfaces VPPAW welds revealed that the solidification cracking nucleated, propagated, and disbonded along the columnar grain boundaries, as shown in Figure 7(a). Also, under higher magnification, as shown in Figure 7(b), secondary cracks and some secondary eutectic phases were observed. The secondary phase eutectic constituents, such as Mg_2Si and Si, surround the columnar structure and constitute a significant fraction of the part surface. This implies that solidification cracks initiated at a time very close to or after final solidification.[2]

For DSAW, the desired dimples, which indicate plastic deformation and higher toughness, are observed on the fracture surface of the weld metal zone. The fracture surface also appears to have less porosity with smaller pores, as shown in Figure 8. Both improvements are attributed to the fine equiaxed grains exhibited in the DSAW weldments.

C. *Porosity in the Weld Metal Zone*

It is desirable to limit porosity defects in aluminum weldments.[1,3–5,32–35] Porosity forms when hydrogen gas is

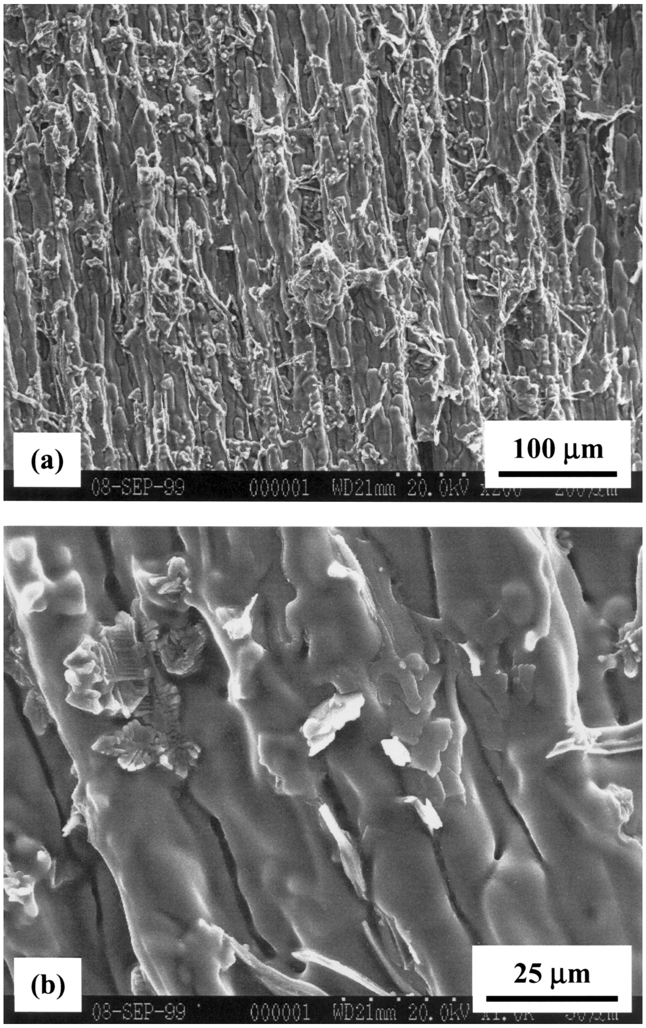


Fig. 7—SEM micrographs of the fracture surface in the weld metal zone of sample S-5 (VPPAW, bead-on-plate): (*a*) low magnification and (*b*) high magnification.

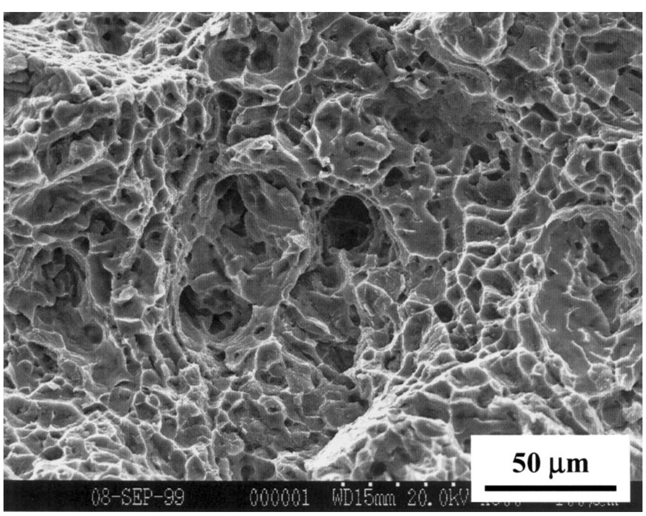


Fig. 8—SEM micrograph of the fracture surface in the weld metal zone of sample S-1 (DSPAW, full penetration).

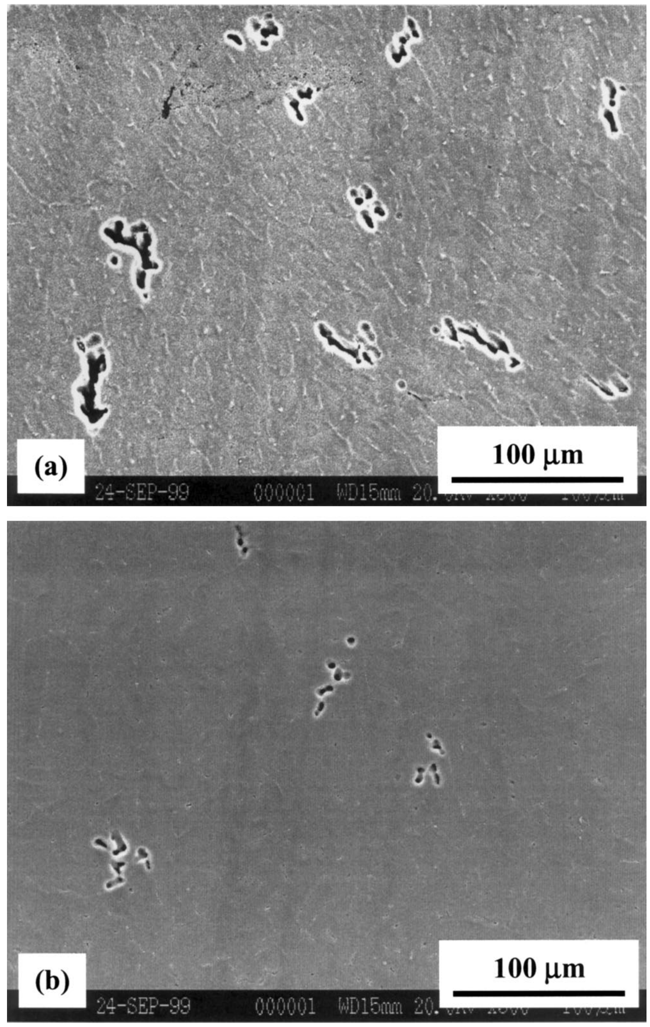


Fig. 9—Low magnification of porosity in the weld metal zones: (*a*) sample S-5, VPPAW, bead-on-plate; and (*b*) sample S-1, DSGTAW, full penetration.

entrapped during solidification.[1] Hydrogen is absorbed into the molten pool during welding because it is highly soluble in molten aluminum. Gas pores form during solidification, because solubility in the solid is less than in the melt and hydrogen is rejected from the solid to the melt causing localized supersaturation, bubble nucleation, and growth.

Increase in porosity is generally associated with high humidity and poor surface preparation. Use of inert gases to shield the weld pool can reduce porosity. In the present study, no special attention was paid to surface cleaning and shielding gas. The conditions were unchanged for VPPAW and DSAW. Bulk pores were not found in the weld metal zones of DSAW weldments. However, from Figure 9, it can be observed that the pore size in the plasma arc weld zone is significantly larger than that found in DSAW joints, that is, about 35 μm in the weld of VPPAW and 10 μm in the weld of DSAW. Higher magnification using an SEM shows clearly that columnar grains tend to produce an elongated porosity, whereas the equiaxed grains tend to form a smaller and more dispersed porosity, as shown in Figure 10. According to the theory of formation of gas porosity in aluminum alloys,[36–38] the long pores precipitate at a later stage of solidification, when crystals/dendrites are growing throughout the melt and are influenced by the hydrogen

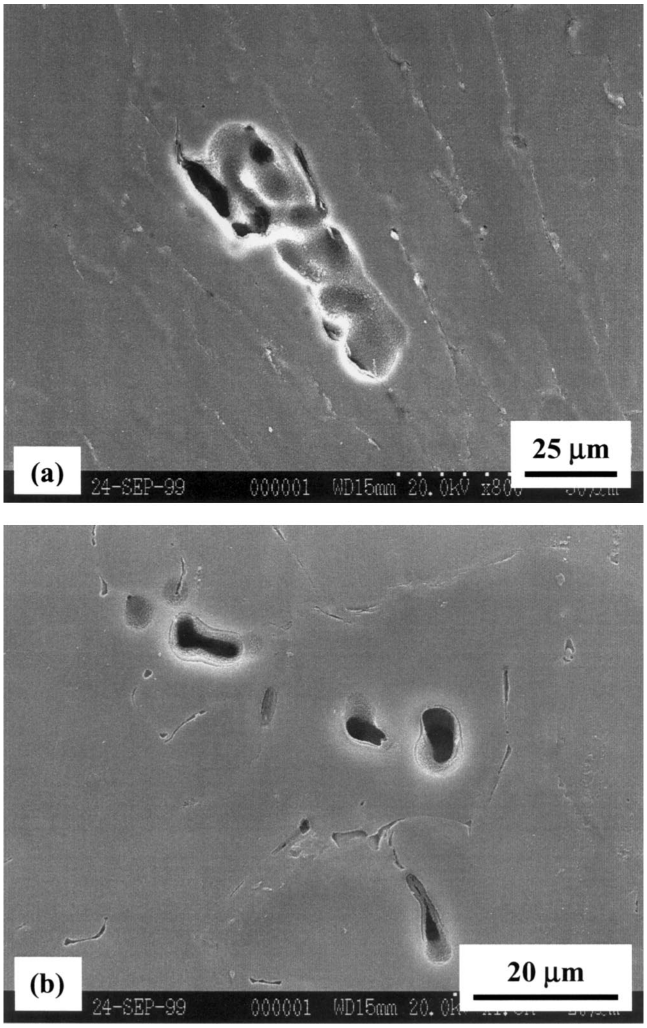


Fig. 10—SEM micrographs of porosity in the weld metal zones: (*a*) sample S-5, VPPAW; and (*b*) sample S-1, DSGTAW, full penetration.

enrichment and the shrinkage pressure in the columnar interdendritic area during solidification. On the other hand, the small and fissured pores precipitate at a very late stage of solidification, the bubble growth is severely limited, and the shape is determined by the interdendritic space available. Therefore, the large amounts of equiaxed grains solidified in the weldments of the DSAW process tend to form the small and dispersed porosity.

In addition, the characteristics of the DSAW process, such as its special bidirectional buoyancy, alternating electromagnetic force inside the weld pool, and dual surface tensions, may also control the formation of porosity. The hydrogen gas can escape from both melted sides of the weld pool, and the amount of pores are reduced. Hence, the solidification behavior of the DSAW process and the resultant size and distribution of porosity in the weld metal zone differs from other welding processes.

Comparing to different welding processes and welding conditions, the fully penetrated joint welded with the DSAW process, which exhibits a high proportion of equiaxed grains as discussed previously, contains smaller pores and less total porosity. This characteristic helps improve the mechanical properties of the joint.

IV. CONCLUSIONS

Compared to bead-on-plate VPPAW welding of 6061 aluminum alloy, the DSAW process has the following advantages.

1. The percent of equiaxed grains is increased and columnar-to-equiaxed grain transition occurs earlier than in partially penetrated DSAW and VPPAW welds.
2. Hot cracking sensitivity is reduced by minimizing residual stresses in the weld, as a result of the symmetrical temperature profile produced during double-sided welding.
3. Pores are smaller and more dispersed among the equiaxed dendrites produced by DSAW with full penetration than in the partially penetrated DSAW and VPPAW welds.

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