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Grain refining by ultrasonic stirring of the weld pool

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ABSTRACT

Grain refining can improve the mechanical properties and solidification-cracking resistance of the weld. Ultrasonic grain refining was conducted by dipping an ultrasonic probe in the weld pool to stir it at a distance behind the arc. This new approach produced effective grain refining in arc welds of Mg alloys AZ31 Mg and AZ91 Mg. Grain refining increased when the probe was positioned farther behind the arc. This suggests the initial crystallites or dendrite fragments generated by ultrasound in a cooler melt farther behind the arc were better able to survive. This also suggests dendrite fragmentation was more likely to occur because the probe was closer to the mushy zone. However, a probe too far behind the arc ended up being inside the mushy zone and grain refining, though highly effective, was restricted to only near the weld centerline. At the same probe position, grain refining increased with increasing ultrasound amplitude. Grains were significantly finer in AZ91 Mg welds than AZ31 Mg welds. This suggests grain refining increased with increasing constitutional supercooling caused by the higher solute content of AZ91 Mg than AZ31 Mg.

1. Introduction

Grain refining of welds has been an active area of research in welding because finer grains can improve the strength, ductility and toughness of the weld and increase its resistance to cracking during solidification [1]. Numerous techniques for grain refining in welding have been studied, such as arc pulsation [2,3], arc oscillation [3,4], inoculation [5–7], electromagnetic weld-pool stirring [8,9], and ultrasonic weld-pool vibration [10–13]. The approach of using advanced welding power sources for grain refining is attractive because it requires no additional devices to oscillate the arc or stir the pool, nor preparation of special filler metal containing inoculants. For example, in gas-tungsten arc welding He et al. [10] excited the arc by using high frequency current to generate ultrasonic waves, which caused weld pool vibration and grain refining in welding Ti–4Al–4V alloy. For another example, using an advanced gas-tungsten arc welding power source that allowed special AC pulsing, Babu and Cross [2] grain refined AZ31 Mg welds. Naturally, advanced welding power sources cannot be expected to work in all situations. For instance, the filler metal can interfere with the arc that is set up to generate ultrasonic waves or fine-tuned to pulse with special current and voltage waveforms. Thus, other approaches to grain refining in welding do have merits. An example is ultrasonic weld pool vibration by mechanical means.

Effective grain refining was achieved by ultrasonic vibration of the workpiece in gas-tungsten arc welding of 7075 Al alloy [11] and in shielded-metal arc welding of 316L stainless steel [12]. The ultrasonic machine in the former was 2 kW in power and 20 kHz in frequency. It was not specified in the latter, but the use of a 1.5 kW, 20 kHz machine was reported in a related study by the same group [13].

The ultrasonic intensity can be defined as $I = \rho c(2\pi fA)^2/2$ (ρ is the liquid density, c speed of sound in the liquid, f ultrasound frequency and A ultrasound amplitude), and fully developed cavitation can occur in liquid Mg when $I \geq 80$ W/cm^2 [14]. With a very small probe for ultrasonic stirring in a very small volume of liquid in a gas-tungsten arc weld pool, melt wave resistance can be expected to be minimal and a smaller and hence less expensive ultrasonic machine may suffice.

Unfortunately, when the workpiece is clamped down tightly to a rigid fixture or connected to a rigid structure, ultrasonic vibration of the workpiece can be difficult. An alternative to overcome this problem was to attach a filler-wire guide to the sonotrode and put the filler wire tip in contact with weld pool edge to transmit ultrasonic waves to the weld pool [15]. The ultrasonic power source was 600 W and 19 kHz. The use of this smaller ultrasonic machine

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was possible because the wire guide and the weld pool were both very small. This can be another advantage of this approach. Unfortunately, due to its low melting point, the filler wire tip had a tendency to melt, ball up and stop grain refining when moved closer to the arc to improve weld pool vibration.

The purpose of the present study was to explore a new approach in which an ultrasonic probe is dipped directly in the weld pool of a Mg alloy and determine how the following factors affect grain refining: 1. the ultrasound amplitude, 2. the distance between the probe and the arc, and 3. the alloy composition.

2. Experimental procedure

The experimental approach was to dip an ultrasonic probe, smaller in diameter and much higher in melting point than a filler wire, directly in the weld pool to stir it at a distance behind the arc. This new approach allowed the workpiece to be clamped down tightly as required to avoid distortion induced by welding. It also allowed the probe position in the weld pool to be changed as needed.

The ultrasonic probe was a tungsten rod of 0.5 mm diameter (melting point 3407 °C). The fine tungsten rod minimized heat extraction from the weld pool. Except for a short section near the weld pool, the rod was inside a 304 stainless steel tube (0.82 mm OD and 0.51 mm ID), and the tube was squeezed (crimped) tight against the rod to stiffen it. The stainless steel tube was mounted on the sonotrode of a STAPLA ultrasonic welding machine, which was available to the authors. The machine was 3 kW, 20 kHz, and the amplitude was adjustable from 14 μm at step one to 28 μm at step ten. The probe vibrated in a horizontal plane in the direction normal to the welding direction.

Fig. 1 shows schematically the ultrasonic grain refining process used in the present study. For convenience of subsequent discussion, three possible mechanisms of grain refining are also included. The tip of the ultrasonic probe was dipped in the weld pool from below as illustrated in Fig. 1a. The distance between the probe and the axis of the electrode is called the offset. The workpiece was mounted on a motor-driven carriage that travels in the direction indicated by the arrowhead. The electrode, pool and probe do not travel.

The welding torch was mounted on an x–y sliding stage driven by precision lead screws that advanced the stage 1 mm per revolution (360 degrees) in either direction. This allowed the horizontal distance between the electrode axis and the probe to be set with a precision much better than 0.1 mm. At the end of welding the arc was turned off abruptly to help preserve the steady–steady pool shape. The travel of the workpiece was stopped simultaneously. The distance between the probe and the weld pool boundary in the welding direction was measured after welding. The sensitivity of controlling the location of the probe from the pool boundary along the welding direction is estimated to be about ±0.2 mm.

In order to investigate the effect of the offset over a wide range, the probe was positioned from 0 to 8 mm behind the electrode axis. After a steady weld pool was established, the sonotrode was raised to dip the probe tip in the weld pool. It is believed that dipping an ultrasonic probe into the weld pool from above, at a short distance behind the arc, is also feasible since the probe is very small. A small water-cooled Cu holder with Ar shielding can be used to protect the probe from the arc.

Two commercial Mg alloys were selected for welding, i.e., wrought alloy AZ31 Mg (nominal composition Mg–3.0Al–1.0Zn–0.6Mn) and casting alloy AZ91 Mg (nominal composition Mg–9.0Al–0.7Zn–0.2Mn). The workpiece was 102 mm long, 102 mm wide and 1.6 mm thick. It was bead-on-plate welded without a filler metal by gas-tungsten arc welding along the centerline of the workpiece top surface. The welding direction was normal to the rolling direction in the case of AZ31 Mg. The welding conditions were as follows: direct current electrode negative, 2%-thoriated tungsten electrode 3.2 mm in diameter with a 50° included angle, 1.5 mm arc gap, and pure Ar shielding at 1 m^3/h (16.5 L/min).

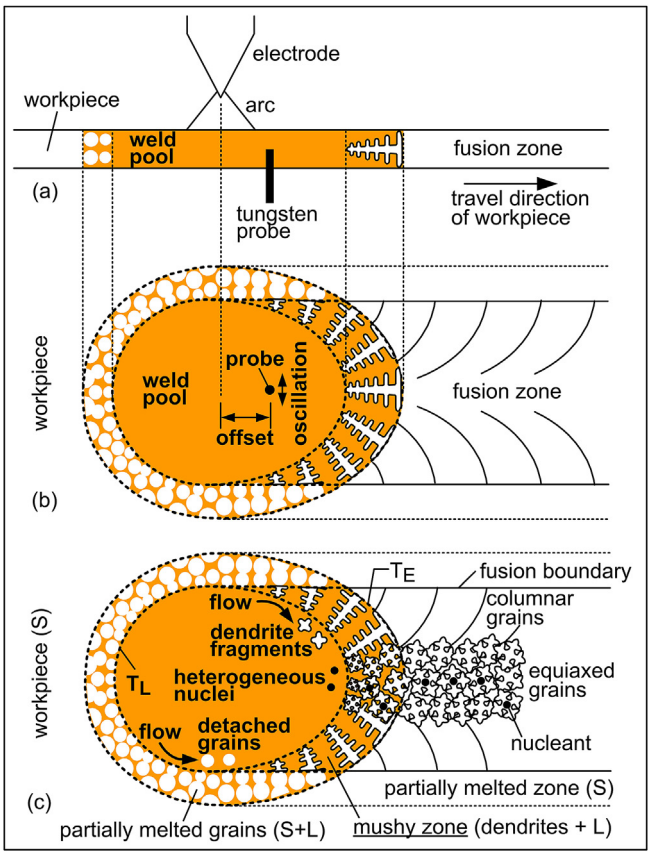

Fig. 1. Schematic sketches illustrating grain refining during welding: (a) vertical longitudinal cross-section along weld centerline showing ultrasonic stirring of weld pool; (b) horizontal longitudinal cross-section; (c) possible mechanisms of grain refining. In (a) the workpiece alone travels and the direction of travel is indicated by the arrowhead.

Table 1 summarizes the conditions used for welding and ultrasonic stirring. After welding, the tip of the tungsten probe was easily separated from the weld. No bonding or reaction with Mg was noticed. The resultant welds were cut and their top surfaces polished and etched to reveal the grain structure. The grain structure at the bottom surfaces was also checked, and it was similar to that at the top surfaces. A shallow track was left by the probe at the weld bottom surface, visible with AZ31 Mg but not AZ91 Mg.

AZ31 Mg welds were etched with a solution consisting of 3 ml HCl and 100 ml anhydrous ethyl alcohol. This revealed the dendritic structure but not the grain structure. A different etching solution was used, containing 10 ml glacial acetic acid, 10 ml distilled water, 6 g picric acid and 100 ml anhydrous ethyl alcohol, and micrographs were taken with polarized light to show different grains in different colors.

No electron back scatter diffraction (EBSD) images were provided to further confirm that the optical micrographs showing grain refining are clear proof of dendrite fragmentation due to ultrasonics instead of due to sectioning effects. However, it should be pointed out that optical micrographs have always been the standard way of studying grain refining and its mechanisms, both in