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Diffusion Bonding and Post-Weld Heat Treatment of Extruded AZ91 Magnesium Alloys

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The grain size of as-extruded AZ91 magnesium alloys was refined to 12.31 μm from 21.41 μm by recrystallization annealing. The vacuum diffusion welding of as-annealed AZ91 magnesium alloys was researched. The results showed that the maximum shear strength of joints reached 64.70 MPa in the situation of 10 MPa bonding pressure, 18 Pa vacuum degree, 470 °C bonding temperature and 90 min bonding time; both bonding temperature and time are the main influence factors on as-extruded AZ91 magnesium alloys diffusion welding. Then the diffusion welded specimens were annealed, and the shear strength of joints was further improved to 76.93 MPa.

Keywords: AZ91 magnesium alloys, recrystallization anneal, diffusion bonding, shear strength, post-weld heat treatment.

1. INTRODUCTION

Magnesium alloys have attracted great attention in many areas recently due to the good features such as good damping characteristics and low density [1 – 5]. However, magnesium alloys also have high coefficient of linear expansion and low melting point. It is easy to form cracks in the conventional welding techniques such as tungsten inert gas arc welding, laser beam welding and friction welding [6, 7]. Diffusion bonding is an effective method to reduce air holes, cracks and welding deformation [8, 9]. Recently, a lot of researches have been carried out on this kind of welding method [10, 11]. Researches about diffusion bonding can be used in the welding of complex and precision parts. However, the residual stress still exists in diffusion bonding. Post-weld heat treatment is an effective way to eliminate the residual stress of magnesium alloys in the welding process and improve the performance of the joints [12 – 14]. The purpose of this paper is to explore the feasibility of magnesium alloy vacuum diffusion bonding and the effectiveness of post-weld heat treatment for improving the joint strength.

2. EXPERIMENTAL DETAILS

The starting material was as-extruded AZ91 magnesium alloys of composition: Mg – 9 wt.% Al – 1 wt.% Zn. The material, that had been cut into cube with 10 mm × 10 mm × 10 mm by wire cutting machine, was refined to make the diffusion more efficient [15]. Recrystallization anneal made the average grain size of AZ91 refined to 12.31 μm from 21.41 μm at 300 °C for the duration of 30 min. The specimens were bonded at 430 °C, 450 °C, 470 °C and 490 °C for durations of 60 min, 90 min and 120 min under 10 MPa pressure in a vacuum of 18 Pa using VFB-150/200 vacuum furnace. The heating rate of the furnace was kept 20 – 30 °C/min. Post-weld heat treatment was carried out on the joints at 320 °C, 350 °C and 380 °C for durations of 1 – 5 h according to references [16]. After the post-weld heat treatment, microstructure was studied by optical microscopy. The shear test was performed in universal testing machine with loading speed of 1mm/min.

3. RESULTS AND DISCUSSION

3.1. The grain refining

The starting material had coarse grains. After the heat treatment, the grain size was refined to 12.31 μm from 21.41 μm. Their microstructures are shown in Fig. 1.

3.2. The effect of temperature

The micrographs of joints at different diffusion temperature for 90 min are shown in Fig. 2. As can be seen from Fig. 2, when temperature was 450 °C, the bonding line was obvious. Because at the lower temperature, atoms could not obtain enough energy, and the diffusion of atoms was not sufficient. As the temperature increased to 470 °C, atoms obtained more abundant energy, and the capability of atomic diffusion was gradually enhanced. The conjunct grains appeared in the weld area, and the bonding line was obviously thinner. As the temperature increased to 490 °C, grain growth was very obvious. Hence, appropriate temperature can make atoms spread quickly within the limited holding time. High bonding temperature leaded to rapid grain growth, and low bonding temperature leaded to insufficient atomic diffusion.

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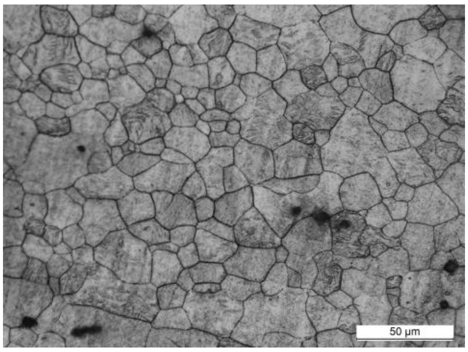

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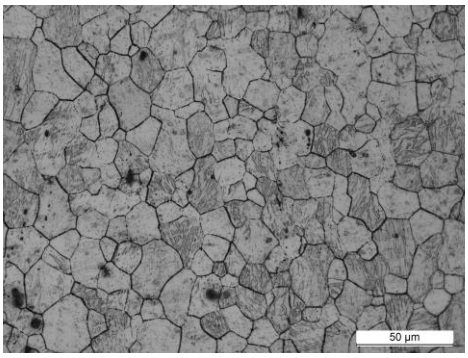

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Fig. 1. Microstructures of AZ91: a – original; b – annealing at 300 °C for 30 min

3.3. The effect of holding time

The joint micrographs in different bonding time at 470 °C are shown in Fig. 3. When the bonding time was 60 min, the bonding line was clearly visible. When the bonding time increased to 90 min, only a few conjunct grains existed in the weld area, and the bonding line was obviously thinner. Due to insufficient time, atoms didn't spread sufficiently. Grain recrystallization and growth process did not complete in the weld area. Because the atomic diffusion was fuller, more conjunct grains existed in the weld area, and weld line was significantly thinner. When the holding time increased to 120 min, atomic diffusion was fuller, the weld continued to fade. However, grains of joint continued to grow up.

According to the basic theory of diffusion bonding, increasing the bonding time can effectively improve the effect of diffusion bonding, but when the bonding time exceeded a certain value, the quality of diffusion welding joint were unable to get improved. So it is crucial to choose a suitable bonding time.

3.4. The shear strength

In order to determine the optimum parameters of diffusion bonding, joint shear strength was tested. Two welded specimens were tested in each parameter, and took the average. The standard deviation is ± 0.5 %. The results are shown in Table 1.

Welding joints did not combine effectively at 430 °C for 60 min. As temperature increased, joint strength for 60 min became large. The extension of bonding time was beneficial to diffusion and the improvement of the mechanical property of welded joints at low temperatures. When bonding time was 90 min and 120 min, with the increase of temperature, the shear strength increased firstly and then decreased.

Test results show that 470 °C is the ideal bonding temperature. In this case, diffusion coefficient, atomic activity and diffusion efficiency greatly increased compared with 450 °C. When the holding time was less than 90 min, the joint strength continued to increase. However, when the holding time was 120 min, the joint strength decreased slightly. Diffusion was still enhanced, but grain size had already become large. The negative impact of increased grain size was larger than the positive impact of diffusion, so joint quality declined slightly. Therefore, the maximum of joint shear strength was 64.70 MPa at 470°C for 90 min, and the joint shear strength is affected by the bonding temperature and time.

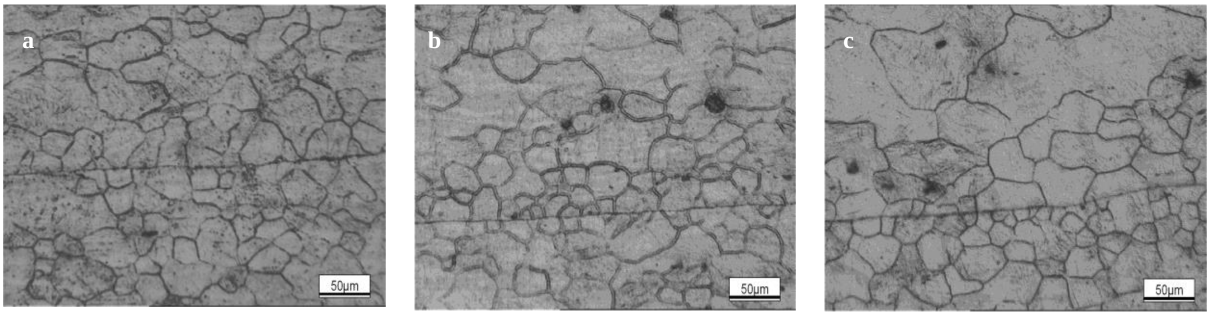


Fig. 2. Microstructures of diffusion bonding joints: a – 450 °C × 90 min; b – 470 °C × 90 min; c – 490 °C × 90 min

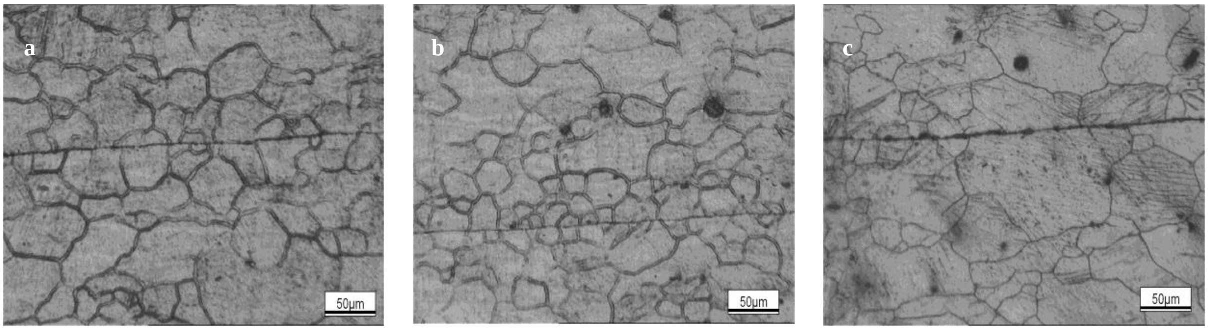


Fig. 3. Microstructures of diffusion bonding joints: a – 470 °C × 60 min; b – 470 °C × 90 min; c – 470 °C × 120 min

Table 1. Joint shear strength in different parameters

Processing parameter, °C × min	Maximum shear strength, MPa	Minimum shear strength, MPa	The average shear strength, MPa
430 × 60	-	-	-
430 × 90	-	-	-
430 × 120	12.57	8.40	10.73
450 × 60	22.78	19.35	21.56
450 × 90	29.82	25.68	28.21
450 × 120	41.66	35.92	39.79
470 × 60	53.98	48.84	52.41
470 × 90	66.90	60.85	64.70
470 × 120	59.74	51.90	56.37
490 × 60	57.08	52.33	54.72
490 × 90	62.15	57.95	60.48
490 × 120	47.92	39.93	44.78

3.5. Post-weld heat treatment

After welding at 470 °C for 90 min, the specimens were annealed, and then joint shear strength was tested. Two specimens were tested in each parameter and took the average was found. The results are shown in Table 2.

Table 2. Shear strength of as-annealed joints in different parameters

Processing parameter, °C × h	Maximum shear strength, MPa	Minimum shear strength, MPa	The average shear strength, MPa
320 × 1	65.67	62.57	64.12
320 × 2	68.75	67.31	68.03
320 × 3	72.86	70.50	71.69
320 × 4	74.38	72.74	73.57
320 × 5	76.85	74.03	75.45
350 × 1	69.78	67.86	68.82
350 × 2	72.36	70.62	71.49
350 × 3	75.94	74.10	75.02
350 × 4	78.02	75.86	76.93
350 × 5	78.34	75.96	77.15
380 × 1	70.86	66.98	68.92
380 × 2	72.11	68.94	70.53
380 × 3	71.36	67.98	69.67
380 × 4	69.80	66.74	68.28
380 × 5	66.21	65.65	65.93

As can be seen from Table 2, magnesium alloy joint strength was improved after post-weld heat treatment.

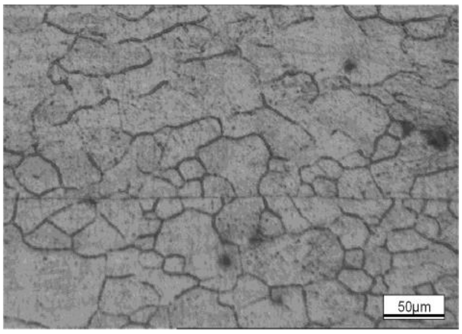
Specimens that had been treated at 350 °C for 4 h were analysed. In Fig. 4, microstructures of the joints that had been welded at 470 °C for 90 min without and after heat treatment are shown in a and b respectively. After a long time of atomic diffusion, welding line narrowed obviously.

The conjunct grains were uniform and fine. The grain size away from the weld area of specimens after the heat treatment became slightly large, but that of the weld area did not change significantly. However, compared with welded specimens without heat treatment, the grain size of weld area was relatively uniform, because microscopic plastic deformation had occurred in the weld area.

Diffusion still existed in the annealing heat treatment process. In order to improve the strength of the welded joint, it is necessary to improve the interface mobility. A better interface mobility can get at higher temperatures. When the annealing temperature was 350 °C, in the case of enough time, the weld line had almost disappeared. If the temperature continued to rise, only considering the role of diffusion, the strength would still be improved. However, parent metal grain size also continued to grow, and the performance of the parent metal was affected.

Time is a factor affecting the diffusion. When temperature was 320 °C and 350 °C, with the increase of annealing holding time, the joint strength was gradually improved. When the time reached 4 h, joint strength was no longer significantly improved at 350 °C. Due to the higher annealing temperature, holding time was much longer than the annealing time of wrought magnesium alloys, and grain growth was obvious. The performance of the parent metal would decrease to some extent. However, the weld area grain size in the process of post-weld heat treatment was still fine and more uniform, due to the plastic deformation and fine grain in the process of diffusion welding. If the holding time further increased, the grain of the weld area would further grow.

Some other researchers have also studied the vacuum diffusion bonding of AZ91 magnesium alloys, and the optimal shear strength of joints is 52.83 MPa at the same parameters of 470 °C for 90 min [17]. The results show that the joint shear strength of specimens after post-weld heat treatment is obviously improved and much greater than 52.83 MPa. It proves that post-weld heat treatment is an effective way to improve the effect of diffusion bonding.



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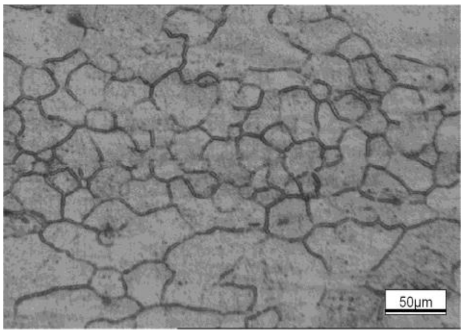

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Fig. 4. Microstructures of diffusion bonding joints: a – without post-weld heat treatment; b – after annealing at 350 °C for 4 h

4. CONCLUSIONS

1. The grain size of AZ91 magnesium alloys was refined to 12.31 µm from 21.41 µm at 300 °C for 30 min.
2. Diffusion bonding at 430 °C, 450 °C, 470 °C and 490 °C for durations of 60 min, 90 min and 120 min under 10 MPa pressure in a vacuum of 18 Pa was all realized; 470 °C and 90 min were the optimal technological parameters of vacuum diffusion bonding. The maximum shear strength reached 64.70 MPa. The quality of the welded joints was affected by the bonding temperature and time. At the higher bonding temperature, the holding time should be shortened accordingly to avoid grain growth. At the lower bonding temperature, the holding time must be appropriately extended to make diffusion full and improve the performance of joints.
3. Post-weld heat treatment was carried out on welded specimens whose mechanical property was best. The shear strength was improved to 76.93 MPa from 64.70 MPa.

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