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Melt flow and grain refining in ultrasonic vibration assisted laser welding process of AZ31B magnesium alloy

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ABSTRACT

During the laser welding process of magnesium (Mg) alloy, it is easy to produce welding defects, which deteriorates the mechanical properties of welded joint. Since ultrasonic vibration can decrease weld defects considerably, the ultrasonic-assisted welding technology has become a hotspot in the current research field of welding and joining. In this study, the ultrasonic vibration assisted laser welding technology used for the joining of AZ31B Mg was carried out. Setting amplitude transformer and welding specimen in contact makes ultrasonic travel to the weld pool as well as promote melt flow and bubble escape by the cavitation, acoustic streaming and thermal effects. Owing to these effects, the weld porosity decreases significantly to less than 1%. Besides, in the crystallization process of the weld pool, ultrasonic vibration increases the number of nucleation particles and refine grain, which improve the mechanical properties of welded joint. As a result, the average grain area in weld center area decreases from 359.9 μm^2 to 213.7 μm^2. Also, compared with laser welding, the tension strength σ_b, and elongation A_{gt} increase from 235.1 MPa to 274.1 MPa and 6.6% to 7.5%, respectively.

1. Introduction

In recent years, Mg and its alloys are widely used in military and civil applications for low density, high specific strength, excellent machinability and good damping capacity [1]. In aerospace and automotive industries, Mg alloys realize weight reduction effectively in the application of structural parts compared with other materials, such as Al and steel [2–4]. More specifically, for the good biocompatibility and similar elastic modulus with human skeleton, they are ideals materials used for surgical implants [5]. Accordingly, Mg alloys have been paid considerable attentions worldwide and been considered as "the greatest potential green engineering material of the 21st century". With the expansion of their application in various fields, the research on the welding and joining technology is becoming more and more important. However, for their unique physical and chemical properties, it is difficult to achieve reliable connection between Mg alloys and other materials. Therefore, many researchers are focus on searching a high quality welding method of Mg alloys.

At present, the traditional welding methods of Mg alloys are as follows: tungsten inert gas (TIG) welding, friction stir welding (FSW), electron beam welding (EBW), laser arc hybrid welding and laser welding [6–10]. Sun et al. [7] demonstrated the effects of welding methods on the microstructure and hardness of the AZ31B joints. The experimental results show that the grain sizes of welded joints change obviously in different energy density and the crack free weld with minimum grain size (10–20 μm) is obtained by Nd:YAG laser welding. However, the hardness in the same area of different welded joints are almost the same, although the microstructures differ from each other. Luo et al. [8] studied the FSW technology of dissimilar joints of AZ91D and ZG61 and evaluated the influence of traverse speed and material positions on microstructure, hardness and tensile strength of the welded joints. The higher heat input, which relates to material arrangement and traverse speed, can make the metal flow easier and improve the joint quality further. Chi et al. [9] investigated the EBW process of AZ series alloys and discussed the effect of Al content on the fracture mode and mechanical performance of welded joints. With the increase of Al content, the precipitate phase ($Mg_{17}Al_{12}$) in fusion zone (FZ) and the strength of welded joints are increased, and the fracture mode changes from a FZ fracture to a heat affect zone (HAZ) fracture.

Due to the less heat input and higher welding efficiency of laser welding, it has many advantages in the welding process of Mg alloys, such as fine microstructure, narrow HAZ and good mechanical properties [10–14]. Hong et al. [10] summarized the research

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results of laser welding technologies of lightweight alloy (Mg, Al and Ti) and systematically discussed their welding characteristics. Yan et al. [11] studied the laser welding process of ZK60 sheets with the thickness of 2.0 mm and found that the tensile strength and elongation, which maximum values are 300 MPa and 12%, increase first and then decrease with the increase of laser power and welding speed. The precipitate and fine grain of the original sheet (4μm) can restrict the grain coarsening in FZ ($4 \sim 8$ μm) and HAZ (8μm). Padmanaban et al. [12] evaluated the fatigue properties of the joints of AZ31B alloy welded by three different technologies (TIG, FSW and laser welding). Laser welding presents the highest fatigue strength of 58 MPa while the figures of TIG and FSW are 44 MPa and 49 MPa respectively. Besides, compared with the other two welding methods, the welded joints of laser welding has a high tensile properties and a fine microstructure. Coelho et al. [13] studied the laser welding process of AZ31B sheets and discussed the deformation mechanisms, texture evolution and phase distribution of the welded joints. The thermal cycle in laser welding process has a significant influence on the microstructure of the weld, which decreases the mechanical properties of joints. At the same time, the welding stability of Mg alloys is so poor that the welded joints are easy to produce porosity and liquation crack defect in the laser welding process, making the comprehensive properties of welded joints further decreased. Wahba et al. [14] analyzed the porosity behavior of die-cast AZ91D Mg alloy in laser deep-penetration welding process and discussed the formation mechanism of weld porosity. The results in this paper show that the weld porosity is mainly caused by two reasons: the original pores in BM and keyhole instability. What's more, the porosity formation can be restricted by a higher welding speed, a lower laser power and an inlay of extruded Mg sheet without pores. In summary, some problems still exist in the laser welding process of Mg alloys. Therefore, a novel welding method that improves the welding quality of Mg alloys is urgently needed.

The ultrasonic vibration plays an important role in the solidification and crystallization behavior of weld pool in welding process. It contributes to promoting grain refinement and melt flow, and decreases the number of porosity and liquation crack defect. Because of this, the mechanical properties of welded joints greatly improved with the application of ultrasonic vibration. Some relevant results in previous researches have illustrated the benefits of ultrasonic vibration in welding process. Ji et al. [15] put forward a new spot welding technology combining the FSW and ultrasonic vibration to join the AZ31 with AA6061 sheet and analyzed the influence of ultrasonic energy on metal flow, grain size and intermetallic compounds (IMC) formation in the stir zone. Xu et al. [16] welded the dissimilar AZ31B Mg alloy and TA2 Ti alloy via an ultrasonic vibration-TIG method and evaluated the effect of ultrasonic energy on grain size and the tensile strength. The maximum tensile strength and the minimum grain size obtained simultaneously when the ultrasonic power is 1.2 kW. Besides, Xu et al. [17] evaluated the corrosion resistance of the two joints and found that the corrosion resistance enhances with grain refinement. In Ref. [18], the microstructure of AZ series Mg alloys welded by arc welding with or without ultrasonic vibration is studied and the mechanisms of grain refinement in the welding process is discussed in detail. The grain refinement of welded joints improves with the increase of ultrasonic amplitude. Ning et al. [19] manufactured some Fe-Cr stainless parts by a novel additive manufacturing method (ultrasonic vibration assisted laser melting deposition). Similarly, the grain size decreases and the tensile properties increase with the application of ultrasonic vibration. Moreover, the welding defects like porosities and cracks decrease significantly. However, the previous works paid little attention to the ultrasonic vibration assisted laser welding. The related mechanisms of ultrasonic vibration and laser welding have not been well understand.

In this paper, the butt joint of AZ31B Mg alloy sheets welded by the laser welding with and without ultrasonic vibration and the influence mechanism of ultrasonic energy on welding characteristics of AZ31B Mg were studied. The changes of tensile properties, microstructure, porosity defect and phase distribution were investigated. The welded joints of ultrasonic vibration assisted laser welding exhibited a high tensile properties and a fine grain size. Moreover, the melt flow and grain refining behavior of weld pool were also discussed in detail.

2. Experiments

The experimental material is AZ31B Mg alloy sheet produced by a Chinese company and the thickness is 3 mm. The chemical composition of this material is listed in Table 1. The welding specimen cut by an electrospark wire-electrode cutting machine is 300 mm long and 100 mm wide. Before welding, the AZ31B sheet metal was processed as follows: mechanically grinding, cleaning, and drying. The ultrasonic vibration assisted laser welding equipment mainly includes 5 kW fiber laser (IPG Photonics, YLS-5000), welding robot (Kuka), and ultrasonic generator (CSHJ-1000). The output power of laser and ultrasonic is $0 \sim 5000$ W and 800 W, respectively. The welding parameters of laser welding are listed in Table 2. The ultrasonic amplitude and vibrational frequency are 6 μm and 40 kHz respectively. Before welding, the AZ31B sheet is fixed on the worktable controlled by a stepping motor. In the welding process, only the AZ31B workpiece moves, other components (laser head and amplitude transformer) remain stationary. The ultrasonic travels to the workpiece surface by amplitude transformer with a constant force (F) of 251.4 N and a distance (d) of 30 mm between the weld pool and contact position. After welding, the tensile specimens and metallographic samples were prepared by the electrospark wire-electrode cutting machine. The size of axial tensile specimen is determined by the international standard (ISO 6892: 1998) of the tensile specimen (see Fig. 1). The tensile test was carried out on an electronic universal testing machine (AGX-plus) with a constant strain rate of 0.001 s^{-1} at 25 °C. Three or more tensile specimens were tested in the same condition and the results were averaged. The metallographic samples are grinded, polished and then chemical etched by a mixed acid solu-

Table 2
Parameters used in the laser welding process.

Parameters	Value
Laser power, W	1400
Focal length of focusing lens, mm	192
Focal point position, mm	0
Focal point diameter of laser beam, mm	0.2
Welding speed, m min^{-1}	1.0
Flow rate of front shielding gas, L min^{-1}	15
Flow rate of back shielding gas, L min^{-1}	5

Table 1
Chemical composition of AZ31B magnesium alloys (mass fraction %).

Elements	Mg	Al	Si	Ca	Zn	Mn	Cu
Wt.%	Balanced	3.2	0.07	0.04	1.2	0.8	0.01