The effects of ultrasonic vibration on microstructural changes and mechanical properties of Mg alloy joint

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Abstract

The weld of AZ31 Mg alloy was performed via ultrasonic vibration assistance process. The metallographic structure observation, scanning electron microscope observation, hardness detection, tensile test and fracture morphology observation were performed to analyze the influences of ultrasonic vibration on the microstructure and mechanical properties of welded joints. In this paper, the ultrasonic vibration with power in the 0–1.5 kW was successfully introduced into the weld pool by filler wire, which had a series of effects on the weld. The results indicated that ultrasonic induced agitation in the molten pool can reduce or even eliminate the porosity in the weld zone. Besides, for joints treated by 1.0 kW ultrasonic process, the average grain size of weld zone decreased to 28 μm, owing to the acoustic flow and cavitation effects caused by ultrasonic process. Under optimized ultrasonic power of 1.0 kW, the sound Mg alloy joint with the maximum tensile strength of 256 MPa was obtained and the fracture surface presented plastic fracture characteristics.

1. Introduction

With the characteristics of low density, high specific strength and recyclable, Mg alloy is an excellent substitute for traditional steel materials in aerospace series, automobile industry and ship construction [1–4]. However, there are numerous difficulties in the reliable welding of Mg alloys due to the defects such as coarse grain, porosity and cracks [5–8]. Grain refinement is considered to be an effective means to improve the microstructure and mechanical properties of weldments. For example, the literature indicates that some alloying elements can refine the matrix of Mg alloy, such as Ce, Mn and Ca [2]. From the binary phase diagram of Mg-Ce/Mn/Ca, it can be seen that the solid solubility of Ce, Mn and Ca in α-Mg is almost negligible at room temperature. Ce, Mn and Ca precipitates into intermetallic compounds such as Mg12Ce, α–Mn and Mg2Ca, which have been proved to be able to refine the matrix of Mg alloy. However, the addition of various alloying elements increased the welding cost, and may cause uneven composition in the complex shape of the weld, thus deteriorating the weldment performance. Ultrasonic vibration assisted tungsten inert gas welding (UV-TIG) is an innovative joining technology that combines high frequency ultrasonic vibration with normal welding process, which has also been proven to achieve refinement of weld seam structure. The combined process is featured by lower heat input, less welding deformation and more economic benefit than traditional fusion welding technologies [9–11]. Hence ultrasonic vibration assisted process shows great prospect of various manufacturing applications.

Thus far, a series of researches on ultrasonic vibration assisted welding technology have been carried out [12–16]. For instance, Fujii et al [17] studied the influences of ultrasonic treatment on the weld formation and interfacial microstructure evolution of dissimilar Al–Cu weldment. The research results show that direct contact between the newly formed surfaces of Cu and Al was obtained and the Al2Cu metallurgical weld was formed [17]. Due to the formation of micro bonds between Cu and Al, severe shear deformation parallel to the direction of ultrasonic vibration occurred, and a recrystallized structure with {111} {011} shear texture was formed in the welding interface area. Padly et al [18] reported the evolution of local microstructure during the ultrasonic
vibration assisted friction stir welding of Al 6061-T6 alloys. According to Padhy, the ultrasonic reinforced joint has higher deformation features in the nugget area, attributed to the ultrasonic softening before welding. In ultrasonic treated joint, the grain orientations were dominant along (111) and (001) directions, which indicated that the ultrasonic treatment induced more grains to orient along the (111) direction. In addition, the author found that the coexistence of a high proportion of fully recrystallized and under recrystallized grains was beneficial to the improvement of the mechanical properties of the weld. Lei et al. investigated the effect of ultrasonic vibration on the grain refinement and fluid flow of laser welded AZ31 Mg alloy weldment. Experimental results reveal that the pore defect of weld reduced markedly to less than one percent owing to thermal, acoustic streaming and cavitation effects. Therefore, the average grain area in the central area of the weld was reduced from 359.9 μm² to 213.7 μm². Compared with laser welding, the elongation δ of the joint was increased from 6.6% to 7.5% and the tensile strength σb increased from 235.1 MPa to 274.1 MPa.

The above researches reveal that the introduction of ultrasonic vibration into various welding processes is beneficial to perfect the microstructure features and joining strength of welding seams. However, previous studies mainly applied ultrasonic vibration to welding parts or even the whole welding device, which may led to deformation of welding parts and required high ultrasonic power. The objective of the present study is to develop a new process to introduce ultrasonic vibration into Mg alloy welds through filler wire, so as to enhance the performances of weld through local application of ultrasonic treatment. The evolution of porosity defect, microstructure characteristics and mechanical properties of Mg alloy joint were observed and discussed.

| Table 1. Chemical composition of base metal and filler metal (wt.%)          |
|-------------------|---|---|---|---|---|---|
| Materials | Zn  | Al  | Mn  | Si  | Fe  | Mg  |
| AZ31          | 0.88| 2.9 | 0.41| 0.05| 0.01| Bal.|
| Filler        | 0.79| 2.8 | 0.32| 0.04|  —  | Bal.|

Figure 1. Schematic diagram of ultrasonic vibration assisted welding device.

Figure 2. Schematic diagram of the sampling location and dimensions of tensile specimen.
2. Experiment details

The experimental materials are AZ31 Mg alloy plates with the thickness of 2 mm. The welded specimens were machined into rectangle of 50 mm × 70 mm by wire-electrode cutting device. The filler material is AZ31 Mg alloy welding wire with a diameter of 1.2 mm. The chemical composition of Mg alloy base metal and filler metal was measured by energy dispersive spectrometer (EDS) of scanning electron microscope (SEM). Table 1 lists the main chemical compositions of base metals and filler material. Prior to welding experiment, all base metal and filler wire were mechanically polished and cleaned with alcohol. Figure 1 illustrates the schematic diagram of the self-designed and modified ultrasonic vibration assisted welding equipment. The whole set of welding equipment mainly includes TIG welding machine (YC-300WP5HGN), automatic walking trolley, ultrasonic generator (GDZ-1012M), transducer and amplitude transformer (DW-20k). The welding parameters adopted in this paper are listed in table 2. Before welding, all filler material and base metal were respectively fixed on the welding platform and the horn. During welding, the base metal stayed still and the automatic walking car drove the welding gun to move. Ultrasonic vibration was persistently introduced into the weld pool while the wire was filled uniformly, as presented in figure 1.

After welding, the metallographic samples and tensile test specimens were machined by the wire-electrode cutting device. Figure 2 illustrates the schematic diagram of the sampling location and dimensions of tensile specimen. The unidirectional tensile test was performed by universal tensile testing device (AG-X, SHIMADZU) at room temperature with a tensile rate of 2 mm min⁻¹. In order to avoid the influence of accidental factors, five or more tensile samples were tested under the same conditions and their average values were taken. Micro hardness of weld area was measured in horizontal direction with a hardness tester (MH-5L). The distance between indentations was 50 μm with a 50 g load for a dwell time of 10 s. Metallographic samples were prepared in turn by sanding, polishing and subsequently etched with picric acid solution (5 g picric acid, 5 ml acetic acid, 30 ml alcohol and 5 ml distilled water) for 8–10 s. Metallographic observation was carried out using SEM equipped with EDS device and an optical microscope (OM). The fracture specimens were immersed in alcohol for ultrasonic cleaning and SEM was employed to explore the fracture characteristics.

3. Result and discussion

3.1. Microstructural characterization

Figure 3 shows the representative metallographic images of AZ31 Mg alloy joint welded with and without ultrasonic assistance. As illustrated in figure 3, the microstructure of AZ31 base metal (BM) is equiaxial crystal with an average crystallite dimension of 19 μm, which is composed of β phase and α-Mg phase. The tiny β phase was identified as Mg₁₇Al₁₂ and distributed uniformly in the Mg matrix. Compared with AZ31 parent metal, the grain size of heat-affected zone (HAZ) increased slightly under the action of welding heat cycle. However,
Figure 3 indicates that the grain growth in the fusion zone (FZ) was obvious, accompanied by the formation of a large number of black precipitates. This is mainly because the Mg alloy base materials selected in this paper were in rolling state and no annealing was performed. During traditional TIG welding process, the grains in the fusion area increased notably after melting and resolidification. Obviously, the coarse grain size of the above area makes it a weak spot of weldment and deteriorates the mechanical properties. The high frequency ultrasonic vibration was introduced into the weld pool through the filler wire. As shown in Figure 3(b), ultrasonic vibration played an active role in improving the microstructure of welding zone. The coarse grains in the welding zone were obviously refined and the average crystallite dimension was about 28 μm with approximate equiaxed crystal features. According to Ramirez et al\cite{20} and Abramov et al\cite{21}, ultrasonic vibration induced grain refinement can be achieved by cavitation induced dendrite fragmentation and cavitation enhanced nucleation. Literature reveal that the propagation and stirring of ultrasonic vibration in liquid could cause acoustic streaming and cavitation. Acoustic streaming can induce the flow of liquid metal in the weld pool, which led to strong mixing and uniform temperature of the melt. Cavitation was usually related to the growth and rupture of tiny bubbles in the melt. The high pressure and high temperature produced at the moment of bubble rupture

Figure 4. Macroscopic morphologies of weld cross-section obtained with various welding current and without ultrasonic treatment: (a) 90 A, (b) 110 A.

Figure 5. Macroscopic morphologies of ultrasonic vibration aided weld cross-section: (a) 90 A, (b) 110 A.
will destroy the initial dendrite and form more nucleation points. Moreover, Martin et al. [22] reported that undercooling decreased under the effect of ultrasonic vibration, which was favorable for grain nucleation. All the above mechanisms were conducive to the formation of fine isometric crystals in the weld zone. Finally, it should be noted that ultrasonic vibration only affected the microstructure of weld zone, but had no obvious effect on parent metal, heat affected zone and precipitates.

Figures 4 and 5 illustrate the typical characteristics of the weld cross-section obtained with and without ultrasonic assistance. As shown in figure 4, plenty of pores with diameters of 100–600 μm were formed in the cross-section of weldment obtained without the aid of ultrasonic treatment. These pores were mainly distributed in the upper part of weld cross-section. The formation of pores was due to the decrease of solubility of hydrogen dissolved in the weld pool during the cooling process of weld, resulting in the precipitation of hydrogen bubbles in the weld pool. The hydrogen bubbles rose gradually with the buoyancy of the melt and finally escaped from the pool into air. However, the temperature of weld pool decreased quickly during the rising of the hydrogen bubble, which eventually led to the failure of some bubbles to escape before the solidification of weld pool. Since the dissolution of hydrogen in the Mg alloy is an endothermic reaction, the increase of welding current will cause the temperature of the molten pool to rise, thus increasing the amount of hydrogen dissolved in the molten pool. Therefore, when the welding current increased from 90 A to 110 A, the increase of heat input will increase the number of pores in the weld. In addition, Mg alloy is a metal with low melting point and low boiling point. Excessive heat input will also cause serious volatilization of Mg alloy and even the formation of pores. However, as the ultrasonic vibration was introduced into the weld pool, the propagation of vibration can stir the liquid metal and accelerate the floating of hydrogen bubbles. For the joints with optimal ultrasonic vibration parameters, the porosity in the weld zone can be greatly reduced and even eliminated completely, as shown in figure 5. Similar phenomena was reported by Abramov et al. [21] during the ultrasonic vibration assisted casting process of Al alloy.

### 3.2. Micro-hardness distribution

Figure 6 illustrates the micro-hardness profiles of Mg alloy weldment obtained with and without the aid of ultrasonic process. The micro-hardness of base material were 56 HV (AZ31). For un-ultrasonic treated Mg alloy weldment, the micro-hardness of heat affected zone and weld zone were 48.0 HV and 51.2 HV. It is obvious that the micro-hardness values of heat affected zone and weld zone decreased compared with the base metal. The decrease of micro-hardness in both areas was mainly due to the apparent grain growth during the welding process, as mentioned in microstructural characterization. Under the help of ultrasonic process, the micro-hardness of heat affected zone between the two processes did not show too many differences, which indicated that the ultrasonic vibration technology had no influence on the heat affected area. However, it can be found that the hardness of weld zone improved to a certain extent under the influence of ultrasonic treatment. In comparison with the weldment without ultrasonic treatment, the micro-hardness of ultrasonic treated weld zone presented less fluctuation owing to the effective refinement of coarse grains. The results revealed that ultrasonic assistance was beneficial to improve the micro-hardness value of weld zone and make the micro-hardness distribution of weld zone more uniform.
3.3. Tensile properties and fracture morphologies

The mechanical properties of AZ31 joint treated by ultrasonic process with various ultrasonic power are illustrated in figure 7. It can be found that the tensile strength of un-ultrasonic treated Mg alloy joint with optimal welding parameters was 235 MPa, far lower than that of Mg alloy base material. Under the help of ultrasonic vibration, the tensile strength increased with the increase of ultrasonic power from 0.5 kW to 1.0 kW.

With ultrasonic power of 1.0 kW, the optimum tensile strength of joint was improved by 8.9% to 256 MPa, compared with the weldment without ultrasonic vibration process. Nevertheless, the tensile strength decreased slightly with the ultrasonic power of 1.5 kW. This was mainly due to the large amplitude vibration of welding wire caused by excessive ultrasonic power, which affected the stability of weld formation. For Mg alloy weldment, we can draw a conclusion that the optimal ultrasonic power was about 1.0 kW. It is widely known that the tensile strength of material is closely related to the crystallite dimension, as described by Hall-Petch formula:

$$\sigma = \sigma_0 + kd^{-1/2}$$  \hspace{1cm} (1)

where $\sigma$ is the tensile strength, $\sigma_0$ is the frictional stress of lattice, $k$ is the slope constant and $d$ is average crystallite dimension. In association with figure 3, it can be deduced that the decrease of crystallite dimension caused by ultrasonic treatment greatly increased the mechanical properties of weldment. At the same time, Tabor empirical equation [23] indicated that the relationship between tensile strength and micro-hardness can be represented as follows:

$$\sigma = H/C$$  \hspace{1cm} (2)

$$H = C(\sigma_0 + kd^{-1/2})$$  \hspace{1cm} (3)

Figure 7. The tensile strength of AZ31 joint: (a) no ultrasonic assistance, (b) treated by ultrasonic process with various ultrasonic power.

Figure 8. Tensile stress-strain curves of Mg alloy weldments: (a) no ultrasonic assistance (90 A), (b) ultrasonic vibration aided joint (1.0 kW, 90 A).
where $H$ is the micro-hardness value and $C$ is a constant related to materials. Based on equation (3), the micro-hardness of material increases with the decrease of crystallite dimension. Therefore, the grain refinement effect induced by ultrasonic assistance process is the key factor to enhance the tensile strength and micro-hardness of weldments.

Figure 8 shows the stress-strain curves of joint welded with and without ultrasonic treatment. It can be found that the grain refinement induced by ultrasound can improve the fracture strength and deformation ability of the weldment.

The fracture positions and fracture appearances of Mg alloy joint obtained with and without the aid of ultrasonic process are shown in figures 9 and 10. It can be found that for joints without ultrasonic treatment, fracture occurred in the weld zone of weldment, as shown in figure 9(a). At this point, the fracture path passed through some pores in the weld zone. Figure 10(a) shows that the fracture surface presents composite fracture features containing river patterns, cleavage platform and some dimples. Moreover, figure 10(a) also reveals that the surface of fracture is also distributed with severe pores. Combined with the microstructure observation, it can be concluded that the formation of pores and coarse grains in the weld zone are the main factors leading to fracture. For the ultrasonic treated joint, the fracture occurred near the HAZ, which was attributed to the grain refining and pore elimination caused by ultrasonic treatment, as shown in figure 9(b). It is obvious that the fracture surface presented plastic fracture characteristics and no pores were observed, as presented in figure 10(b).
4. Conclusions

In this paper, an attempt was made to introduce ultrasonic vibration into the welding process of Mg alloy by ultrasonic vibratory wire. The effects of ultrasonic treatment on the microstructure characterizations and mechanical performances of weldment were investigated. The main conclusions that can be drawn from the experimental results are as follows.

(1) For Mg alloy joint with traditional TIG process, plenty of pores were formed in the weld zone. Under the assistance of ultrasonic treatment, the introduction of ultrasonic vibration played a stirring role on the molten pool, which led to a great reduction or even elimination of the pores in the weld zone.

(2) For joints treated with ultrasonic process, the average grain size of weld zone decreased to 28 μm, attributed to the acoustic flow and cavitation effect caused by ultrasonic process.

(3) The ultrasonic induced grain refinement of weld zone improved the micro hardness and tensile strength of Mg alloy joint. With ultrasonic power of 1.0 kW, the optimum tensile strength of joint was increased by 8.9% to 256 MPa and the fracture surface presented plastic fracture characteristics.

Acknowledgments

The authors are grateful to Chongqing Natural Science Foundation (No. cstc2019jcyj–msxm2640) for the financial support to this study.

Conflicts of interest

No potential conflict of interest was reported by the authors.

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