Acta Materialia 116 (2016) 166–176

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Grain refining of magnesium welds by arc oscillation

T. Yuan [a], Z. Luo [a], S. Kou [b,*]

[a] School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China
[b] Department of Materials Science and Engineering, University of Wisconsin, Madison, WI 53706, USA

ARTICLE INFO

Article history:
Received 30 May 2016
Accepted 14 June 2016
Available online 24 June 2016

Keywords:
Welding
Grain refining
Heat flow
Fluid flow
Mg alloys
Arc oscillation

ABSTRACT

Grain refining is known to improve the solidification-cracking resistance and mechanical properties of welds. Mg alloys are increasingly used for vehicle weight reduction. The present study was conducted to grain refine Mg welds by arc oscillation, which has not been investigated so far. First, significant grain refining was demonstrated by transverse arc oscillation. The effects of oscillation amplitude, oscillation frequency and torch travel speed on grain refining were shown. The effect of the alloy composition on grain refining was also demonstrated. Second, by using an overlap welding procedure, the grain refining mechanism was identified as dendrite fragmentation. Third, cooling curves recorded during welding showed that transverse arc oscillation caused reheating during solidification, which has been shown in casting/solidification to cause dendrite fragmentation by melting off dendrite arms. The cooling curves also showed that transverse arc oscillation significantly reduced the temperature gradient *G* along the torch travel direction, which suggested constitutional supercooling was increased. Thus, transverse arc oscillation not only caused dendrite fragmentation but also increased constitutional supercooling to help dendrite fragments survive and grow into fine equiaxed grains. Dendrite fragmentation by remelting, instead of mechanical breakup, of dendrites was discussed in the context of welding.

1. Introduction

In welding Al alloys by gas-tungsten arc welding (GTAW), which is also called tungsten inert gas (TIG) welding, the grain structure in the fusion zone can be manipulated by magnetically oscillating the arc during welding. This was first demonstrated by Kou and Le [1–3], who used magnetic arc oscillation, either transverse or circular, to create grain structures that significantly improved both the resistance to solidification cracking during welding and the mechanical properties of the resultant welds. Subsequent studies on Al alloys by other investigators [4–8] confirmed the work of Kou and Le [1–3]. More recently, magnetic arc oscillation was also used in GTAW of steel [9] and Ni alloys [10,11].

By quenching the weld pool and its surrounding area with ice water during GTAW of Al alloys, Kou and Le [12] preserved the development of microstructure during welding. Three types of microstructure were preserved and revealed clearly: partially melted grains around the weld pool, dendrites behind the weld pool, and heterogeneous nuclei inside the weld pool. Based on them, the microstructure around the pool boundary was proposed as shown schematically in Fig. 1. Each type of microstructure can lead to a different mechanism for nucleation of new grains in the fusion zone, that is, grain detachment, dendrite fragmentation or heterogeneous nucleation [12]. These new grains grow ahead of and can thus block off the columnar grains that grow originally from the fusion boundary by epitaxial growth [13]. The more new grains are, the wider the band of equiaxed grains in the resultant fusion zone.

The use of Mg alloys for vehicle weight reduction has increased significantly recently [14–16]. So far, GTAW is the most widely used arc welding process for Mg alloys because of the excellent weld quality, though significant advancements have been recently made to improve the quality of Mg welds made by gas-metal arc welding (GMAW) [17–19]. There have been few studies on grain refining in Mg welds, much less than those on Al welds. Babu and Cross [20] grain refined AZ31 Mg by pulsation of alternating current (AC) using an advanced GTAW power source. Tao et al. [21] grain refined AZ31 Mg and AZ91 Mg by ultrasonic stirring of the weld pool. Grain refining of Mg welds by arc oscillation has not been investigated so far. Ram et al. [22] pointed out that arc oscillation worked effectively for some materials but not for other materials. It is unclear if arc oscillation can grain refine Mg welds effectively.

* Corresponding author.
E-mail address: kou@engr.wisc.edu (S. Kou).

http://dx.doi.org/10.1016/j.actamat.2016.06.036

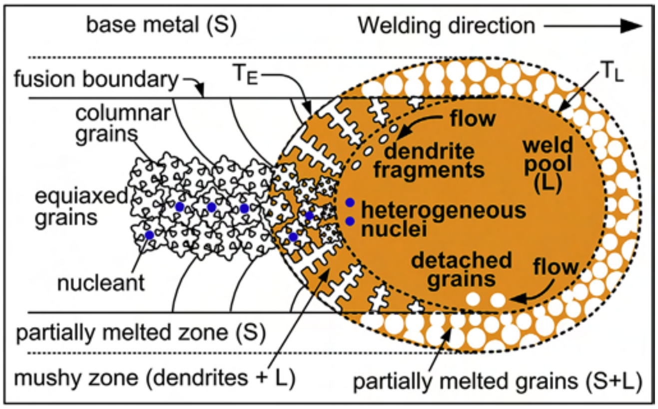

Fig. 1. Three possible mechanisms of grain refining in welds based on microstructure around aluminum-alloy weld pool preserved by quenching with ice water during welding [12].

The present study investigated grain refining of Mg welds by transverse arc oscillation. This is because, as mentioned previously, the use of Mg alloys has been increasing rapidly but grain refining of Mg welds has not been studied much. The purpose was to demonstrate that significant grain refining could be achieved by transverse arc oscillation, identify the grain refining mechanism and explain how arc oscillation help the mechanism achieve grain refining.

2. Experimental procedure

The magnetic arc oscillator used in the present study was a Model 90 A arc pattern control along with a 4613 A magnetic probe, both manufactured by Cyclomatic Industries, San Diego, CA, which was subsequently taken over by JetLine Engineering. The magnetic probe was in the form of a short cylinder, with a round hole along its axis to allow mounting around a gas-tungsten arc welding torch. The welding torch itself was mounted on a carriage that moved on a track at a constant predetermined speed. The four poles of the magnetic probe, 90° apart, were positioned to surround the tip of the tungsten electrode. Two opposite poles were lined up normal to the torch travel direction and activated to cause transverse arc oscillation. The magnetic arc oscillator was designed to provide arc oscillation at an amplitude equal to the arc length, though amplitudes lower than this maximum one can also be selected. Thus, with a 2 mm arc length, for instance, the amplitude of arc oscillation could be adjusted between 0 and 2 mm. The minimum oscillation frequency provided by the magnetic arc oscillator was 1 Hz and the maximum 50 Hz.

Two commercial Mg alloys were studied. The first one was AZ31 Mg, the most widely used Mg wrought alloy. It was manufactured by Magnesium Elektron in the form of 1.6 mm sheets and its composition is shown in Table 1. The second Mg alloy was AZ91 Mg, the most widely used Mg casting alloy. It was manufactured by US Magnesium in the form of ingots and its composition is also shown in Table 1.

The workpiece was prepared in the form of a 102 mm × 102 mm × 1.6 mm sheet for welding. It was bead-on-plate welded without filler metal by gas-tungsten arc welding (GTAW) along the centerline of the workpiece. GTAW was conducted with direct current electrode negative (DCEN). The electrode, 3.2 mm in diameter, had a 50 included angle at the tip. The arc gap was 2 mm and the shielding gas pure Ar at 1 m^3/h (16.5 L/min). The welding conditions are shown in Table 2.

The cooling curve was recorded during welding, with and without arc oscillation. A K-type thermocouple with a stainless steel sheath of 0.5 mm outer diameter was used. With a mechanical device the thermocouple tip was plunged into the weld pool at a short distance behind the welding arc along the centerline of the weld pool. The cooling curves were recorded with a computer-based data acquisition system, the data acquisition frequency being 20 Hz.

In order to identify which mechanism was responsible for grain refining in a weld made with transverse arc oscillation, the overlap welding procedure that Kou and Le [12] developed for identifying nucleation mechanisms in Al welds was used. This procedure is illustrated in Fig. 2. The weld in which the nucleation mechanism of equiaxed grains is to be identified is called the test weld. Before the test weld was made, a wider and shorter weld was made, called the preweld. After the preweld cooled to the room temperature, the test weld was made to run into and overlap with the preweld. The test weld was a 1-pass weld made with grain refining by transverse arc oscillation at 1 Hz oscillation frequency and 2 mm oscillation amplitude. The preweld was made without arc oscillation, either single- or multiple-pass.

In Fig. 2a the preweld is a single-pass weld made without arc oscillation. If coarse columnar grains dominate its bulk fusion zone, they are interlocked firmly with one another, unable to be detached and carried as small grains into the weld pool of the test weld. Rather, they grow into the test weld by epitaxial growth [13]. Thus, grain refining can be expected to stop after the test weld runs into the preweld. If this does happen, grain detachment is likely the grain refining mechanism in the test weld outside the preweld. For grains to be detached from the partially melted zone, they need to be loosely held small grains that are completely surrounded by the liquid in the partially melted zone so that they can be swept by fluid flow into the weld pool, such as in the case of 7004 Al alloy [23]. However, if grain refining continues after the test weld runs into the preweld, either heterogeneous nucleation or dendrite fragmentation is likely to be the grain refining mechanism as illustrated in Fig. 2b.

In Al ingot casting, an Al—Ti—B type master alloy containing Al_3Ti and TiB_2 particles is added to liquid Al as a grain refiner. Al_3Ti particles can nucleate solid Al effectively, but it can dissolve in liquid Al despite its very high melting point of about 1350 °C. TiB_2 can also nucleate solid Al effectively and it dissolves in liquid Al much more slowly, but it can be easily contaminated by impurities to become ineffective unless covered with a thin layer of Al_3Ti [24,25]. Even if the understanding of the nucleation mechanism may still improve, the practice has been to solidify the Al melt shortly after the addition of the grain refiner. After casting and rolling down to thin sheets, these particles are still present and they can act as heterogeneous nuclei again during weld pool solidification [12,13]. To dissolve these particles or make them ineffective, a preweld can be made with multiple passes to melt back and forth

Table 1
Compositions of AZ31 Mg and AZ61 Mg in wt %.

	Al	Zn	Mn	Ca	Cu	Fe	Ni	Si	Others	Mg
AZ31 Mg	3.0	1.0	0.6	<0.04	<0.05	<0.005	<0.005	<0.05	<0.30	Balance
AZ91 Mg	8.5	0.71	0.29	–	0.001	<0.002	0.001	<0.010	<0.01	Balance