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Research for microstructure and mechanical properties of AZ91 magnesium alloy welded joint with magnetic field and activated flux

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1. Introduction

As the lightest engineering materials, magnesium alloys have been extensively used in aerospace, automobile industry and 3 C products due to their low density, high specific strength, excellent damping capacity and easy recovery [1–3]. Because of the specific chemical and physical characteristics of magnesium alloys, e.g. high chemical activity, low melting point, strong thermal expansion, many defects can form easily in the welding process, such as cracks, porosity and slag inclusion, that reduce the mechanical properties of welded joint [4]. In order to obtain high-quality welded joints, some new welding technologies have been developed in recent years, which have well solved the welding difficulties of magnesium alloys. Welding technologies have been reported including tungsten insert gas (TIG) arc welding [5, 6], electron beam welding (EBW) [7, 8], laser beam welding (LBW) [9, 10], friction stir welding (FSW) [11, 12]. Owing to its adaptability, stability and economy, TIG welding has become a common technology used for welding magnesium alloys [13]. However, relatively shallow penetration limits the application of this technology.

Activated tungsten insert gas (A-TIG) welding process was developed by Paton Electric Welding Institute to improve the penetration of TIG welding. In this process, activated flux was applied to the plate surface to be welded. An increase in penetration was achieved by the effect of flux on the welding arc and pool [14–16]. A-TIG welding is a combination of TIG welding and magnetic field (MF) welding, which can improve welding efficiency and mechanical properties of welded joints, the longitudinal alternating magnetic field and NiCl₂ activated flux were used during TIG welding of AZ91 magnesium alloy. The formation, mechanical properties, phase composition and crystal growth pattern of the weld seam were tested and analyzed to study the mechanism. The experimental results reveal that with proper parameter matching (magnetic field and activated flux), larger weld penetration and smaller form factor can be obtained, welding efficiency is improved accordingly, but the form factor with the magnetic field is bigger than that without magnetic field. When the activated flux amount is 3 mg cm⁻² with the magnetic field, the optimal value of mechanical properties of welded joint is obtained, tensile strength is 385 MPa, elongation is 13.3%, micohardness is 67 HV, respectively. All of these are better than those without the magnetic field, the optimal activated flux amount is 2 mg cm⁻². The application of magnetic field and activated flux has no noticeable effect on the phase composition of weld seam. Under the combined action of magnetic field and activated flux, the crystallization nucleation condition of molten pool was changed, the grain size was refined, the formation of twins was promoted, and the crystals selectively grew within the basal (0001) plane.

Abstract

Although many experimental researches have been carried out on the effect of different fluxes and the mechanism responsible for the higher penetration in activated TIG welding of magnesium alloy, few works as reported in literatures are available concerning the grain refinement and the improvement of mechanical properties of welded joints. This is because the activated flux has very limited or even negative effects on improving the mechanical properties of welded joints. In order to find a method that can improve welding efficiency and mechanical properties of welded joints, the longitudinal alternating magnetic field and NiCl₂ activated flux were used during TIG welding of AZ91 magnesium alloy. The formation, mechanical properties, phase composition and crystal growth pattern of the weld seam were tested and analyzed to study the mechanism. The experimental results reveal that with proper parameter matching (magnetic field and activated flux), larger weld penetration and smaller form factor can be obtained, welding efficiency is improved accordingly, but the form factor with the magnetic field is bigger than that without magnetic field. When the activated flux amount is 3 mg cm⁻² with the magnetic field, the optimal value of mechanical properties of welded joint is obtained, tensile strength is 385 MPa, elongation is 13.3%, micohardness is 67 HV, respectively. All of these are better than those without the magnetic field, the optimal activated flux amount is 2 mg cm⁻². The application of magnetic field and activated flux has no noticeable effect on the phase composition of weld seam. Under the combined action of magnetic field and activated flux, the crystallization nucleation condition of molten pool was changed, the grain size was refined, the formation of twins was promoted, and the crystals selectively grew within the basal (0001) plane.

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welding can improve production efficiency and reduce production cost compared to conventional TIG welding [17].

At present, lots of studies have been conducted on A-TIG welding of magnesium alloy. Zhang et al studied the effects of oxide activated fluxes [18], metal activated fluxes [19] and chloride activated fluxes [14] on A-TIG welding of magnesium alloys. They confirmed the increase of penetration and discussed the mechanism responsible for the change to higher penetration. They assumed that the microstructure with activated flux was lightly coarsened than the microstructure without activated flux. Qin et al. [20] reported the effect of TIG/A-TIG on microstructure and mechanical properties of AZ61/ZK60 magnesium alloys welded joints. The results showed that TIG welded joints exhibited finer grain size and higher tensile strength at a welding current of 80 A, compared with A-TIG welded joints. Generally, grain refinement can improve the mechanical properties of welded joints. However, to the best of our knowledge, the research on grain refinement and improvement of mechanical properties of A-TIG welded joints is rarely reported. Zhou et al. [21] investigated the effect of post-weld aging treatment on A-TIG welded joints, they revealed that aging treatment resulted in finer $\beta$-Mg$_{17}(\text{Al, Zn})_12$ phase and superior mechanical properties of welded joints. Despite the success of this work, the evolution process kept complex ambiguous.

It is well known that the welding process under the action of magnetic field has attracted more and more attentions, due to its advantage in simple process, low cost, low energy consumption and grain refinement [22–26]. Extensive studies have reported the influence of magnetic field on the welding process of magnesium alloy. Luo et al. [27] applied the longitudinal steady magnetic field in the TIG welding of AZ31 magnesium alloy, and founded that the microstructure was refined and the mechanical properties were improved at a proper excitation current. More studies [28–30] adopted a longitudinal alternating magnetic field in magnesium alloy welding and reported that the magnetic field could refine the crystal grain and improve the tensile strength and hardness at proper parameters. According to the previous studies mentioned above, a longitudinal magnetic field was usually applied to the magnesium alloy welding. That is mainly because the longitudinal magnetic field can make the arc rotate, change the radial distribution of arc column plasma flow and current density, affect the heating and melting of the base metal, refine the grain and improve the performance of welded joints [31].

Although the application of steady and alternating magnetic field can both refine the microstructure and improve the mechanical properties of welded joint, the steady magnetic field is liable to cause the arc magnetic deflection blow, which affects the weld appearance quality. Furthermore, Ban et al. [32] proposed that, compared to the sample treated by steady magnetic field, the grain of AZ80 Mg alloy was refined obviously in the sample treated by alternating magnetic field. Therefore, applying a longitudinal alternating magnetic field will obtain better experimental results. The influence of magnetic field on traditional TIG welding of magnesium alloy has been investigated in previous studies, but researches on the effect of magnetic field on A-TIG welding were rarely reported. Both magnetic field and activated flux can affect the welding arc and molten pool, the combined effects on morphology, microstructure and mechanical properties of magnesium alloy welded joints are still unclear. We previously applied a longitudinal steady magnetic field and an activated flux to magnesium alloy welding, and found that the the comprehensive mechanical properties of the welded joint can be improved by combined magnetic field and activated flux [33]. Hence, in this work, the longitudinal alternating magnetic field was applied in the A-TIG welding of magnesium alloy, the influences of magnetic field on the formation of weld seam, mechanical properties, phase composition, microstructure were systematically investigated. The mechanism of grain refinement was discussed further.

### 2. Experimental

AZ91 magnesium alloy plates, with a dimension of 100 mm × 100 mm × 5 mm, were selected as the base metal. The surface of plates were polished to remove surface contaminants and oxide. The chemical composition and the mechanical properties of base metal are shown in tables 1 and 2.

NiCl$_2$ activated flux in powder form was used in the experiments. The powder flux was mixed uniformly with ethanol and applied to the surface of plates with a brush. The coating amounts of activated flux were 1 mg cm$^{-2}$, 2 mg cm$^{-2}$, 3 mg cm$^{-2}$, 4 mg cm$^{-2}$, 5 mg cm$^{-2}$, respectively. After being placed for 24 h at room temperature, the plates were welded under the TIG condition of WSE-50 welding machine. The longitudinal magnetic field was generated by the magnetic coil installed directly on welding torch. The arc was limited at the

| Table 1. Chemical composition of the base metal (wt.%). |
| --- |
| Al | Zn | Mn | Si | Cu | Fe | Mg |
| 8.3–9.7 | 0.35–1 | 0.15–0.5 | <0.01 | <0.03 | <0.005 | Balance |
center of activated flux coating area and moved at a constant and stable speed under the influence of electric feeding mechanism. Therefore, the heat gained in the weld seam during the welding operation was homogeneous. The experimental device is shown in figure 1. The process parameters are given in table 3. The parameters of welding current, excitation current and oscillation frequency of magnetic field are the optimal parameters obtained through orthogonality optimization experiments.

After welding, macroscopic seam appearance was evaluated by naked eye to confirm no defects existence, including cracks and slag inclusions. The actual shape of welded joint and sampling method are shown in figures 2(a), (b). Weld penetration and width were measured using a body vision microscope, as shown in figure 2(c). The microstructure was observed by scanning electron microscopy (Hitachi S-3400). A corrosive solution used to reveal the microstructure, that is mixture of 20 ml ethylene glycol, 60 ml glacial acetic acid, 1 ml nitric acid, and 19 ml distilled water. XRD and EDS were used to determine the phase composition and distribution in welded joints. The grain size and orientation of welded joints were characterized by EBSD (ZEISS G300). EBSD specimens were mechanically polished to 5000 grit, and electrolytic polishing was performed using

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**Table 2. Mechanical properties of the base metal.**

| Property               | Value     |
|------------------------|-----------|
| Tensile Strength (MPa) | 280       |
| Yield Strength (MPa)   | 160       |
| Elongation (%)         | 8         |
| Microhardness (HV)     | 64.5      |

| Property     | Value     |
|--------------|-----------|
| Welding current (A) | 85       |
| Welding speed (mm min⁻¹) | 300     |
| Extension of tungsten (mm) | 2       |
| Gas flow rate (l min⁻¹)   | 10–15    |
| Excitation current (A)   | 3.5      |
| Excitation frequency (Hz) | 30      |

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**Figure 1.** Schematic diagram of experimental device.

**Figure 2.** Schematic diagram of processed samples and welded joints. (a) Sampling method; (b) Actual shape of welded joints; (c) Measuring method of weld penetration and width.
a solution containing 10% perchloric acid and 90% alcohol. The temperature of electrolyte solution was −30 °C, the electrolytic voltage and the polishing time were 15 V and 120 s, respectively. The morphology of welded joints was studied by TEM. Microhardness tests were conducted with THVS-5 Vickers hardness tester in a period of 15 s with a load of 500 g. The tensile test specimen was prepared according to GB/T 228, and the test was carried out at 3 mm min⁻¹ by using a universal testing machine. Three specimens for the same condition were tested in this work.

3. Results

3.1. Formation of weld seams

A graphical representation of weld seam dimensions is shown in figure 3. It can be seen that in A-TIG welding process without magnetic field, the width of weld seam presents a negative correlation with coating amount of activated flux until it arrives to 3 mg cm⁻², the width increases afterwards. An opposite trend is observed in penetration of weld seam. The maximum penetration is obtained at the coating amount of activated flux of 3 mg cm⁻², the increase in penetration is up to 150% compared to the conventional TIG welding. The form factor of weld without magnetic field initially decreases, when the coating amount of activated flux exceeds 3 mg cm⁻², the form factor increases.

When the magnetic field is applied, a similar trend is observed in curve of weld width, penetration and form factor. Meanwhile, the maximum penetration (up to 150% compared to conventional TIG welding) and minimum form factor of weld seam are also achieved under 3 mg cm⁻² activated flux. The same increase in penetration shows that the introduction of magnetic field doesn’t change the effect of activated flux on the increase of weld seam penetration. However, there is still a difference in the width of weld seam with or without magnetic field. The width of weld with the magnetic field is obviously wider than that without the magnetic field. The variation of penetration and width makes the form factor of weld with magnetic field slightly larger than that without magnetic field.

The effect of activated flux on the welding arc is opposite to that of magnetic field. During the welding process, the chloride activated flux is heated and vaporized into arc column in atomic form. Atoms of flux capture free electrons and form negative ions, which can compress the arc, increase arc stiffness, and thus increase penetration [36, 37]. Moreover, because of the poor conductivity of NiCl₂ activated flux, it needs to absorb a lot of heat when evaporating, which results in a considerable increase in temperature at the center of arc [38]. The combined effect of magnetic field and activated flux on arc makes the arc shrinkage degree weaken, compared to the independent effect of activated flux. As a result, the welded joint obtains a bigger width and smaller form factor.

3.2. Mechanical properties

In order to analyze the influence of magnetic field and activated flux on the mechanical properties of welded joints, the microhardness and tensile properties of welded joints were tested, the results are shown in figures 4 and 5. Figure 4 shows the microhardness of welded joint with and without magnetic field. It can be found that no
matter whether the magnetic field is applied or not, the hardness variation of weld zone are all the same. The microhardness of weld seam increases first and then decreases with the increase of activated flux. The maximum microhardness of weld seam is obtained at the activated flux coating amount of 3 mg cm\(^{-2}\). The microhardness of weld zone with magnetic field is higher than that without magnetic field, i.e. 67 HV and 65.5 HV, respectively. The change law of microhardness in heat affected zone (HAZ) is not obvious when the magnetic field is applied, and the error fluctuation range is large. This result shows that the effect of magnetic field and activated flux on the weld zone is considerable, but the effect on the HAZ is irregular and out of the current study purpose.

Figure 5 indicates the tensile test results with and without magnetic field. Figure 5(a) is the curve of the tensile strength of welded joint in relation with the coating amount of activated flux. When the magnetic field is applied, the tensile strength initially increases with activated flux amount and attains a maximum value (338 MPa) at 3 mg cm\(^{-2}\). After that, it declines with a further increase of activated flux amount. The tensile strength change law of welded joint without magnetic field is the same as that with magnetic field. But, the maximum tensile strength of welded joint without magnetic field is 312 MPa at the activated flux amount of 2 mg cm\(^{-2}\). It is lower than that with magnetic field. Elongation change trends of welded joint under different activated flux are similar to that of tensile strength, as illustrated in figure 5(b). The largest elongation of 13.3\% is obtained at 3 mg cm\(^{-2}\) with magnetic field. The largest elongation of 12.3\% is obtained at 2 mg cm\(^{-2}\) without magnetic field. From there, it can be observed that the tensile properties can be improved at the optimum parameters of magnetic field and activated flux. The mechanical properties are in line with the microstructure change of welded joint. Since the tensile strength and elongation have been improved at the same time, it shows that there is fine grain strengthening under the influence of magnetic field, the correlation analysis is shown in figure 7.
Figures 6(a)–(e) shows the image of typical tensile fractures under the effect of magnetic field. Besides, the fracture morphology for the best tensile performance without magnetic field is also listed for comparison, as displayed in figure 6(f). Dimples are rarely included from the fracture in figure 6. A large number of cleavage planes with a certain direction can be clearly observed (seen the red arrow in figures 6(a)–(e)). Therefore, the fracture form of magnesium alloy welded joint with magnetic field and activated flux should be intergranular fracture with a few of dimples. This is also the reason for poor plasticity of welded joints. The tensile fracture morphology under the best parameters is also obviously different from other parameters. The directional cleavage plane disappears, a large number of tearing edges (see the red arrow in figures 6(c) and (f)) and a certain number of dimples (see also the yellow arrow in figures 6(c) and (f)) appeared. This reflects the improved plasticity of welded joint.

3.3. Phase composition and microstructural observation

Figure 7 gives the XRD patterns of weld seam. It displays that the weld seam with magnetic field is composed of $\alpha$-Mg, Al$_2$Mg, MgZn and MgO. $\alpha$-Mg is the primary phase which comes from the base metal. Al$_2$Mg and MgZn are the second phases which are newly produced during the welding process. MgO is a kind of inclusions formed due to poor protection during welding. The phase composition of weld seam without magnetic field is the same as the weld seam with magnetic field. According to the diffraction peak intensities, the MgO content in welded joints with magnetic field increases compared with that without magnetic field. This is mainly due to the arc-blow during welding process. Although no difference presents in the phase composition, there are still some...
differences in the diffraction peaks. When the magnetic field and the activated flux are used together, the intensity of diffraction peak of the α-Mg crystal significantly changes with the amount of activated flux. When the amount of activated flux is no more than 2 mg cm⁻², the crystal plane corresponding to the strongest diffraction peak is (100). When the amount is more than 2 mg cm⁻², the crystal plane corresponding to the strongest diffraction peak is transformed to (002). However, when only the activated flux is used, the crystal plane corresponding to diffraction peaks does not change. This phenomenon indicates that the application of magnetic field affects the crystal growth mode. Besides, comparing the diffraction pattern with the standard pattern, it was found that the diffraction peak was shifted to the right by 0.19°, indicating that grain refinement occurred.

The microstructures of weld seams in relation with the magnetic field are shown in figures 8(a)–(e). It can be seen that the size of the grains initially decrease with the coating amount of activated flux and attain the minimum size at 3 mg cm⁻², and then the grain size increases. In order to analyze the grain refinement ability of magnetic field, the microstructure with the smallest grain size, which was obtained at the coating amount of activated flux of 2 mg cm⁻² without magnetic field, is shown in figure 8(f) for comparison. As can be observed, there is no obvious difference in the phase composition with or without magnetic field. They are mainly composed of the primary phase and some second phases. The second phase distributes along the grain boundaries. The grain size with magnetic field (figure 8(c)) is significantly smaller as compared to that without magnetic field (figure 8(f)). The result indicates that the grain size is greatly refined due to the external magnetic field. This is also the reason for that the mechanical properties of welded joints are improved under the magnetic field. This phenomenon is attributed to the coupled action of magnetic field and activated flux on the welding arc. On the one hand, the welding arc rotated under the action of Lorentz force generated by magnetic field and electromagnet of itself; on the other hand, the welding arc was constrained under the influence of evaporation and ionization of activated flux. Hence, the welding arc shows a compression-rotation mode and the rotation radius and speed of arc increases to some extent, which would effectively stir the molten pool. The stirred molten pool scours dendrite arms and breaks them off, inhibiting the growth of dendrites. Moreover, the broken-up dendrites are transported into the molten pool by convection and becomes new nucleation sites, so that the nucleation rate increases remarkably and then smaller grains form as a result.

The phase composition of weld seam with and without magnetic field has no difference, so only the weld seam coated with 3 mg cm⁻² activated flux was selected for EDS analysis to identify the element distribution in microstructure. The results are shown in figure 9.

Four sites are analyzed, including the highlighted zone in matrix, the highlighted zone at grain boundary, the matrix crystal and the general zone at grain boundary. It is observed that two chemical elements (Mg and Al) are contained in sites A, B and C, three chemical elements (Mg, Al and Zn) are contained in site D. The contents of Mg in site C is higher than sites A and B. According to the Mg-Al binary phase diagram, the eutectic reaction of Mg-Al binary alloy took place at the temperature of 437 °C, and formed α-Mg phase and β/γ phase. In the two-phase equilibrium state, the solubility of Al in Mg was 11.5 wt% at high temperature and 1.5 wt% at room
temperature. In fact, the solidification of weld pool metal was non-equilibrium state due to rapid heating and rapid cooling in the welding process, the composition would deviate from the equilibrium composition. EDS analysis results indicate that site A (shown in figure 9(b)) and site B (shown in figure 9(c)) are composed of 88.48 wt% Mg, 11.52 wt% Al and 89.64 wt% Mg, 10.36 wt% Al, respectively, suggesting that they are mixtures of $\alpha$-Mg and $\text{Al}_2\text{Mg}$. Site C is composed of 96.89 wt% Mg, 3.11 wt% Al (shown in figure 9(d)), it is considered as $\alpha$-Mg. Site D contains 87.92 wt% Mg, 7.73 wt% Al and 4.36 wt% Zn (shown in figure 9(e)), suggesting that it is a mixture of $\alpha$-Mg, $\text{Al}_2\text{Mg}$ and MgZn. MgO phase is not observed in the EDS results, it is most likely that it mainly distributed on or near the surface of weld seam, it can’t be found on the cross-section of welded joint.

4. Analysis and discussion

Generally, the welding arc continuously transports arc energy to the surface of material and makes the base material melt to form a molten pool, which is under the action of electromagnetic pinch force, plasma flow force, arc spot force, explosion force and fine droplet impact force. For the TIG welding, the arc is not affected by the explosion force and fine droplet impact force, but only affected by the electromagnetic pinch force, plasma flow force and arc spot force. In this paper, the experiment with magnetic field and activated flux is carried out based on conventional TIG welding, and the original force mode of arc will be changed. For AC TIG welding, the arc generates alternating current by itself. According to the electromagnetic theory, an AC magnetic field will
emerge around it. With the introduction of an external magnetic field, the arc plasma will be affected by two magnetic fields in the whole system. The force mode of arc plasma is shown in figure 10. It can be found that the arc is influenced by two forces, one is the spontaneous electromagnetic force generated by the interaction of welding current and self-magnetic field, the other is the electromagnetic force generated by the external longitudinal magnetic field. The spontaneous electromagnetic force is decomposed into axial and radial components $j \times B_{m} - j \times B_{p}$, respectively. Whereas the external magnetic field is longitudinal, the direction of which is parallel to the arc axis. Hence, only the radial component of current density interacts with the external magnetic field, and forms a centripetal force causing the rotation of charged particles of arc at high speed. The external electromagnetic force can be obtained from the equation (1):

$$F_{\text{ext}} = jB_{\text{ext}}$$ (1)

Where $F_{\text{ext}}$ is external electromagnetic force, $j$ is current density, $B_{\text{ext}}$ is intensity of external magnetic field which is from the inductive magnetic field generated by the electrified coil. The intensity can be derived from Biot–Savart Law using Formula (2):

$$B_{\text{ext}} = \frac{\mu_{0}NI_{c}}{2} \left[ \frac{1 - 2z}{\sqrt{(1 - 2z)^2 + 4a^2}} + \frac{1 + 2z}{\sqrt{(1 + 2z)^2 + 4a^2}} \right]$$ (2)

Where $I_{c}$ is excitation current, $N$ is coil turn, the turn number of 720 was used in this paper, $l$ is coil length, 125 mm was used, $z$ is axial distance from the center of coil, $a$ is coil radius.

Since NiCl$_2$ activated flux mainly affects on the arc during welding process, the temperature field and fluid field of arc under the influence of magnetic field are analyzed. Based on the force model mentioned above, corresponding boundary conditions and reported theoretical models [39, 40], the temperature field and fluid field of arc plasma under different magnetic field intensities were analyzed, the results are shown in figure 11. The results of electric potential field, maximum axial current density, heat flux distribution were shown in [39, 40]. For comparative analysis, three intensities of the magnetic field were selected in the calculation, including 0 T, 0.01 T and 0.03 T. The value of 0 T stands for the state with no magnetic field. The value of 0.01 T is the magnetic field intensity under the magnetic field condition in this paper. The value of 0.03 T is the maximum intensity, which is used to compare with the effect at 0.01 T. From the characteristics of temperature field distribution under different intensity, it can be found that the maximum temperature in arc column area increases with the increase of magnetic field intensity. But divergence appears at the bottom of arc pillar, the shape of arc changes from ‘cone-shaped’ to ‘bell-shaped’. From the characteristics of fluid field, it can be found that the velocity of arc plasma decrease with the increase of magnetic field intensity, and the vacuum zone and
even the phenomenon of ‘magnetic suction’ [40] appeared at the lower end of arc (shown in figure 11(c)). Therefore, it can be concluded that the arc diameter tends to increase when only the magnetic field is applied. This phenomenon will result in greater weld width and weld form factor (shown in figure 3), and reduce the welding production efficiency. Although the introduction of magnetic field has no positive effect on improving welding production efficiency, the rotating arc affected by electromagnetic force will drive the molten pool to

Figure 11. Temperature field and fluid field of arc plasma under different magnetic field parameters. (a) $B = 0$ T; (b) $B = 0.01$ T; (c) $B = 0.03$ T.
move and change the crystal nucleation conditions in molten pool. Finally, it imposes a positive effect on improving the mechanical properties of welded joint (shown in figures 4 and 5).

NiCl₂ is used as a single activated flux, and its structure is consistent with CdCl₂. As a compound, NiCl₂ is difficult to ionize, so the introduction of NiCl₂ is not conducive to arc striking. However, when the arc burns steadily, NiCl₂ in the arc column area will be ionized to form Cl ions. The Cl ion has a higher affinity and can capture free electrons to form negative ions. The negative ions with large mass will distribute outside the arc, which can compress the arc, improve the arc stiffness, and then enhance the weld penetration. The combined action of external magnetic field and activated flux reduces the diameter of ‘bell’ at the bottom of arc, weakens the phenomenon of ‘magnetic suction’, and makes the arc in a spiral sinking mode. The spiral movement of molten pool generated by the above arc mode, erodes the crystallization edge of the molten pool, changes the nucleation condition of liquid metal, and then promotes the grain to be refined.

Furthermore, the molten pool, as a part of conductive circuit, is also a part of magnetic fluid. Hence, it is also affected by the Lorentz force, which has a positive effect on the microstructure purification and grain growth. In order to study the crystal growth characteristics under the magnetic field, EBSD analysis was used. The EBSD pattern is shown in figures 12 and 13.

Figure 12 is the result of specimen at the activated flux coating amount of 3 mg cm⁻² with the magnetic field. Figure 13 is the result of specimen at the activated flux coating amount of 2 mg cm⁻² without magnetic field. It can be seen that the precipitates at grain boundary increase obviously and the distribution of the crystal plane is random, when the coating amount of activated flux is 3 mg cm⁻² with magnetic field. In contrast, the precipitates are relatively fewer and the grain boundary is clear when no magnetic field was applied. The grain size is statistically analyzed, and the result shows that the average sizes of grain are 12.9248 μm and 17.176 μm, respectively, with and without magnetic field. It suggests that the effect of the magnetic field on grain refinement is obvious, and the grain refinement ratio is up to 24.8%, which effectively improves the mechanical properties of welded joint. The crystal grains of red color in figures 12(a) and 13(a) are twins. There are more twins in the weld seam with magnetic field than that without magnetic field. The increase of twins has a positive effect on the mechanical properties of welded joint. It can release the stress, reduce the nucleation of crack, blunt the crack-tip and inhibit the crack expansion, for the prevention of hot crack. Moreover, the increase of twins leads to the increase of twin boundary, which can divide the original grains and then refine the grains. As shown in figure 12(b), the grains are uniformly distributed and have no obvious orientation. Whereas, the grain orientation behavior changes when applied magnetic field, the preferred growth of grains is obviously parallel with the (0001) basal plane.
5. Conclusions

The effect of magnetic field on microstructure and mechanical properties of AZ91 magnesium alloy welded joint in A-TIG welding was investigated. The results were compared with that without magnetic field. The conclusions are as follows:

(1) The weld width of welded joint with magnetic field was wider than that without magnetic field. When the parameters matched (magnetic field and activated flux), larger weld penetration and smaller form factor were obtained. Welding efficiency was improved accordingly.

(2) When the activated flux amount was 3 mg cm$^{-2}$ with magnetic field, the optimal value of mechanical properties of welded joint was obtained: tensile strength 385 MPa, elongation 13.3%, and hardness 67 HV. All of these were better than those without magnetic field, at an optimal activated flux amount of 2 mg cm$^{-2}$.

(3) The application of magnetic field and activated flux had no obvious effect on the phase composition of weld seam. Under the combined action of magnetic field and activated flux, the crystallization nucleation condition of molten pool was changed, the grain size was refined, the formation of twins was promoted, and the crystal should selectively grow parallel with the (0001) basal plane.

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Figure 13. EBSD map of weld seam with magnetic field. (a) Grain orientation figure; (b) Pole figure.
References

[1] Zhao X H, Zhang Y J and Liu Y 2017 Surface characteristics and fatigue behavior of gradient nano-structured magnesium alloy Metals 7 62–73

[2] Chang W, Shen Y P, Su Y J, Zhao L, Zhang Y Y, Chen X R, Sun M, Dai J C and Zhai Q J 2019 Grain refinement of AZ91 magnesium alloy induced by Al-V-B master alloy Metals 9 1333–44

[3] Karakulak I 2019 A review: present, future and of grain refining of magnesium castings J. Magn. Alloy. 7 355–69

[4] Zhang D T, Mayumi S and Kouchi M 2005 Microstructural evolution of a heat-resistant magnesium alloy due to friction stir welding Sci. Mater. 52 899–903

[5] Razalrose A, Manisekar K, Balasubramanian V and Rajakumar S 2012 Prediction and optimization of pulsed current tungsten inert gas welding parameters to attain maximum tensile strength in AZ61A magnesium alloy Mater. Des. 37 334–48

[6] Liu H T, Zhou J X, Zhao D Q, Liu Y T, Wu H J, Yang Y S, Ma B C and Zhuang H H 2017 Characteristics of AZ31 Mg alloy joint using automatic TIG welding Int. J. Miner. Metall. Mater. 24 102–8

[7] Zhang Y M 2003 Electron beam welding properties of pure magnesium and AZ31 magnesium alloys Rare Met. Lett. 4 25–6 (http://www.wanfangdata.com.cn/details/detail.do?_type=perio&id=92)

[8] Munitz A, Cotler C, Shalam H and Kohn G 2000 Electron beam welding of magnesium AZ91D plates Weld. J. 79 202a–8

[9] Shen J, Wen L B, Li Y and Min D 2013 Effects of welding speed on the microstructures and mechanical properties of laser welded AZ61 magnesium alloy joints Mater. Sci. Eng. A 578 303–9

[10] Zhao X Y, Tan C W, Meng S H, Chen B, Song X G, Li L Q and Feng J C 2018 Fiber laser welding-brazing characteristics of dissimilar metals AZ31 Mg alloys to copper with mg-based filler JIMEPEG. 27 1427–39

[11] Sevel P and Jaiganesh V 2016 Impact of process parameters during friction stir welding of AZ80A Mg alloy Scu. Technol. Weld. Joi. 21 63–90

[12] Carbone P, Asturita A, Rubino F and Pasquino N 2016 Microstructural aspects in FSW and TIG welding of cast ZE41A magnesium alloy Metall. Mater. Trans. B 47 1–7

[13] Hu Y B, Zhao C and Deng J 2010 Research status and prospects of magnesium alloys welding technology Hot Work. Technol. 39 124–8

[14] Zhang Z D and Fan Q F 2013 Study on effect of metal chlorides on penetration depth in A-TIG welding Trans. China Weld. Inst. 34 29–32 (http://www.wanfangdata.com.cn/details/detail.do?_type=perio&id=hjxb201305008)

[15] Liu Z J, Li L and Su Y H 2015 Weld penetration increasing mechanism of magnesium alloy with oxide activated fluxes J. Shenyang Univ. Technol. 37 138–47

[16] Wei Y H, Xu Y L, Sun Y J, Dong Z B and Yang C L 2009 Mechanism of increasing welding penetration with A-TIG welding Trans. China Weld. Inst. 30 37–40

[17] Peng X Y, Ling Z M, Liao J and Li J G 2013 Research progress of A-TIG welding Mater. Mech. Eng. 37 1–4 (http://www.wanfangdata.com.cn/details/detail.do?_type=perio&id=92)

[18] Zhang Z D, Liu L M and Wang L 2004 Microstructure feature analysis of activating TIG welded joint Trans. China Weld. Inst. 25 55–8

[19] Zhang Z D and Cao Q J 2011 Effects of activated metal chlorides on flux TIG welding of magnesium alloy Trans. China Weld. Inst. 32 37–40 (http://www.wanfangdata.com.cn/details/detail.do?_type=perio&id=hjxb2011109010)

[20] Qing B, Ying F C, Zeng C Z, Xie J C and Shen J 2019 Microstructure and mechanical properties of TIG/A-TIG welded AZ61/ZK60 magnesium alloy joints Trans. Nonferrous Met. Soc. 29 1964–72

[21] Zhou M B, Shen J, Hu D, Gao R H and Li S Z 2017 Effects of heat treatment on the activated flux TIG-welded AZS1 magnesium alloy joints Int. J. Adv. Manuf. Technol. 92 1983–90

[22] Demchenko V L and Yurchenko M V 2017 Structure and properties of the welded joints of single-type polyethylenes formed under the action of constant magnetic fields Mater. Sci. 53 186–93

[23] Wang Y, Zeng X, Ding W, Luo A A and Sachdev A K 2007 Grain refinement of AZ31 magnesium alloy by titanium and low-frequency electromagnetic casting Metall. Mater. Trans. A 38 1358–66

[24] Hu S P, Chen L P, Zhou Q, Wang J, Zhang L and Wu H 2018 Effects of compound magnetic field of pulsed and alternate field on solidified structure and mechanical properties of AZ31 magnesium alloy Spec. Cast. Nonfer. Alloy. 38 363–8

[25] Huang M Q, Zhou Q, Li J and Huang J J 2016 Effect of DC magnetic field on solidification structure and mechanical properties of AZ91D magnesium alloy Spec. Cast. Nonfer. Alloy. 6 328–3

[26] Luo T J, Li H M, Cui J, Zhao F Z, Feng X H, Li Y J and Yang Y S 2015 As-cast structure and tensile properties of AZ280 magnesium alloy DC cast with low-voltage pulsed magnetic field T Nonfer. Met. Soc. 25 1665–71

[27] Luo J, Liu Z J, Su Y H and Tian Y 2007 Influence of longitudinal direct-current magnetic field on microstructure and property of A31 magnesium alloy TIG welded joint Trans. China Weld. Inst. 28 53–6

[28] Su Y H, Jiang H W, Wu D G and Liu Z J 2012 Optimum design of magnesium alloy welding parameters with GTA welding under magnetic field Trans. China Weld. Inst. 33 85–8 (http://www.wanfangdata.com.cn/details/detail.do?_type=perio&id=hjxb201212021)

[29] Su Y H, Jiang H W, Qin H and Liu Z J 2013 Forming characteristics, microstructure and properties of magnesium alloy under TIG welding Trans. China Weld. Inst. 34 85–8 (http://www.wanfangdata.com.cn/details/detail.do?_type=perio&id=hjxb201304021)

[30] Nie X L, Liu Z J and Zhang Y 2015 Effect of additional magnetic field on microstructure and properties of aged treated AZ91 magnesium alloy welding joint Nonfer. Met. Eng. 5 17–9

[31] Su Y H, Liu Z J, Wang Y and Zhang Q G 2006 Effect of longitudinal magnetic field on microstructure and properties of welded joint of AZ31 magnesium alloy Hot Work. Technol. 35 4–6

[32] Ban C Y, Liu L, Jiang D D, Ba Q X and Cui J Z 2011 Influence of magnetic field on solidification structure of AZ80 Mg alloy T. Mater. Heat Treat. 32 13–6

[33] Zhang G Q, Ren Y L, Liu K and Su Y H 2016 Optimization of magnesium alloy TIG welding parameters under magnetic field Trans. China Weld. Inst. 37 105–9 (http://www.wanfangdata.com.cn/details/detail.do?_type=perio&id=hjxb201608023)

[34] Zhang G Y, Sui F F, Mao J Q, Liu S X and Guan S K 2009 Effect of external magnetic field on arc shape and weld quality of magnesium alloy TIG welding Hot Work. Technol. 38 113–5

[35] Su Y H, Liu Z J, Wang Y and Zhang G Q 2007 Effect of magnetic field parameters on microstructure and properties of welded joint of AZ31 magnesium alloy Trans. China Weld. Inst. 28 45–8

[36] Lin S B, Yang C L, He W B, Dai H B and Zhu Q 2005 Effects of fluxes with single component on weld depth in A-TIG welding of magnesium alloy Trans. Nonferrous Met. Soc. China 15 56–9 (https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFQ&dbname=ZTSY&FullRecordTotalNum=5&filename=ZTSY2005052120126&rptid=MjcxNTdXZTIzOCc0NjYxNjk4OTg5VWltTV86VkBkNDk0MHlHJmdjZOUVUabI4ZgsTHV4WVVMRGlzVDNDc2I3–)}
[37] Huang Y, Wu F H, He C D and Yang L 2011 Effect of activated fluxes on weld formation with TIG welding of titanium alloy J. Lanzhou Univ. Technol. 37 27–9

[38] Marya M 2002 Theoretical and experimental assessment of chloride effects in the A-TIG welding of magnesium Weld. World 46 7–21

[39] Li Y H 2018 The heat transfer and fluid flow characteristics of welding arc and weld pool for magnesium alloy under applied longitudinal magnetic field M.S. Thesis Shenyang University of Technology, Shenyang (https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD201802&filename=1018090155.nh&v=MDE3ODBGckNVUjdxZll1WnVGeS9oV3J2SVZGMjZGck94SHRESnFwRWQSV14ZVgcTHV4WVM3RGgxVDNsVHJXTE=)

[40] Liu Z J, Li Y H and Su Y H 2018 Simulation and analysis of heat transfer and fluid flow characteristics of arc plasma in longitudinal magnetic field–tungsten inert gas hybrid welding Int. J. Adv. Manuf. Tech. 98 2015–30