Original Article

Laser welding of AZ31B magnesium alloy with beam oscillation

Kangda Hao\textsuperscript{a}, Hekang Wang\textsuperscript{b}, Ming Gao\textsuperscript{b,\ast}, Run Wu\textsuperscript{a}, Xiaoyan Zeng\textsuperscript{b}

\textsuperscript{a} The State Key Laboratory of Refractories and Metallurgy, Wuhan University of Science and Technology, Wuhan 430081, China
\textsuperscript{b} Wuhan National Laboratory for Optoelectronics (WNLO), Huazhong University of Science and Technology, Wuhan 430074, China

1. Introduction

As the lightest structural metal, magnesium (Mg) alloy has advantages of high specific strength, specific stiffness and shock absorption, which is beneficial to achieve weight reduction and energy conservation for the fields of electronics, automobiles and aerospace [1]. However, its weld-ability is poor, defects like coarse-grain brittleness, pores and evaporation loss of the elements are generally occurred, and the solidification crack is easily induced by eutectic with low melting point in Mg weld, because of the high thermal conductivity, low solid solubility of hydrogen, easy oxidation and evaporation of magnesium and zinc. How to achieve high-quality weld of Mg alloy is then one of the most concerned issues.

Due to the high energy density and low heat input, laser welding would be potential for the welding of Mg alloy. During laser welding of 2 mm-thick AZ31 Mg alloy, the weld with narrow heat-affected zone (HAZ) could be obtained under laser power of 2.2 kW and welding speed of 5.5 m/min, the coarse grain neighboring the fusion line was eliminated, and the
hardness distribution was more homogeneous across the HAZ and the fusion zone [2]. The strength of the laser weld of Mg alloy could approach 90% of the base metal [3]. However, critical clamping accuracy is indispensable for laser welding because of the small spot of laser beam. In laser welding of die-casted AZ91D Mg alloy, the weld strength decreased by 10% once the gap width reached 5% of the sheet thickness [4]. Besides, the pores pre-existing in the base metal were easily gathered and grew up, because the liquid magnesium solidified quickly owing to the fast cooling rates of welding. The larger the heat input, the higher the porosity within the Mg weld [5].

Relatively, laser-arc hybrid welding can obtain better gap tolerance and weld quality by filling the welding wire. In laser-TIG hybrid welding of 1.7 mm-thick AZ31 Mg alloy, it was found that the hybrid welding not only had advantages of low heat input and narrow HAZ, it could also stabilize the arc and improve the weld performance [6]. In laser-MIG hybrid welding of 5 mm-thick AZ31 Mg alloy, it was found that the arc was compressed and stabilized by the laser beam, which promoted the droplet transferring from the wire tip to the weld pool smoothly, and the occurrence of the droplet explosion caused by low boiling point and high steam pressure of Mg was prevented to a certain extent [7]. However, the laser-TIG hybrid welding has problem of electrode burning, while the droplet explosion during laser-MIG hybrid welding hasn’t been solved fundamentally for the Mg alloy yet.

Thus, supplementary method was indispensable to achieve high-quality weld of the Mg alloy. By moving the welding head mechanically to achieve oscillating of the laser beam, it was found that the N2 porosity could be eliminated because of decreased aspect ratio, while the Ar porosity was also reduced due to the stirring effect of the oscillated laser, indicating the potential of beam oscillation in improving the weld quality of Mg alloy [8]. In arc oscillating welding of Mg alloy, it was confirmed that the oscillating behavior could promote the re-melting of the weld metal. On one hand, the re-melting preferentially occurred at the root of the secondary dendrite, which inhibited the growth of columnar grains and promoted the broken of dendrite. On the other hand, the temperature gradient was reduced and the composition super-cooling was easily obtained by the re-melting, which promoted the columnar grains transforming to equiaxed grains [9], indicating the oscillating behavior would be beneficial to improve the weld microstructure of the Mg alloy.

With the rapid development of high frequency galvanometer scanner recently, laser oscillating welding is considered one of the most promising welding technologies because of more precise modulation of oscillating parameters, which is significant to achieve sound weld of Mg alloy, and promote its industrial applications [10]. By laser oscillating welding of 6k21 aluminum alloy, the shear-tensile strength increased by 29% comparing with the conventional laser weld [11]. It was also demonstrated the spatter number was reduced either increasing the welding speed or decreasing the laser power [12]. By laser oscillating welding of AISI 304 austenite stainless steel, it was confirmed that the oscillating behavior could affect the weld appearance. With the increasing of oscillating frequency, the weld cross-section changed from slender nail to dumpy nail, V-shape and U-shape in sequence [13]. By laser oscillating welding of 6061 aluminum alloy, it was found that more equiaxed grains were obtained and the strain increased by 38% comparing with conventional laser weld [14].

The researches mentioned above indicate that laser oscillating welding is potential to improve the weld quality of Mg alloys due to the precise energy modulation. However, no attention has been addressed on laser oscillating welding of Mg alloys. Then, current study aims to reveal the effects of beam oscillating parameters on the characterization of Mg laser weld. The new phenomena in weld formation were studied, the difference of which with aluminum alloy and steel were discussed. Especially, the relationship of oscillating parameters, microstructure, and tensile properties was established, and the related mechanisms of microstructure evolutions were discussed, which is beneficial to deepen the understanding of laser oscillating welding of Mg alloys.

2. Experiment

The base metal used was 2 mm-thick AZ31 Mg alloy with chemical compositions shown in Table 1. The sheet size was 100 mm in length and 50 mm in width. Before welding, the sheets were steel brushed to remove the surface oxidation layer, cleaned by acetone and assembled in butt configuration.

The laser oscillating welding system was composed of a Fanuc M-710 six-axis robot, an IPG YLS-6000 fiber laser and a SCANLAB hurrySCAN30 scanning system, as shown in Fig. 1. The maximum power of the laser source was 6 kW with beam quality parameter of 6.9 mm-mrad. The laser beam with wavelength of 1070 nm was firstly transmitted by a fiber to a collimator, reflected by a copper mirror, and finally focused on the sheet surface with spot diameter about 0.35 mm. The focal lengths of the collimator and the focus lens were 150 mm and 350 mm, respectively. During welding, the molten pool was observed using a Phantom V2012 high-speed camera with a Cavilux HF light source. Besides, the top and root surfaces of the weld were shielded by Ar with flow rate of 20 L/min and 8 L/min, respectively.

In this study, circular beam oscillation was employed. The welding parameters used were listed in Table 2. After welding, the welds were cut down to prepare the metallurgical, electron back-scattered diffraction (EBSD) and tensile samples. The metallurgical samples were grinded and polished, and etched by a solution of 3 g picric acid, 20 ml acetic acid, 20 ml distilled water and 50 ml alcohol. The microstructure was observed by optical microscope (OM) and FEI Quanta-200 environmental scanning electron microscope (SEM). The EBSD samples were electrolytically polished with the voltage of 15 V for 120 s by the solution containing 10 ml perchloric acid and 90 ml ethanol, and tested by EDAX-TSL OIM system equipped on FEI Sirion-200 field emission SEM. Besides, the tensile tests were carried out with the sample size as shown in Fig. 2. The tensile results were the average of three samples.
Table 1 – Chemical compositions of base metal (wt. %).

<table>
<thead>
<tr>
<th>Element</th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Ni</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31</td>
<td>2.5–3.5</td>
<td>0.5–1.5</td>
<td>0.2–0.6</td>
<td>≤0.1</td>
<td>≤0.005</td>
<td>≤0.05</td>
<td>≤0.005</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Fig. 1 – Experimental set up for laser oscillating welding.

Table 2 – Welding parameters, where, r is the oscillating radius, f is the oscillating frequency, the laser power is 2 kW, the welding speed is 2 m/min.

<table>
<thead>
<tr>
<th>Weld no.</th>
<th>#0</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
<th>#8</th>
<th>#9</th>
<th>#10</th>
</tr>
</thead>
<tbody>
<tr>
<td>r (mm)</td>
<td>-</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>f (Hz)</td>
<td>-</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>10</td>
<td>25</td>
<td>75</td>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

Fig. 2 – Schematic drawing of the tensile sample.
3. Results and discussions

3.1. Weld appearance

As shown in Fig. 3, the undercut defect is general existed for the weld of Mg alloy whether employing beam oscillation or not, because the weight of the molten pool is hard to be held up due to the low surface tension coefficient of the liquid Mg. By modulating the longitudinal temperature gradient and the intensities of the eddying and convection effects within the molten pool via beam oscillation, the weld appearance can be improved [15], which will be subsequently discussed in detail according to the dynamic behavior of the molten pool.

Moreover, it can be found that the weld surface changes from wavy shape to continuous line with the frequency increasing to just 50 Hz under the radius of 1.0 mm. The undercut forms at 75 Hz, and the collapse occurs at 150 Hz. In laser oscillating welding of austenitic stainless steel, the frequency threshold achieving continuous weld surface was high up to 500 Hz by vertical oscillating with amplitude of 1.0 mm, and the undercut defect was negligible [13]. In laser oscillating welding of 6061 aluminum alloy, the weld appearance was also satisfied at frequency of 200 Hz under radius of 1.0 mm [14]. For the studied Mg alloy, the continuous weld surface is achieved at lower frequency, and complete collapse even occurs, because of lower boiling temperature, higher vapor pressure and heat sensitivity of the Mg alloy comparing with the above materials.

3.2. Characteristics of molten pool

As shown in Fig. 4a and b, shrinkage and expanding of the keyhole appears during one cycle, indicating its fluctuation to the energy absorption. For the molten pool without beam oscillation, the melted metal flows from near the keyhole to the edge of the molten pool. The beam oscillation with radius of 1.0 mm and frequency of 50 Hz promotes the melted metal flowing along the oscillating direction, and is beneficial to expand the keyhole to 1.5 mm², 5 times larger than that without beam oscillation, which increases the eruption of the metallic vapor and reduces the instability of the molten pool.

**Fig. 3** - Macro-profiles of the surface and cross-sectional welds, (a) without beam oscillation, (b) r = 1.0 mm and f = 10 Hz, (c) r = 1.0 mm and f = 25 Hz, (d) r = 1.0 mm and f = 50 Hz, (e) r = 1.0 mm and f = 75 Hz, (f) r = 1.0 mm and f = 100 Hz, (g) r = 1.0 mm and f = 150 Hz, (h) r = 0.5 mm and f = 50 Hz, (i) with r = 1.5 mm and f = 50 Hz, (j) r = 2.0 mm and f = 50 Hz, (k) r = 2.5 mm and f = 50 Hz.
As shown in Fig. 4c, the heat is concentrated on the right side of the weld with the frequency increasing from 50 to 100 Hz under radius of 1.0 mm, because of the inflection point for the circular scanning path, and the enhanced stirring intensity of the oscillating laser to the molten pool makes the melt flow at the left side moves reversely. As shown in Fig. 4d, the molten pool is significantly enlarged with the oscillating radius increasing from 1.0 to 2.0 mm at frequency of 50 Hz. At time of 203.571 ms, partly melted metal flows to the left side, causing excessive element burning and the formation of undercut.

### 3.3. Microstructure characteristics

As shown in Fig. 5, the columnar zone neighboring the fusion line is continuous for the sample without beam oscillation, while that with beam oscillation is discontinuous. As shown in Fig. 6, the length of the columnar grain achieves 20 µm under radius of 0.5 mm and frequency of 50 Hz, about 33% of the sample without beam oscillation. It then keeps about 35 µm with the radius increasing and about 42 µm with the frequency varying at radius of 1.0 mm. It can be concluded that the length is more likely to be affected by the oscillating radius, but nearly irrelevant to the frequency.

As shown in Fig. 7, the weld microstructure was inhomogeneously mixed with columnar and equiaxed grains for the sample without beam oscillating. At radius of 1.0 mm, the weld center is composed of homogeneous equiaxed grains at frequency of 25 Hz, mixed structure with coarser columnar and equiaxed grains at 75 Hz, and almost total refined columnar grains at 100 Hz. Under frequency of 50 Hz, the weld center is mostly composed of fine and homogeneous equiaxed grains at radius of 0.5 mm, and coarse columnar grains at radius of 2.0 mm.

According to the statistical data of the microstructure characteristics, as shown in Fig. 8, the proportion of the equiaxed zone (P_{EQ}) within the weld decreases from 85% to 42% with the frequency increasing at radius of 1.0 mm, while the average grain size (S_g) reaches the maximum of 37.5 µm at 75 Hz. On the other hand, the P_{EQ} decreases from 92% to 14%, and the S_g increases from 21 µm to 44 µm with the radius increasing at frequency of 50 Hz.

The results above show that the beam oscillation can not only break up the columnar grains near the fusion line and reduce the grain size, but also promote the formation of equiaxed grains. However, the equiaxed grains at the weld center may be replaced by coarse columnar grains when employing excessive frequency or radius. Thus, the effects
Fig. 5 – SEM images of the weld microstructure neighboring the fusion line, (a) without beam oscillation, (b) \( r = 0.5 \) mm and \( f = 50 \) Hz, (c) \( r = 1 \) mm and \( f = 50 \) Hz, (d) \( r = 1 \) mm and \( f = 75 \) Hz, where the BM denoted base metal, the FZ denoted the fusion zone.

Fig. 6 – The average length of the columnar grains, (a) effect of beam oscillating radius at frequency of 50 Hz, (b) effect of beam oscillating frequency at radius of 1.0 mm.

of the oscillating behavior on the weld microstructure can be explained as following.

As shown in Fig. 9a, the temperature gradient (G) is not homogeneous for the molten pool without beam oscillation, because the heat is transferred from the keyhole to the edge of the molten pool. The columnar grains are formed at the edge due to the high enough G. However, partly columnar grains start to be broken up because of the critical composition super-cooling caused by the decrease of the G. Then, the broken grains move within the molten pool for re-nucleation with
the convection provided by the surface tension and the thermal buoyancy. In this case, only a small amount of equiaxed grains form since partly nucleation sites are melted under the high enough temperature.

As shown in Fig. 9b, the keyhole moves along the oscillating path of the laser, and the heat is transferred from the keyhole to the surrounding areas by Marangoni flow. According to the simulation results of Wang (2016) and Gao et al. (2017) [15,16], the G within the molten pool tends to be homogeneous, and the composition super-cooling is easier to be achieved under appropriate oscillating parameters. This phenomenon was also observed in arc oscillating welding of AZ31 Mg alloy [9]. The eddying and convection effects are thus enhanced by the Marangoni melt flow. A large amount of fine turbulent flows from the tail of the molten pool to the mushy zone, and acts on the root of the secondary dendrite. Then, the columnar grains are broken up in addition with the re-melting effect. On the other hand, the broken grains are immediately rolled from the edge to the center by the melt flow, the number of the nucleation sites is increased and the maximum atomic group is enlarged, which promotes the occurrence of nucleation. Due to the reasons above, the equiaxed grains are more likely to form at the weld center under appropriate oscillating parameters.

At frequency higher than 75 Hz, as shown in Fig. 9c, the G at the weld center is more homogeneous due to more
concentrated distribution of the heat, which promotes the formation of the equiaxed grains. However, the merge and coarsening of the sub-grains may be nurtured, and the actual nucleation sites are reduced, because of the enlarged molten pool and the prolonged holding time at high temperature according to the results of high-speed photography, which promotes the formation of partly columnar grains at the weld center.

At radius larger than 1.5 mm, as shown in Fig. 9d, the molten pool is obviously enlarged. The previously melted metal starts to be solidified when the base metal heating by the laser is just melted. Then, the heat is dispersed, and the weld center is mixed with solid and liquid states. Besides, the melted metal at the tail of the molten pool flows along the welding direction to transfer the heat to the surrounded areas, especially the weld edge. Thus, the G at the weld edge is reduced, and the columnar grains are broken up. Moreover, the holding time at high temperature of the weld center is further prolonged because of the enlarged molten pool and decreased solidifying rate, the nucleation sites are then rapidly reduced, and the weld center is mainly composed of columnar grains with small portion of equiaxed grains.

Fig. 8 – Statistical data of the microstructure characteristics, (a) effect of beam oscillating frequency at radius of 1.0 mm, (b) effect of beam oscillating radius at frequency of 50 Hz.

Fig. 9 – Schematic drawing of the microstructure formation, (a) without laser oscillation, (b) oscillation with appropriate parameters, (c) oscillation with frequency higher than 75 Hz, (d) oscillation with radius larger than 1.5 mm.
3.4. **Tensile properties and plastic deformation mechanism**

All the welds crack along the fusion zone during tensile tests. It should be noted that the weld tensile properties cannot be improved by the beam oscillation, but are obviously affected, as shown in **Fig. 10**. The ultimate tensile strength (UTS) decreases from 240 to 208 MPa with the oscillating radius increasing from 0.5 to 2.0 mm at frequency of 50 Hz, while the elongation rate (EL) decreases from 9.6% to 7.5%. With the frequency increasing at radius of 1.0 mm, the EL achieves the maximum of 9.2% at 75 Hz, while the UTS keeps about 232 MPa when the frequency is lower than 75 Hz, and decreases to 222 MPa when it increases to 100 Hz.

According to the above results, it is found that the weld tensile properties are closely related to the \( F_{\text{TZ}} \) and the \( S_D \). The \( F_{\text{TZ}} \) decreases while the \( S_D \) increases with the increase of the oscillating radius at the frequency of 50 Hz, which is corresponding with the decrease of the UTS and the EL. With the increase of the frequency at radius of 1.0 mm, the \( F_{\text{TZ}} \) also decreases and the \( S_D \) reaches the maximum at 75 Hz, but the higher UTS and EL are reversely obtained. By further analysis, as shown in **Fig. 11**, it is related to the formation of tension twins found within the fracture surface of this sample. The slip system of Mg alloy is few due to its close-packed hexagonal structure, which couldn’t coordinate any deformation. Other than the slipping deformation activated under high temperature, the twining deformation is induced by stress, which can compensate for the lack of the slip systems and coordinate the plastic deformation, and then improve the weld ductility under room temperature. The related researches [17–20] showed that the dislocation slip path was short for the fine grains of Mg alloy, the stress then was relieved by cross-slip, non-basal slip or dynamic recovery. Thereby the twin nucleation was suppressed. However, the dislocation slip path was long, and the local stress neighboring the grain boundaries

**Fig. 10** – Tensile properties of the welds, (a) effect of beam oscillating frequency at radius of 1 mm, (b) effect of beam oscillating radius at frequency of 50 Hz.

**Fig. 11** – Crystallographic characteristics of the fractured weld, (a) IPF of the fractured weld with \( f = 75 \text{ Hz} \) and \( r = 1.0 \text{ mm} \), (b) IPF of the fractured weld with \( f = 25 \text{ Hz} \) and \( r = 1.0 \text{ mm} \), (c) Orientation analysis of the black rectangle area.
was high for the coarse grains, the twin nucleation is then activated easier, which improves the weld ductility.

4. Conclusion

(1) The continuous weld surface is achieved at frequency of 50 Hz, and the undercut defect appears at frequency higher than 75 Hz or radius larger than 1.5 mm, which are obviously lower than the thresholds of the aluminum alloy or steel. Under the given parameters of laser power 2 kW, welding speed 2 m/min and beam oscillating diameter 0.35 mm, the beam oscillation with small radius about 0.5 mm and low frequency about 50 Hz is more beneficial to achieve better weld appearance.

(2) The columnar grains neighboring the fusion line are broken up by the beam oscillation, and are rolled to the center acting as nucleation sites. The number of the nucleation sites is reduced increasing whether the oscillating frequency or the radius, resulting in the melt of the nucleation sites and the formation of coarse columnar grains.

(3) The proportion of the equiaxed zone (P_EQ) within the weld decreases from 85% to 42% with the frequency increasing at radius of 1.0 mm, while the average grain size (S_v) reaches the maximum of 37.5 μm at 75 Hz. On the other hand, the P_EQ decreases from 92% to 14%, and the S_v increases from 21 μm to 44 μm with the radius increasing at frequency of 50 Hz.

(4) The weld tensile properties cannot be improved by the beam oscillation, but are obviously affected, which are closely related to the P_EQ, the S_v and the twins. The decrease of the P_EQ and the increase of the S_v decrease the UTS and the EL with the increase of the oscillating radius. On the other hand, the P_EQ also decreases with the increase of the oscillating frequency and the S_v reaches the maximum at 75 Hz, but the formation of tension twins during tensile deformation promotes the improvement of the tensile properties.

Conflicts of interest

The authors declare no competing financial interests.

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References


