Hot Cracking of Resistance Spot Welded Magnesium Alloy

B. LANG,1) D. Q. SUN,1) Z. Z. XUAN1) and X. F. QIN2)

1) Key Laboratory of Automobile Materials, School of Materials Science and Engineering, Jilin University, Changchun 130025, China. E-mail: psdq@sina.com 2) Engineering Experimental Base, Zhejiang University, Hangzhou 310058, China.

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Crack features of resistance spot welded magnesium alloy joint and effects of welding parameters on susceptibility of the joint to hot cracking have been investigated. In the spot welded joints, solidification cracking in weld nugget and liquation cracking in heat-affected zone (HAZ) were often observed. The formation of solidification cracking is related to low melting point liquid films between dendrites due to segregation of Al and Mn atoms and tensile stress developed during cooling. In HAZ, the grain boundary melting occurred and grain became coarser. The liquation cracking appears in HAZ just adjacent to weld nugget and may be induced by solidification cracking at the edge of weld nugget. The welding parameters (heat input) have an obvious effect on susceptibility of weld nugget to hot cracking. The results show that relatively high heat input (i.e. relatively high welding current, long welding time or low electrode force) increase the hot cracking tendency. It is favorable to select relatively low heat input for reducing susceptibility of spot welded magnesium alloy joint to hot cracking.

KEY WORDS: resistance spot welding; magnesium alloy; solidification cracking; liquation cracking.

1. Introduction

During the past few years, weight and emission reduction has promoted focus on magnesium and its alloys in the automobile industry.1,2) Magnesium and its alloys have low density, high specific strength and rigidity, excellent machinability and good castability, which has attracted some researchers’ attention.3–5) And a considerable increase on the use of magnesium and its alloys has been noticed in the automotive, aerospace and micro-electronics industries.

The welding technology of magnesium parts may be crucial for industrial usage, which is used to optimize product design and decrease the cost. Consequently, the increasing application of magnesium and its alloys has motivated the investigation of their weldability. Many welding methods such as laser welding (LSW), electron beam welding (EBW), tungsten inert gas welding (TIG), friction stir welding (FSW), transient liquid phase bonding (TLP), and hybrid laser–TIG welding have been applied in investigations and some beneficial information has been obtained.6–16)

Because resistance spot welding is a widest used process in automotive industry, the investigation on spot welded magnesium alloy is very critical for increasing its application at present. The physical and mechanical features of magnesium alloys easily raise various welding problems, such as hot cracking, deformation and porosity in the welded joint. And hot cracking is the most detrimental to mechanical properties of spot welded magnesium alloy joint, which is attributed to high coefficients of thermal expansion and volume shrinkage. But, literatures are limited about hot cracking of resistance spot welded magnesium alloys.

The present work investigates crack features in spot welded magnesium alloy joints and effects of welding parameters on the cracking susceptibility. Its purpose was to understand the mechanism of crack formation and provide some foundation for improving the weldability of magnesium alloys.

2. Experimental

The base metal used in the present work is hot-extruded magnesium alloy sheet with 1.2 mm thickness, its chemical composition being listed in Table 1. Spot welding specimens were machined into the required dimensions (100 mm×25 mm×1.2 mm). Prior to welding, the specimen surfaces were ground and degreased with acetone for removing oxide film and lubricant, and then two specimens were installed as a lap joint, as shown in Fig. 1. The resistance spot welding test was carried out by a TDZ-3X100 three-phase secondary rectification spot welding machine. The electrode employed was a copper–chromium alloy cap tip type of 20 mm diameter and the electrode tip shape was a standardized dome with 100 mm radius. Effects of welding parameters on hot cracking susceptibility were investigated by changing welding current (15–27 kA), welding time (2–8 cycles) and electrode force (1.5–4.5 kN). To ensure the reliability of the results, the spot welding experi-

Table 1. Chemical composition of magnesium alloy base metal (wt%).

| Element | Value |
|---------|-------|
| Al      | 2.90  |
| Zn      | 0.837 |
| Si      | 0.067 |
| Fe      | 0.0045|
| Cu      | 0.005 |
| Mn      | 0.431 |
| Ni      | 0.0013|
| Mg      | balance |
ment was repeated three times at the same welding condition and proved to have good reproducibility. After welding, the spot welded joints were sectioned through the weld nugget center normal to the plane of specimens. The cross-sections were ground, polished, and etched in 5 g oxalic acid+100 mL H₂O solution, followed by metallographic examination. And the joint specimens were opened along free surfaces of cracks for investigating crack features in weld nugget and HAZ.

The microstructure of weld nuggets and opened crack surface morphology were examined using optical microscopy (OPM) and scanning electron microscopy (SEM; Model JSM-5310, Japan) equipped with energy-dispersive spectrum (EDS; Model Link-Isis, Britain).

3. Results and Discussion

3.1. Solidification Cracking

Metallographic examination revealed that magnesium alloy weld nuggets contain two different structures, a cellular-dendritic structure developing at the edge of the nuggets and growing epitaxially from the unmelt base metal (Fig. 2), and the equiaxed dendritic structure appearing in the central portion of the nuggets, as shown in Fig. 3. The cracks were often observed in the magnesium alloy weld nuggets. In cross section of the nuggets the direction of cracks was approximately perpendicular to the faying surface. Effects of spot welding parameters (welding current, welding time and electrode force) on the cracking susceptibility are illustrated in Fig. 4, Fig. 5 and Fig. 6, respectively. Figure 4 indicates that the cracks appear above 15 kA welding current under the conditions of 8 cycle welding time and 2.5 kN electrode force. Figure 5 shows that the cracks occur above 4 cycle welding time for 23 kA welding current and 2.5 kN electrode force. From Fig. 6 the cracks appear below 4.5 kN electrode force for 23 kA welding current and 8 cycle welding time. The results suggest that relatively high heat input (i.e. relatively high welding current, long welding time or low electrode force) increase the cracking susceptibility of the weld nuggets.

From Fig. 7 it can be seen that the crack in the weld nugget propagates in the mode of an intergranular and or interdendritic cracking at higher magnification. At the edge of the crack, segregation of Al and Mn could be detected by EDS (Fig. 8), which contributes to the formation of low melting point liquid film. Figures 9 and 10 show SEM opened crack surface morphology of the weld nuggets. The equiaxed dendritic and cellular-dendritic appearances can be seen clearly and the dendrite tips are rounded, smooth and undamaged, indicating the existence of liquid films along grain boundaries at the moment of straining. Intergranular and or interdendritic characteristics of the cracks and dendritic morphology of opened crack surfaces are typical features of hot cracking and evidence of crack formation within the solid–liquid temperature range. The results confirm that the cracks in magnesium alloy weld nuggets are solidification cracking, according to the classification by Hemsworth, et al. The causes of solidification crack-
ing are in general well understood. The partition and rejection of alloying elements at grain boundaries and ahead of the advancing solid–liquid interface cause marked segregation. The segregants form low melting point liquid films at grain boundaries. These films weaken the structure to the extent that cracks form at boundaries under the influence of the tensile residual stresses that occur during cooling.\textsuperscript{18}

During the later stages of weld nugget solidification, the low melting point liquid films formed between dendrites due to segregation of Al and Mn, but the amount of the liquid films was not enough to link up the liquid metal in the nugget. Under this condition, it is very difficult for liquid films to flow. The liquid films between dendrites are too weak to bear high level of tensile stress and transmit the deformation to solid grains. As a result, the weld nugget metal separated along liquid films between dendrites, when the cooling of joint resulted in contraction of the weld nugget metal and base metal, which imposed tensile stress upon the weld nugget metal. The separation gap which could not be filled completely with liquid metal led to forming cracks at grain boundaries under the influence of the tensile stress developed during cooling. Therefore, the initiation and propagation of the solidification cracking are mostly dependent on low melting point liquid film and tensile stress.

Fig. 4. Effect of welding current on crack for 8 cycle welding time and 2.5 kN electrode force: (a) 15 kA; (b) 19 kA; (c) 23 kA; (d) 27 kA.

Fig. 5. Effect of welding time on crack for 23 kA welding current and 2.5 kN electrode force: (a) 2 cycles; (b) 4 cycles; (c) 6 cycles; (d) 8 cycles.

Fig. 6. Effect of electrode force on crack for 23 kA welding current and 8 cycle welding time: (a) 1.5 kN; (b) 2.5 kN; (c) 3.5 kN; (d) 4.5 kN.

Fig. 7. Morphology of cracks in weld nuggets: (a) equiaxed dendritic zone; (b) cellular-dendritic zone.

Fig. 8. Results of EDS line analysis of alloy elements across a crack in weld nugget.
As shown in Figs. 4–6, the susceptibility of magnesium alloy weld nugget to solidification cracking is related to welding parameters (welding current, welding time and electrode force) and the welding parameters have an obvious effect on the weld nugget size, which strongly affects to tensile stress caused by the shrinkage of the nugget. Higher welding current or longer welding time resulted in increasing heat input and nugget size. The higher the heat input, the larger the nugget size and hence the greater the tensile stress caused by the shrinkage of the nugget, which is one of main reason that relatively high welding current and long welding time increase the cracking susceptibility of the weld nugget. The effect of electrode force on susceptibility of the weld nugget to solidification cracking is also related to heat input, nugget size and tensile force. The heat input is influenced by electrode force through its effect on contact resistance at the interface between two magnesium alloy sheets. The relative low electrode force results in increasing the contact resistance, heat input and nugget size, hence the greater tensile stress caused by the shrinkage of the nugget and the higher cracking susceptibility. On the other hand, the welding parameters also affect the cracking susceptibility by changing microstructures of the weld nugget. From Figs. 2 and 3 it can be seen that nugget microstructures coarsen obviously with increasing welding current due to reducing cooling rate. For the case of coarse microstructure, the total grain boundary area per unit volume in the weld nugget decreases and the solute atoms such as Al and Mn segregate with greater concentration, which results in further lowering the melting point of liquid films between dendrites and interdendritic strength. Under these conditions, the nugget microstructure tends to be weaker, the tensile stress spends more time on the low melting point liquid films and hence the weld nugget has higher susceptibility to solidification cracking under tensile stress. From opened crack surface morphology shown in Figs. 9 and 10, the crack surface at higher welding current is relatively flat due to developed secondary arms of dendrites. It favors the formation of solidification cracking because of decreasing resistance to crack propagation. Based on above the results, it is favorable to select relatively low heat input (i.e. relatively low welding current, short welding time or high electrode force) for reducing the susceptibility of magnesium alloy weld nugget to solidification cracking.

In this investigation, it was found that two kinds of microcracks were present in weld nuggets. One is induced by porosity, initiating at the tip of porosity due to stress concentration and propagating along the grain boundaries, as shown in Fig. 11. The other is also related to low melting point liquid film and tensile stress, as shown in Fig. 12. They also belong to the solidification cracking which occurs during the later stages of weld nugget solidification.
3.2. Liquation Cracking

Figure 13 illustrates the crack which occurs in HAZ of spot welded magnesium alloy. The crack is found in the HAZ just adjacent to weld nugget and joins solidification cracking in the weld nugget at the interface between HAZ and weld nugget. The direction of the crack is similar to that of solidification cracking in weld nugget and its length is often several grain diameters. When high heat input was used, the thickness of weld nugget increased obviously and the crack in HAZ could extend to the surface of spot welded joint, as shown in Fig. 14. From Fig. 15, the opened crack surface morphology in HAZ is different from that in weld nugget, the crack in HAZ propagates along grain boundaries and the trace of liquation is observed, indicating that the grain boundaries were weaker and contained a little amount of low melting point liquid films when the crack took place. These features confirm that the crack in HAZ of spot welded magnesium alloy belongs to liquation cracking.

The causes of liquation cracking are associated with grain boundary segregation aggravated by melting of boundaries near the weld. High residual stresses that occur as the weld cools then tend to rupture these weakened boundaries. During spot welding, the grain in HAZ became coarser than that in base metal and melting of grain boundaries occurred, as shown in Fig. 16. Since melting nucleates preferentially at high energy crystal defects, such as boundaries and surfaces, there is a gradual increase in melted boundary width up to the weld nugget. Under these conditions, solute atoms of low solubility in the matrix tend to diffuse to the melted boundaries to lower melting point of the liquid. At the same time, the HAZ is forced to upset because its expansion to match the temperature rise is constrained by adjacent base metal at a lower temperature. On being cooled, the low melting point liquid films form at grain boundaries to reduce the boundary strength and the tensile stress begins to develop in HAZ because of earlier upsetting. Liquation cracking in HAZ occurs along grain boundaries when the strength of grain boundaries weakened by low melting point liquid films is below the developed tensile stress.

In this investigation, liquation cracking in HAZ of spot welded magnesium alloy was found to be accompanied by solidification cracking in the weld nugget and was joined.
together with the solidification cracking. Liquation cracking in HAZ was not observed when solidification cracking disappeared in the weld nugget. It means that the occurrence of the liquation cracking may have been triggered by the formation of the solidification cracking. As is well known, the temperature in the nugget is higher than those in HAZ and base metal, and solidification process of HAZ is prior to that of the nugget. However, when solidification cracking forms in the nugget, the melted boundaries in HAZ may not resolidify completely and there is a little amount of low melting point liquid left. Under these conditions, solidification cracking at the edge of the nugget can induce the formation of liquation cracking in HAZ. Therefore, it is also favorable to select relatively low heat input for reducing the susceptibility of spot welded magnesium alloy HAZ to liquation cracking.

4. Conclusions

(1) The magnesium alloy weld nugget has a high susceptibility to solidification cracking. The formation of solidification cracking is attributed to low melting point liquid films between dendrites from segregation of Al and Mn and tensile stress developed during cooling.

(2) Spot welding parameters (heat input) have an obvious effect on susceptibility of the weld nugget to solidification cracking. The solidification cracking appears in the weld nugget when the welding current is higher than 15 kA for 8 cycle welding time and 2.5 kN electrode force, the welding time is longer than 4 cycles for 23 kA welding current and 2.5 kN electrode force, or the electrode force is lower than 4.5 kN for 23 kA welding current and 8 cycle welding time. The susceptibility of solidification cracking increases with heat input rising due to increasing tensile stress caused by the shrinkage of the nugget, lowering the melting point of liquid films due to solute atom segregation with greater concentration and prolonging time for tensile stress affecting.

(3) In HAZ of spot welded magnesium alloy, the grain become coarser and melting of grain boundaries occurs. The liquation cracking appears in HAZ just adjacent to weld nugget and joins solidification cracking at the edge of weld nugget. The formation of liquation cracking is mainly associated with low melting point liquid films from solute atoms of low solubility diffusing to the melted boundaries and tensile stress developed during cooling. Liquation cracking in HAZ may be induced by solidification cracking at the edge of weld nugget by propagating it to HAZ.

(4) It is favorable to select relatively low heat input (i.e. relatively low welding current, short welding time or high electrode force) for reducing the susceptibility of weld nugget and HAZ to hot cracking (solidification cracking and liquation cracking).

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