JOURNAL OF MATERIALS SCIENCE LETTERS **19** (2000) 831 – 833

Solidification behavior of Al-Mg aluminum alloy using double-sided arc welding process

Y. M. ZHANG, C. PAN*, A. T. MALE
Center for Robotics and Manufacturing System, College of Engineering, University of Kentucky, Lexington, KY 40506-0108, USA
E-mail: ymzhang@engr.uky.edu

As popular aluminum alloys, the 5*xxx* Al-Mg series, such as 5050 and 5052, etc., are widely used in applications such as automobile, pressure vessels, armor plate, and components for marine and cryogenic service. In this, as in all non-heat-treatable aluminum alloys, the weld metal zone is considered to be the weakest part of the joint and is the location of failure when the joint is loaded in tension during welding [1]. Solidification behavior of the weld pool, which controls the microstructure of the weld metal zone, plays a critical role in determining the ultimate strength of the joint.

Joint strength is assisted by laser beam and electron beam welding processes, which produce deep narrow penetration and minimize the heat input. These results are beneficial in aluminum welding because reduced heat input decreases thermal stress, solidification shrinkage, and the partially melted region, thus decreasing both weld zone solidification cracking and HAZ liquidation cracking. However, their high cost limits their use in production. The authors recently developed a patented new welding process, referred to as Double-Sided Arc Welding (DSAW) [2]. In this process, two welding torches are placed on opposite sides of the base metal and are directly connected to the two terminals of the power supply. The welding current flows through the workpiece more or less normally from one torch to another. The arc is significantly concentrated. As a result, the penetration is increased and the heat input is reduced at low cost.

Extensive experiments have been conducted for different materials using the DSAW process. Unique characteristics and advantages were observed: high depth-to-width ratio, reduced distortion, decreased discontinuities, improved microstructures, and improved mechanical properties. In the present work, the solidification behavior of aluminum alloy in the DSAW weld pool will be studied in comparison to conventional arc welding.

Commercial 5050 aluminum-magnesium alloy (1.4 wt% Mg) plates 6.4 mm thick, 50 mm in width and 250 mm in length, were chosen as the base metal and welded at flat position by using the double-sided arc welding process with one plasma arc welding (PAW) torch and one gas tungsten arc welding (GTAW) torch. No filler metal was added. The welding parameters used in the experiments were: welding speed 4.7 mm s^{-1}, arc voltage 46 V, torch polarity ratio 15 ms/15 ms, flow rate of plasma gas 1.2 L min^{-1}, diameter of orifice 2.57 mm. To compare the solidification characteristics of the weld pool, three samples were made using different welding currents: 80 A, 95 A and 105 A. The corresponding weld pool was partially penetrated, barely penetrated and fully penetrated, respectively, as shown in Fig. 1.

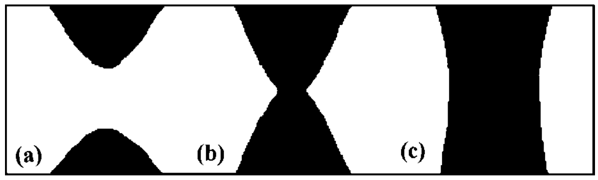

Figure 1 Schematic diagram of the weld pool: (a) partially penetrated; (b) barely penetrated; (c) fully penetrated.

Fig. 2 illustrates the solidification structures around the fusion boundaries. It shows that the well-developed columnar grains are nucleated and grown epitaxially from the solid–liquid boundary or partially melted grains. The intermetallic phase (Mg_2Al_3) is precipitated along the columnar grain boundaries. The columnar grains adjacent to the boundary are larger than those inside the weld zone. This is the result of epitaxial solidification, which grows towards the center in a direction along the maximum thermal gradient [3, 4]. The growth rate increases from zero at the fusion boundary to a maximum at the weld center [4]. Comparing the three joints, the major difference is that the columnar grains grow towards the upper surface in the joint with partial penetration, and grow horizontally towards the center of the weld metal in the joint with full penetration because of the symmetrical heat flow condition. There was an obvious partially melted zone (PMZ) along the fusion boundary. It is formed because of the partial melting along the grain boundary of the base metal during welding. The PMZ consists of large heat-affected grains with grain boundary eutectic.

For the weld metal zone, generally, the columnar-to-equiaxed grain transition (CET) may reduce solidification cracking and brittle fracture and improve mechanical properties of the welded joint. This is because equiaxed grains accommodate strains more uniformly or permit easier transport of liquid between grains [5]. However, unlike in casting, the natural occurrence of

* On leave from the Department of Materials Science and Engineering, Wuhan Transportation University, Box 188, Wuhan, Hubei 430063, People's Republic of China.

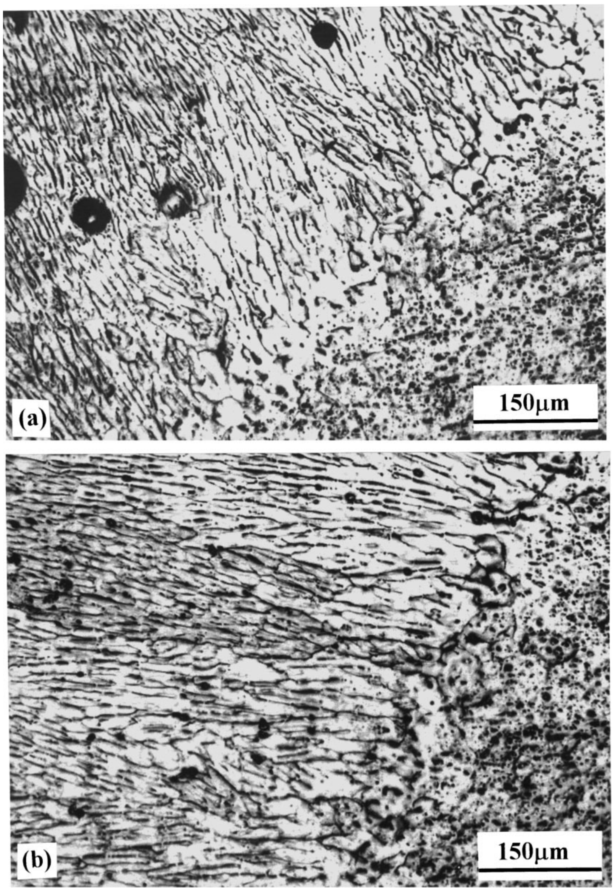

Figure 2 Solidification structures around the fusion boundaries: (a) in the partially penetrated joint with the welding current $I = 80$ A; (b) in the fully penetrated joint with the welding current $I = 105$ A.

CET in the grain structure of the weld is not very common [3]. 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 [6]. Clark *et al.* [7] demonstrated that a CET which is favored in GTA welding of Al-Cu alloy may be achieved by using a high current and welding speed combination, increasing copper content, and increasing the wt% of the nucleating agent for equiaxed grains. Brooks [4] found that a large equiaxed zone existed in the 6061 Al weld because of a high degree of constitutional supercooling. Gutierrez and Lippold [8] also noticed the formation of equiaxed zone along the fusion boundary in Al-Cu-Li alloy.

In the present work, observations revealed that the partially penetrated weld metal zones exhibit entirely as a cast columnar structure, and along with the increase of penetration, the equiaxed grain gradually becomes the major solidification structure, as shown in Fig. 3. 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 reduces. This tends to increase the amount of equiaxed grains. However, equiaxed grains are observed throughout nearly the whole weld metal zone. This cannot be explained by the reduced thermal gradient. The authors believe that the alternative fluid flow in the weld pool may be the major cause of such formation of equiaxed zone. In fact, in conventional arc welding, the welding current is grounded through the surface of the workpiece and no current flows through the weld pool. In the double-sided arc welding process, the welding current flows directly through the weld pool from one side of the workpiece to the other. The presence of the welding current inside the weld pool causes an electromagnetic force driven fluid flow in the weld pool. Due to the varying polarity of the current, the direction of such fluid flow is subjected to periodical change. Such change may tend to generate a stirring effect in the weld pool [9], and increase the formation of the equiaxed structure.

The porosity in aluminum weldments is one of the most undesired defects [10, 11]. It forms when hydrogen gas is entrapped during solidification [1]. That is, hydrogen is absorbed into the molten pool during welding because of its high solubility, and it forms gas pores upon solidification due to the decrease in solubility [12]. In the present study, no special attention was paid to the surface cleaning and the shielding gas. From Fig. 2 and Fig. 3, it is observed that the size of porosity in the plasma arc weld zone of the partially penetrated joint is much larger than that in the fully penetrated joints. And along with the increase of penetration, the size

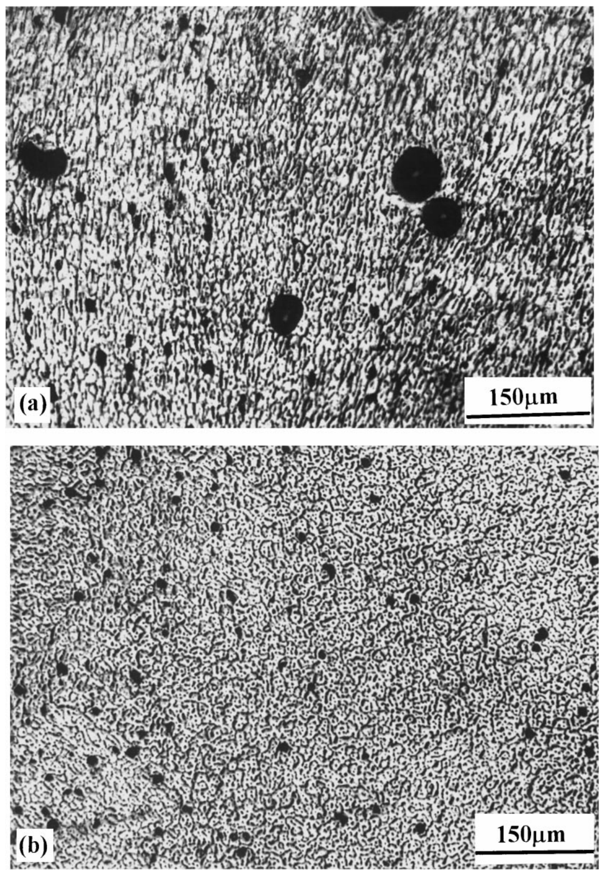

Figure 3 Solidification structures in the weld metal zones: (a) in the partially penetrated joint with the welding current $I = 80$ A; (b) in the fully penetrated joint with the weld current $I = 105$ A.

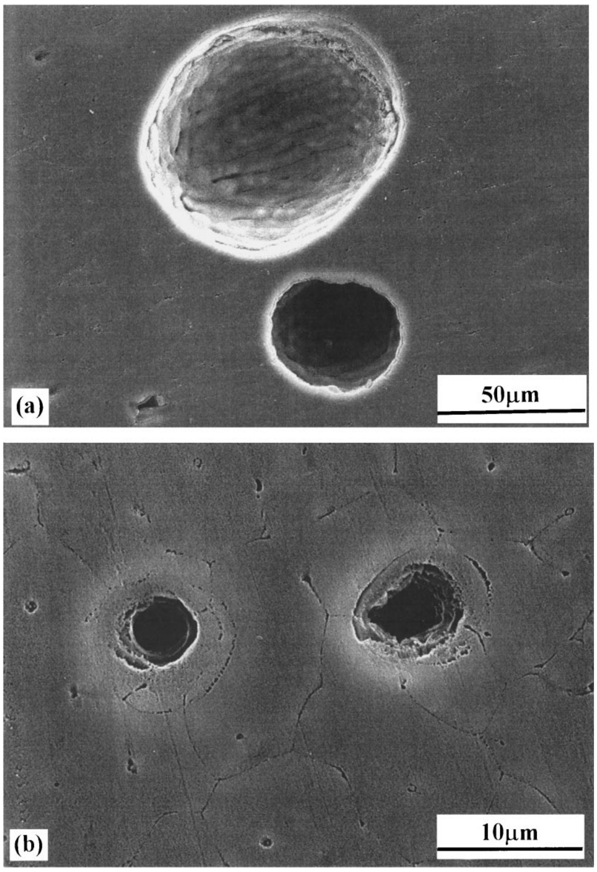

Figure 4 SEM micrographs of porosity in the weld metal zone: (a) in the partially penetrated joint with the welding current $I = 80$ A; (b) in the fully penetrated joint with the welding current $I = 105$ A.

and amount of porosity become smaller and less. In the partially penetrated joint, the largest size of porosity is about 400 μm, the middle size is about 80 μm and the smallest is about 15 μm. However, in the fully penetrated joint, the average size of porosity is only about 15 μm.

Generally, once a gas bubble forms, it may be expelled from the weld by natural buoyancy or forced convection within the molten pool. In the full penetration condition, the hydrogen gas may be expelled from both sides of the plate. In addition, the special heat flow of double-sided arc welding may help force the gas escape from the molten pool. Detailed SEM observations revealed that the larger porosity is related to the columnar grains and the smaller is formed in the equiaxed grains, as shown in Fig. 4. This implies that the size of porosity is also determined by the solidification structures. A full understanding of such phenomena requires further studies.

In conclusion, the double-sided arc welding (DSAW) process increases the columnar-to-equiaxed grain transition (CET) and decreases the size and amount of porosity in the weld metal zone of Al-Mg aluminum alloy.

Acknowledgments
This work is supported by the National Science Foundation (DMI 9812981) and the Center for Robotics and Manufacturing Systems (CRMS) at the University of Kentucky. The authors wish to express appreciation to Dr S. B. Zhang for his cooperation in this work.

References
1. J. R. DAVIS (ed.), "ASM specialty handbook: aluminum and aluminum alloys" (ASM International, Materials Park, Ohio, 1994) p. 400.
2. Y. M. ZHANG and S. B. ZHANG, *Weld. J.* **77** (1998) 57.
3. S. A. DAVID and J. M. VITEK, in Proceedings of the 3rd International Conference on International Trends in Welding Science and Technology, Gatlinburg, Tennessee, June 1992, edited by S. A. David and J. M. Vitek (ASM International, Materials Park, Ohio, 1993) p. 147.
4. J. A. BROOKS, in Proceedings of the 4th International Conference on Trends in Welding Research, Gatlinburg, Tennessee, June 1995, edited by H. B. Smartt, J. A. Johnson and S. A. David (ASM International, Materials Park, Ohio, 1996) p. 123.
5. S. KOU, "Welding metallurgy" (John Wiley & Sons, New York, 1987) p. 211.
6. S. A. DAVID and J. M. VITEK, *Int. Mater. Rev.* **34** (1989) 213.
7. J. CLARKE, D. C. WECKMAN and H. W. KERR, in Proceedings of the 5th International Conference on International Trends in Welding Research, Pine mountain, Georgia, June 1998, edited by J. M. Vitek, S. A. David, J. A. Johnson, H. B. Smartt and T. Debroy (ASM International, Materials Park, Ohio, 1999) p. 72.
8. A. GUTIERREZ and J. C. LIPPOLD, *Weld. J.* **77** (1998) 123-s.
9. Y. M. ZHANG and S. B. ZHANG, *ibid.* **78** (1999) 202-s.
10. P. A. MOLIAN and T. S. SRIVATSAN, *Aluminum* **66** (1990) 69.
11. D. M. DOUGLASS, J. MAZUMDER and K. NAGARATHNAM, in Proceedings of the 4th International Conference on Trends in Welding Research, Gatlinburg, Tennessee, June 1995, edited by H. B. Smartt, J. A. Johnson and S. A. David (ASM International, Materials Park, Ohio, 1996) p. 467.
12. M. UDA and S. OHNO, *Trans. Natl. Res. Inst. Met. (Jpn).* **16** (1974) 2.

Received 6 October
and accepted 6 December 1999