Hot Cracking of Metal Inert Gas Arc Welded Magnesium Alloy AZ91D

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The microstructure and cracking characteristics of MIG welded magnesium alloy (AZ91D) joint, and the effect of welding speed on cracking susceptibility have been investigated. The welded joint consists of primary α -Mg and divorced phases (eutectic α -Mg+eutectic β -Mg₁₇Al₁₂), the latter mainly distributing along the α -Mg grain boundaries. Solidification cracking often occurred in the crater and was also observed at weld center line when welding speed was 300 mm/min, which are associated with segregation of Mn, Al and Zn and high tensile stresses in the welds. Liquation cracking appeared in HAZ immediately adjacent to the fusion line when low welding speed was used (300 mm/min). It is mainly related to the low welding speed resulting in increasing heat input and tensile stresses in the HAZ. It is favorable to decrease heat input for improving the susceptibility of hot cracking during MIG welding of magnesium alloys.

KEY WORDS: magnesium alloy AZ91D; MIG arc welding; solidification cracking; liquation cracking.

1. Introduction

Magnesium alloys have low density, high specific strength and excellent recyclability, and have gained increased interest in a wide variety of applications.^{1–4)} Among the commercial magnesium alloys, AZ91D is widely used.⁵⁾ Besides the development of new alloy types, manufacturing techniques such as welding and joining play an important role in exploiting the new fields of applications.

There has been some research activity on welding of magnesium alloys in recent years. Various welding processes, principally laser beam welding, electron beam welding, tungsten inert-gas welding, friction stir welding, resistance spot welding and transient liquid phase bonding, were employed in the researches and many useful insights and data have been obtained.^{6–16)} Hot cracking is known as one of major problems in welding of magnesium alloys.¹⁷⁾ When cracking problems are encountered, it is important to be able to identify the type and characteristics of cracking so that the cause can be found and efficient remedial action taken. However, reports in published literature concerning cracking problems of welded magnesium alloy joints are limited.^{18,19)} This is because most of researchers used high energy density welding methods such as laser beam welding and electron beam welding, and thin magnesium alloy plates. Under these conditions, the welded joints have low cracking susceptibility due to low net heat input and degree of restraint causing relatively low tensile stress in the joints. For welding of relatively thick plates, metal inert gas (MIG) arc welding method is often used in engineering practice, so the welding stress and cracking susceptibility are ex-

pected to be higher during welding of magnesium alloys.

The present work investigates the microstructure and cracking characteristics of MIG welded magnesium alloy (AZ91D) joints and the effect of welding speed on cracking susceptibility. Its purpose was to obtain better understanding of weldability of magnesium alloys and provide some foundation for improving the susceptibility of cracking in welded magnesium alloy joints.

2. Experimental Procedure

In this investigation, as-cast AZ91D magnesium alloy test plates (base metal) with dimensions of 120 mm×80 mm×10 mm and a magnesium alloy welding wire with the diameter of 1.6 mm were employed. The chemical compositions of the base metal and the welding wire are listed in **Table 1**.

MIG welding machine was used to weld the magnesium alloy plates in the form of butt joints. Prior to welding, a longitudinal single V-groove with 60° angle and 8.4 mm in depth was machined on the test plates, and the oxidation, oil and dirt on surfaces of the test plates and welding wire were removed using the sand paper. The weld metal was deposited in the V-groove with Ar shielding gas, the welding parameters being welding current of 170 A, welding voltage of 24 V and welding speeds of 300 mm/min and 450 mm/min, respectively. After welding, the welded test plates cooled to room temperature in air. The welded joint specimens were cut down from the welded plates and were prepared by standard metallographic procedures. Microstructures and cracking characteristics of the welded joints were

Table 1. Chemical compositions of base metal and welding wire (wt%).

Base metal and welding wire	Al	Zn	Mn	Si	Fe	Cu	Ni	Mg
Base metal	9.4	0.62	0.24	0.015	0.005	0.014	0.001	Bal
Welding wire	6.1	1.08	0.34	0.021	0.003	0.011	0.003	Bal

Fig. 1. MIG welded magnesium joint. **Fig. 2.** XRD pattern of magnesium alloy weld. **Fig. 3.** The microstructure of weld: (a) microstructure, (b) divorced eutectic morphology.

examined using scanning electron microscopy (SEM) and X-ray diffraction (XRD). The distribution of alloy elements was measured using energy dispersive X-ray spectroscopy (EDS).

3. Results and Discussion

3.1. Microstructure

MIG welded magnesium alloy joint including weld metal and heat-affected zone (HAZ) is illustrated in **Fig. 1**. From XRD pattern shown in **Fig. 2**, it can be seen that the weld with 7.09 wt% Al consists of magnesium solid solution (α -Mg) and intermetallic compound (β -Mg₁₇Al₁₂). **Figure 3** shows the microstructure of the weld. As can be seen, the β -Mg₁₇Al₁₂ mainly distributes along α -Mg grain boundaries (**Fig. 3(a)**) and the boundary microstructure has a divorced eutectic morphology, which is characterized by 'islands' of eutectic α -Mg within the β -particles, as shown in **Fig. 3(b)**. This is different to the microstructure of discontinuous precipitation of $\alpha + \beta$ which are lamellar in appearance. According to the magnesium–aluminum equilibrium phase diagram (**Fig. 4**), the maximum solid solubility at the eutectic temperature is about 13 wt% Al, and the eutectic phase (β -Mg₁₇Al₁₂) is expected to appear when the Al content reaches around 13 wt%. However, the eutectic phase appears in the magnesium alloy weld containing 7.09 wt% Al for non-equilibrium cooling conditions normally en-

Fig. 4. Mg–Al equilibrium phase diagram.

countered in the weld metal. It is well known that the weld molten pool has rapid solidification rate and there is little diffusion in the solid. During solidification of the magnesium alloy weld molten pool, the first α -Mg grain to form was purer than the liquid from which it formed and the solutes (Al, Zn and Mn) had to be rejected into the liquid. With further solidification, the liquid between α -Mg grains became progressively richer in Al, Zn and Mn. In the final stages of the solidification, the solutes (Al, Zn and Mn) were compressed into a comparatively small volume of liquid between α -Mg grains and solute concentration was thus

expected to rise rapidly to reach the eutectic composition at the eutectic temperature. During welding, the fast cooling rate tended to move the liquidus, solidus and eutectic point in the Mg–Al equilibrium phase diagram to lower temperatures. These solidification characteristics of weld molten pool result in the segregation of Al, Zn and Mn at primary α -Mg grain boundaries and the formation of the divorced eutectic phases (eutectic α -Mg+eutectic β -Mg₁₇Al₁₂) along the grain boundaries.

During welding of magnesium alloy, HAZ immediately adjacent to the fusion line was heated to the temperature

Fig. 5. The microstructure of HAZ.

range between the liquidus and eutectic temperature. In this region, part of primary α -Mg and eutectic phases (eutectic α -Mg+eutectic β -Mg₁₇Al₁₂) at grain boundaries melted, there being a gradual increase in melted boundary width up to the fusion line. The melted portion resolidified through a divorced eutectic reaction resulting in islands of eutectic α -Mg surrounded by the β -Mg₁₇Al₁₂ particles, as shown in Fig. 5.

3.2. Solidification Cracking

The experimental results show that the magnesium alloy weld metal has a high cracking susceptibility. Figure 6 shows the appearance of cracks in magnesium alloy welds. The crack often occurred in the crater at the end of a weld (crater cracking) under the conditions of this investigation (welding current of 170 A, welding voltage of 24 V and welding speeds of 300 mm/min and 450 mm/min), as shown in Fig. 6(a). In addition, the crack at the weld centre line (centre line cracking) was also observed when the welding speed was 300 mm/min (Fig. 6 (b)). The former is finer than the latter.

In cross section of welded joints, the direction of cracks (crater cracking and centre line cracking) is approximately perpendicular to the weld surface (Figs. 7(a) and 7(b)), and

Fig. 6. The appearance of cracks in welds: (a) crater cracking, (b) centerline cracking.

Fig. 7. The morphology of cracks in cross section of welded joints: (a) crater cracking, (b) centerline cracking, (c) high magnification of (a), (d) high magnification of (b).

Fig. 8. SEM opened crack surface morphology: (a) dendritic appearance, (b) dendrite tips, (c) bridges of solid metal.

Table 2. Chemical compositions on the crack surface (wt%).

Element contents	Al	Zn	Mn	Si	Fe	Cu	Ni	Mg
Average contents	7.09	0.94	0.31	0.019	0.004	0.015	0.002	Bal
Metal bridge	8.95	1.06	0.89	0.020	0.004	0.017	0.003	Bal

they are interdendritic and usually intergranular with respect to the solidifying grains, as shown in Figs. 7(c) and 7(d). **Figure 8** shows SEM opened crack surface morphology. A marked dendritic appearance can be seen clearly and the dendrite tips are rounded, smooth and undamaged (Figs. 8(a) and 8(b)). Sometimes bridges of solid metal are observed on the opened crack surface, which have necked down as the faces of the crack have moved apart, as shown in Fig. 8(c). EDS analysis indicates that the metal bridge Mn and Al contents (0.89 wt% Mn and 8.95 wt% Al) are much higher than the average Mn and Al contents in the weld (0.31 wt% Mn and 7.09 wt% Al) and its Zn content (1.06 wt% Zn) is lightly higher than the average Zn content (0.94 wt% Zn), as presented in **Table 2**. The result suggests that there is another particle, $MnAl_6$ in the metal bridge due to increasing Mn content. Intergranular characteristics of the cracks, dendritic morphology of opened crack surface and segregation of Mn, Al and Zn at the metal bridges suggest that the cracks form during the final stages of solidification and a low melting point liquid film exists between the dendrites at the moment of crack formation. Therefore, the crater cracking and centre line cracking in the magnesium alloy welds should belong to solidification cracking type (hot cracking).

According to the theory about the mechanism of solidification cracking,²⁰⁾ the solidification cracking occurs in brittleness temperature range (BTR) during the solidification of the weld metal. In BTR, low melting point liquid film existing between the grains greatly decreases the strength of weld, so the solidification cracking is more susceptible to this range. When the thermal strain (stress) or strain rate developed during welding surpasses the endurance of the weld metal, the solidification cracking forms in the weld. Metallurgical factor and mechanical factor are always the two main factors causing crack formation. As indicated by Fig. 4, Mg–Al alloys display a wide freezing range, hence a wide BTR for magnesium alloy weld. In the final stages of the weld solidification, the solutes (Mn, Al and Zn) segregated in liquid between α -Mg grains to form low melting point liquid film, decreasing the strength of the weld. On the other hand, magnesium alloys have high thermal expansion coefficient ($16.1 \times 10^{-6} \text{ } ^\circ\text{C}$ between 20 and 400°C), so

Fig. 9. The crack in HAZ.

the tensile stresses in the magnesium alloy weld are expected to be high. During welding of magnesium alloys, the crater cracking often occurs, because the final crater at the end of the weld has high segregation levels of Mn, Al and Zn, and high stress level. The weld centre line cracking at the welding speed of 300 mm/min is mainly associated with higher tensile stresses in the weld due to low welding speed resulting in increasing the heat input, hence higher tensile stresses. Therefore, it is favorable to decrease the heat input for improving the susceptibility of solidification cracking in magnesium alloy welds.

3.3. Liquation Cracking

In this investigation, it was found that during MIG welding of magnesium alloy the cracks occurred not only in the weld metal but also in HAZ. No crack was observed in HAZ at the welding speed of 450 mm/min. The crack in HAZ appeared when welding speed was 300 mm/min. The crack is located in the HAZ immediately adjacent to the fusion line, not propagating into the weld, as shown in **Fig. 9**. There is a gradual increase in crack width up to the fusion line (**Fig. 10**). Besides the relatively long crack, some fine cracks were also observed in HAZ near to the fusion line (**Fig. 11(a)**). As can be seen from Fig. 11(b), the fine cracks are interdendritic and the partial melting occurs at the crack faces. These crack characteristics suggest that the cracks in HAZ form at high temperatures, so it should belong to liquation cracking type (hot cracking). The causes of this type of hot cracking are associated with grain boundary

Fig. 10. The change of crack width in HAZ: (a) crack width near the fusion line, (b) crack width far from the fusion line.

Fig. 11. Fine cracks in HAZ near the fusion line: (a) fine cracks, (b) high magnification of (a).

segregation aggravated by melting of boundaries near the fusion line. High tensile stresses that occur as the weld cools then tend to rupture these weakened boundaries.²¹⁾ The liquation cracking formed in magnesium alloy HAZ at the welding speed of 300 mm/min is mainly related to the segregation of the solutes (Mn, Al and Zn) at grain boundaries and the higher tensile stress due to low welding speed resulting in increasing the heat input. Therefore, it is also favorable to decrease the heat input for improving the susceptibility of liquation cracking in magnesium alloy HAZ.

4. Conclusions

(1) Microstructures of MIG welded magnesium alloy (AZ91D) joint consist of primary α -Mg and divorced eutectic phases (eutectic α -Mg + eutectic β -Mg₁₇Al₁₂) distributing along the α -Mg grain boundaries. It is mainly associated with the fast cooling rate of the joint and the segregation of the solutes (Mn, Al and Zn) at the grain boundaries.

(2) During MIG welding of magnesium alloy (AZ91D), the welded joint has a high cracking susceptibility. The cracking in the joint belongs to hot cracking due to forming at high temperatures, including solidification cracking in the weld and liquation cracking in HAZ.

(3) The solidification cracking easily occurs in the crater at the end of a weld, because the crater has high segregation levels of Mn, Al and Zn and high tensile stress level. When low welding speed is used (300 mm/min), solidification cracking at welding center line and liquation cracking in HAZ appear, which are mainly related to the low welding speed increasing heat input and tensile stresses. It is favorable to decrease the heat input for improving the susceptibility of hot cracking during MIG welding of magnesium alloys.

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