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Abnormal macropore formation during double-sided gas tungsten arc welding of magnesium AZ91D alloy

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ABSTRACT

One of the major concerns during gas tungsten arc (GTA) welding of cast magnesium alloys is the presence of large macroporosity in weldments, normally thought to occur from the presence of gas in the castings. In this study, a double-sided GTA welding process was adopted to join wrought magnesium AZ91D alloy plates. Micropores were formed in the weld zone of the first side that was welded, due to precipitation of H_2 as the mushy zone freezes. When the reverse side was welded, the heat generated caused the mushy zone in the initial weld to reform. The micropores in the initial weld then coalesced and expanded to form macropores by means of gas expansion through small holes that are present at the grain boundaries in the partially melted zone. Macropores in the partially melted zone increase with increased heat input, so that when a filler metal is used the macropores are smaller in number and in size.

1. Introduction

Magnesium alloys have been widely used in automobile, aerospace, and electronic industries for their desirable combination of properties such as low density and high strength-to-weight ratio, improved damping and electromagnetic shielding capacity, excellent machinability, and good castability. Their weight reduction potential when used as structural material in transportation vehicles improves fuel economy and emissions regardless of the propulsion system used [1,2]. AZ91D alloy (9Al–1Zn–0.2Mn) is the most widely and commercially used Mg alloy system in the automotive industry. However, applications of this alloy are restricted by its poor (<3%) ductility. Moreover, more complicated manufacturing processes result in increased product price. It may be possible to reduce overall manufacturing cost by joining easily-cast segments into a more complex shape using a welding procedure [3].

Compared with mechanical fastening, welding usually provides better performance in magnesium alloys. In general, because of its utility and economy, gas tungsten arc (GTA) welding is the most prevalent welding method used with magnesium alloys [4]. However, large pores present in the weldment can degrade the tensile strength and elongation [5–7].

Much research has concentrated on the study of porosity formation during welding of magnesium alloys. Mikucki and Shearouse [8] found that the amount of porosity in cast magnesium AZ91 alloy was proportional to the dissolved H_2 present. They also found that the rejection of H_2 from the $Mg_{17}Al_{12}$ intermetallic compound assisted in the nucleation and/or growth of microporosity during the last stages of solidification. The H_2 solubility difference between the solid and liquid phases of Al-containing Mg alloys has been shown in previous solidification studies and indicates H_2 rejection needs to be considered as a possible cause of porosity formation during solidification of these alloys [8]. Haferkamp et al. observed more porosity in conventional die-cast alloy AM60B than in vacuum die-cast alloy AZ91D. During Nd:YAG laser welding of magnesium alloys, the presence of gas inclusions in the base metal was thought to be an important

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Table 1 – The nominal chemical composition of AZ91D wrought alloy

Element	Al	Zn	Mn	Si	Fe	Cu	Ni	Mg
wt.%	8.6–9.4	0.65–0.96	0.18–0.30	<0.05	<0.004	<0.025	<0.001	Balance

Table 2 – Standard welding conditions used for this program

Power supply	Shielding gas	Current (A)	Welding speed (mm/s)	Wire feed rate (mm/s)	Arc length (mm)	Gas flow rate (l/min)
AC	Argon	80	2	6	5	10

factor contributing to the formation of macropores [9]. For example, during welding of AM60B alloy, Zhao and Debroy observed that preexisting pores in the base metal casting coalesced and expanded; as a result, macropores were commonly present in the weld [10].

These previous investigations of laser welding cast magnesium alloys concluded that macropores result from preexisting micropores in the base metal which coalesce and expand during welding. However, these results cannot explain macropore formation during GTA welding of wrought magnesium alloys, which have less gas inclusions in the base metal. In this paper, the intrinsic mechanism of macropore formation in GTA double-sided welded wrought AZ91D alloy plates is examined in detail.

2. Experimental Procedures

Two plates with thickness of 5 mm, and 120×60 mm in area, were machined from hot-extruded AZ91D magnesium alloy bars. The nominal chemical composition of this alloy is presented in Table 1. An AC penetrating square-wave welding procedure was used to produce GTA welds in the flat plates. The surfaces of the samples were chemically cleaned with acetone to eliminate surface contamination before welding. Side A or side B of the samples was placed on top of a 100 mm wide steel-backing plate prior to welding. AZ91D magnesium alloy welding wires, with a dimension of ϕ2.6×1000 mm, were used as filler metal. The standard welding conditions used for these welds are listed in Table 2.

The process of double-sided GTA welding of magnesium AZ91D alloy was as follows, see Fig. 1. Side A was welded; after cooling, it was turned over so that side B could be welded. Two series of samples were studied, those prepared with a filler wire (Sample 1) and those prepared without a filler (Sample 2).

After welding, the weld seam surfaces were photographed, and cross-sections were prepared using standard procedures (grinding, polishing, and etching with a solution of 5 vol.% HNO_3+95 vol.% C_2H_5OH). The microstructure was characterized by optical microscopy and scanning electron microscopy (FEI, Inc. NOVA 400 NanoSEM and TESCAN, Inc. Vega II LMU SEM). Elemental distribution was determined with energy dispersive spectroscopy (OXFORD, Inc. ISIS300).

3. Results and Discussion

3.1. *Formation of Macropores*

In order to investigate the macropores formed in welding of magnesium alloy, we need to define what a macropore is. As reported in Ref. [10], pores with diameters larger than 0.2 mm, which can be observed radiographically, are called macropores. Pores with diameters of several micrometers, which can only be observed by optical microscopy or SEM, are called micropores.

Fig. 2 shows the top-face of two welds taken on the center of the weld seam. Fig. 2a shows that there are a few macropores on side A of Sample 1 (after welding the obverse side B). Fig. 2b shows that side B has a smooth weld seam surface without pores. Fig. 2c (side A of Sample 2) displays many macropores and bulges after its obverse side B was welded. Fig. 2d shows that side B of Sample 2 is also smooth and without pores.

It should be pointed out that no macropores were observed during the initial welding (side A) of either samples. The surfaces were smooth and without bulges. Macropores appeared in side A only after the samples were turned over and their second side (side B) was welded. Moreover, the number of macropores present in Sample 2 (without filler) is larger than that present in Sample 1 (with filler).

These results are different from the formation mechanism of macropores in classical welding theory [11]. Macropores should form from generated gas, in the side being welded, and appear near the upper surface since gas is lighter than the melt. But in this study, macropores formed on the side that was initially welded (and smooth), after it was turned over and its obverse side was welded. This is the first demonstration of an abnormal appearance of macropores during GTA double-sided welding.

3.2. *Microstructural Observation of Macropores*

Fig. 3 presents the microstructure of a cross-section of Sample 2 after double-sided GTA welding. No pores are present in the base metal, see Fig. 3a. Hence, macropore formation cannot be ascribed to preexisting pores in the base metal. Fig. 3b shows an SEM image of side A after side B was welded. This microstructure consists of a major hot-crack at the center of the

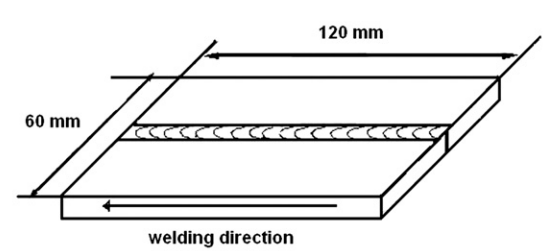

Fig. 1 – Schematic representation of the samples used in the GTA welding of magnesium AZ91D alloy.