MICROSTRUCTURES AND PROPERTIES OF AZ31 MAGNESIUM ALLOYS FORMED BY MULTI-CHANNEL PORTHOLE EXTRUSION

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Abstract:

This study investigated the effects of different extrusion temperatures and extrusion ratios on the microstructures and properties of AZ31 magnesium alloys formed by multi-channel porthole extrusion. The experimental results showed that equiaxed grains were formed during the dynamic recrystallization process and that alloy grains were refined by extrusion. Increased extrusion temperatures (from 340 ℃ to 420 ℃) resulted in larger alloy grains and decreased tensile strength of the alloy. Increased extrusion ratios (from 9 to 25) resulted in refined alloy grains and increased tensile strength of the alloy. Under conditions of low extrusion temperature and high extrusion ratio, the tensile strength and elongation of magnesium alloys were effectively improved. AZ31 magnesium alloys produced by multi-channel porthole extrusion at the extrusion temperature of 340℃ and the extrusion ratio of 25 possessed the finest average grain sizes (1.6 μm in the weld zone, 6.6 μm in the non-weld zone) and the maximum tensile strength (290 MPa) and elongation (20.8 %).

1 Introduction

Magnesium alloys are the lightest structural metals [1] and have many advantageous features [2], such as low density, high strength, and good damping [3-5]. These alloys have a broad range of applicability and have been used in fields such as aviation, aerospace, automotive, among many others [6]. Compared with as-cast magnesium alloys, wrought magnesium alloys can better meet the needs of various structural parts due to their higher strength and increased ductility [7]. The crystal structure of magnesium alloys have few slip systems, limiting the development of wrought magnesium alloys [8]. Therefore, several thermal deformation [9] methods, such as rolling, stamping [10], and extrusion, have been employed to produce magnesium alloys. Extrusion, a popular thermal deformation method [11], has a three-dimensional stress state, thus producing as-extruded metals with higher strength and better ductility than metals produced by rolling or stamping [12].

AZ31 magnesium alloys are typical Mg-Al-Zn alloys and are currently the most widely used wrought magnesium alloys [13-14]. These materials possess moderate strength, good formability, and

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strong corrosion resistance [15-16]. This experiment studied the effects of extrusion ratios and extrusion temperatures on the microstructural evolution and mechanical properties of AZ31 magnesium alloys produced by multi-channel porthole extrusion. The results of this study explain the theoretical and experimental bases for the plastic formation of AZ31 alloys.

2 Experimental methods

The chemical compositions of the raw materials for the AZ31 magnesium alloys used in this experiment are shown in Table 1. The as-cast AZ31 magnesium alloys bars were homogenized at 400 ℃ for 15 h in a furnace. After homogenization, the diameter of the as-cast bars was machined to ф 30 mm. All homogenized bars were extruded. The extrusion rate was 0.8 mm/s for all bars, and the extrusion ratios were 9, 14, or 25. The different extrusion conditions for the as-extruded alloys are shown in Table 2.

Table 1. Chemical composition of AZ31 magnesium alloy (mass fraction %)

Al	Mn	Zn	Ca	Ni	Si	Mg
2.78	0.19	0.87	0.05	0.005	0.1	Bal.

A GX51 inverted microscope was used to analyze the microstructures of the alloys. The etchant for the extruded samples contained 5 g picric acid, 10 ml glacial acetic acid, 10 ml distilled water, and 80 ml anhydrous ethanol. Image-pro plus software was used to determine the average grain sizes. The tensile properties of the samples at room temperature were evaluated on an Instron 1186 electronic universal tensile tester with a tensile speed of 0.5 mm/min. The tensile fracture morphology of the samples was scanned by a JSM-6360LV scanning electron microscope (SEM).

A schematic diagram of the multi-channel porthole extrusion device is shown in Fig. 1. The multi-channel porthole mould had three channels, each with a diameter of 10 mm. The inlet diameter of the single channel concave mould was 30 mm and the extrusion diameter was 10 mm. The diameter of the extrusion tube was 30 mm. The magnesium alloy bars were divided into three bars when they were extruded through the multi-channel porthole mould. After passing through the three channels, the three bars were merged and passed through a single channel concave mould. Thus, the three bars were welded together to form a single bar whose microstructural cross-section exhibited weld zones. The cross-section microstructures of these AZ31 magnesium alloys are shown in Fig. 2.

Table. Different extrusion conditions of AZ31 magnesium alloys formed by multi-channel porthole extrusion (No. 1~No. 9)

Alloy number	1	2	3	4	5	6	7	8	9
Extrusion ratio	25	25	25	14	14	14	9	9	9
Extrusion temperature (°C)	340	380	420	340	380	420	340	380	420

The microstructures of the as-extruded alloys were very uniform and fine. Due to the increase in deformation energy storage in the weld zones, the grains in the weld zones were finer and more uniform than that in the non-weld zones.

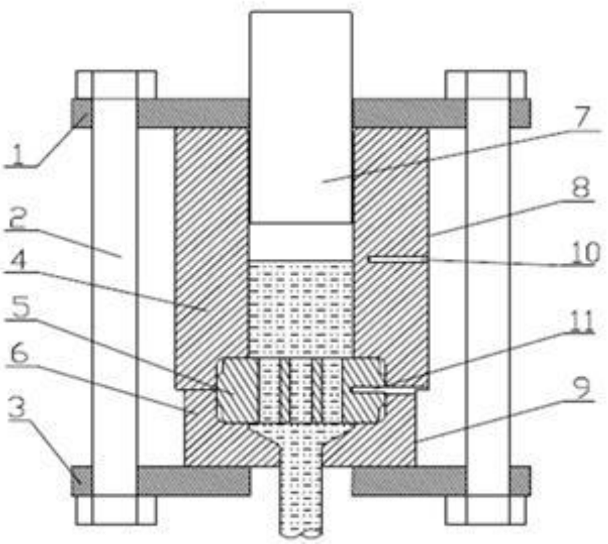


Figure 1. Schematic diagram of multi-channel porthole extrusion device: (1) above platen; (2) below platen; (3) connecting bolt; (4) extrusion tube; (5) multi-channel porthole mould; (6) single channel concave mould; (7) extrusion lever; (8) heating body of extrusion tube; (9) heating body of single channel concave mould; (10) thermocouple of extrusion tube；(11) thermocouple of multi-channel porthole mould.

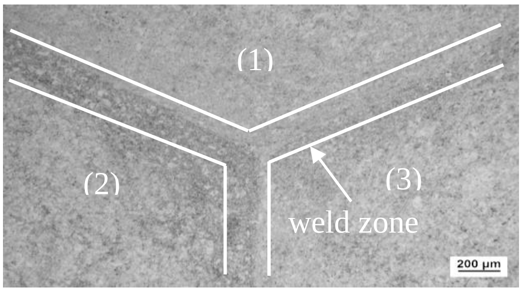
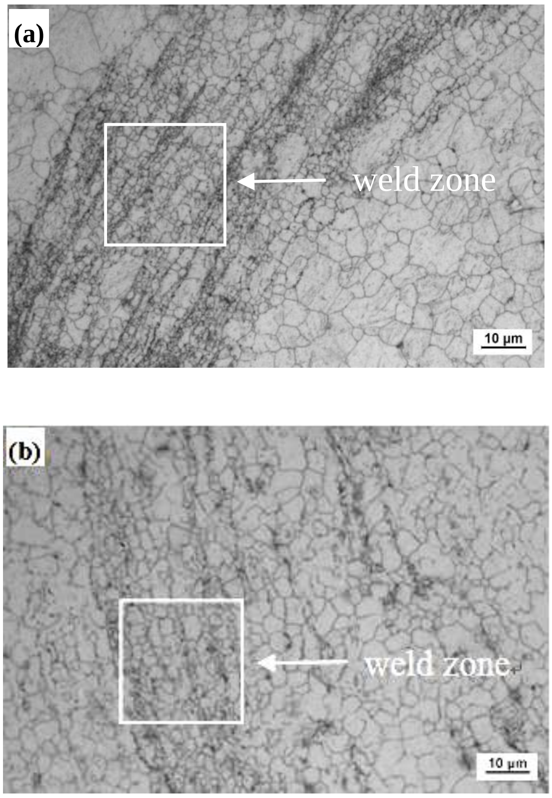


Figure 2. Cross-section microstructures of AZ31 alloys formed by multi-channel porthole extrusion.

3 Results and discussion

3.1 Effect of extrusion ratios on the microstructures of the weld zones

We first studied the effect of different extrusion ratios on the microstructures of the weld zones of AZ31 alloys. Fig. 3 (a-c) shows the microstructures of the as-extruded AZ31 alloys formed at extrusion ratios of 25, 14, and 9, respectively, under an extrusion temperature of 340 ℃. In Fig. 3 (a-c), the regions enclosed by the white border are sections of the weld zone microstructures.



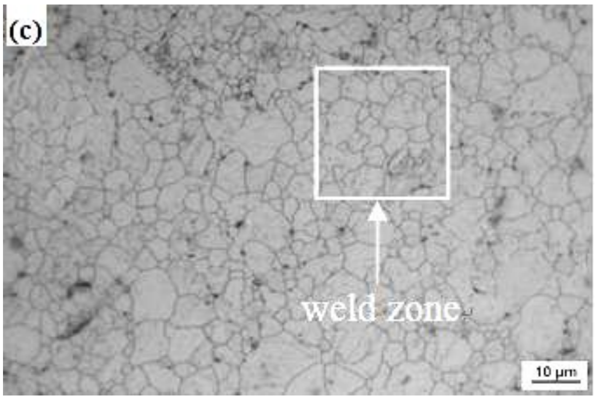


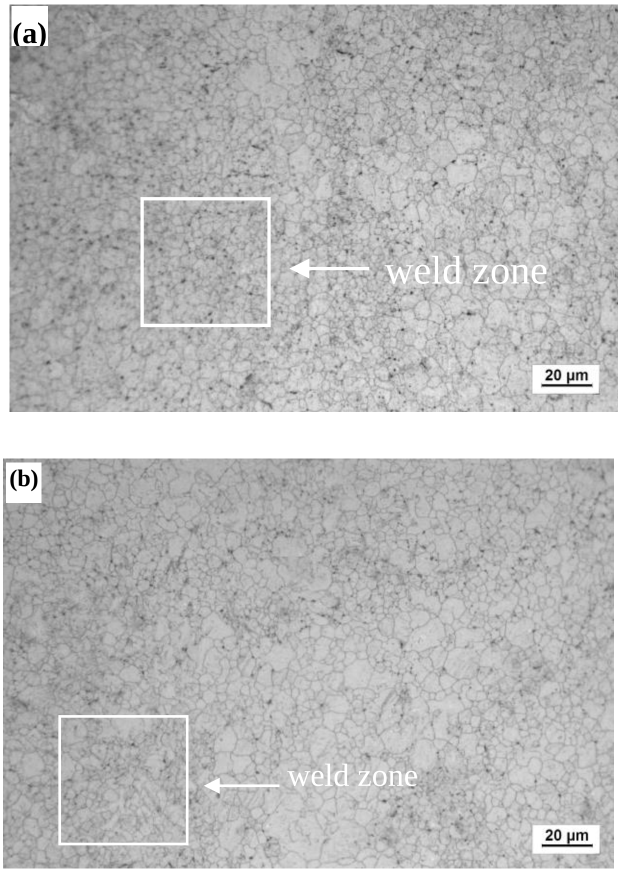
Figure 3. Microstructures of the weld zones in the AZ31 alloys formed by multi-channel porthole extrusion at different extrusion ratios, and the extrusion temperatures are 340 ℃: (a) extrusion ratio of 25; (b) extrusion ratio of 14; (c) extrusion ratio of 9.

The average grain sizes of the enclosed weld zones were 1.6, 2.5, and 3.6 μm for extrusion ratios of 25, 14, and 9, respectively. The average grain sizes were, therefore, gradually increased by decreasing extrusion ratios. When the extrusion ratio was 25, the grains of the welded zones were the most uniform and fine. Studies have shown that the stacking fault energy of magnesium alloys is very low (approximately 78 J/m^2); thus, dynamic recrystallization of the alloys is likely to occur. The deformation process results in the refinement of the grains of the alloys. Fig. 3 (a-c) shows that a large amount of equiaxed grains are formed during the process of dynamic recrystallization in the alloys. By increasing extrusion ratios, the degree of deformation of the alloys are increased, causing an increase in the deformation energy storage of the weld zones and an increase in the extent of dynamic recrystallization and grain refinement of the weld zones. Thus, at a constant extrusion temperature, higher extrusion ratios (within a certain range) are more beneficial for dynamic recrystallization in the weld zones of the alloy.

3.2 Effect of extrusion temperatures on the microstructures of the weld zones

The effect of extrusion temperatures on the microstructures of the weld zones of AZ31 alloys was investigated. The AZ31 alloys were extruded at an extrusion ratio of 14 with extrusion temperatures of

340, 380, and 420 ℃. In Fig. 4 (a-c), the regions enclosed by the white border are sections of the weld zones. The average grain sizes of the weld zones enclosed by the white border were 2.5, 3.1, and 4 μm for extrusion temperatures of 340, 380, and 420 ℃, respectively. When the extrusion temperature was 340 ℃, the grains of the weld zones were a little finer and more uniform. Dynamic recrystallization is an effective mechanism of grain refinement and is used to control the deformation of magnesium alloys and improve the plastic deformation and mechanical properties of the alloys. Because the extrusion temperature was higher than the dynamic recrystallization temperature, as seen in Fig. 4 (a-c), dynamic recrystallization occurred for the alloys formed at the three different extrusion temperatures, resulting in the formation of extensive equiaxed grains. However, higher extrusion temperatures result in higher extrusion forces, lower accumulated strain energy of the extruded alloys, and coarser grain sizes. Thus, the extrusion temperatures should be reasonable and not excessively high.



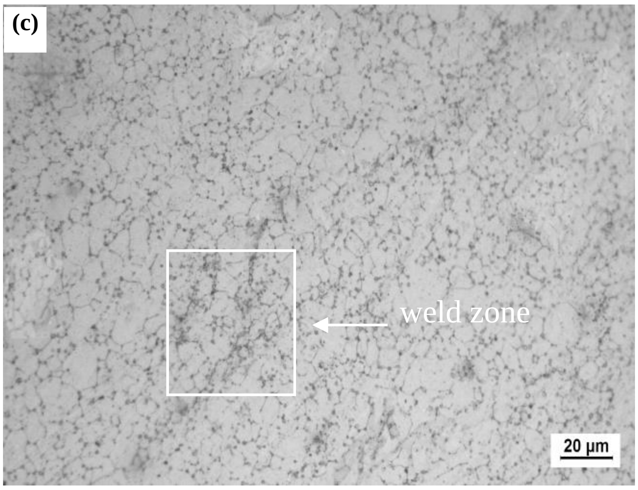


Figure 4. Microstructures of the weld zones in the AZ31 alloys formed by multi-channel porthole extrusion at different extrusion temperatures, and the extrusion ratios are 14: (a) extrusion temperature of 340 ℃; (b) extrusion temperature of 380 ℃; (c) extrusion temperature of 420 ℃.

3.3 Effect of extrusion ratios on the microstructures of the non-weld zones

Fig. 5 (a-c) shows the microstructures of the extruded alloys formed at an extrusion temperature of 340 ℃ with extrusion ratios of 25, 14, and 9, respectively. The average grain sizes were 6.6, 9.2, and 14 μm, at extrusion ratios of 25, 14, and 9, respectively. The grain sizes of the non-weld zones gradually increased with decreased extrusion ratios. When the extrusion ratio was 25, the grain of the non-weld zones were the most uniform and fine. Thus, similar to the weld zones, increased extrusion ratios decreased the average grain sizes of the non-weld zones. At a constant extrusion temperature, increased extrusion ratios result in larger extrusion forces, greater degrees of grain crushing and dynamic recrystallization, and finer grain sizes. In addition, Fig. 5 (a-c) shows that due to the high extrusion temperature, the dynamic recrystallization nucleation rate increased and caused some grains to grow abnormally coarse compared with other grains.

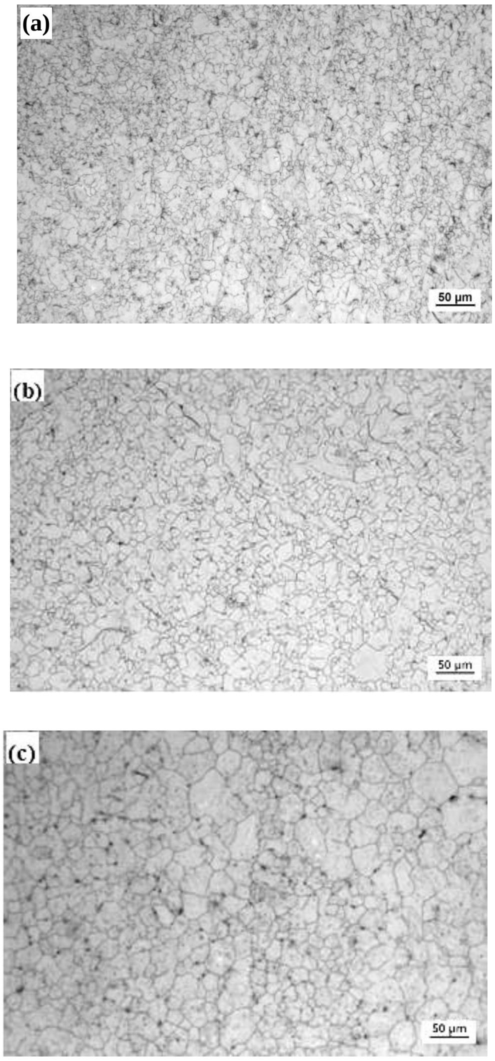


Figure 5. Microstructures of the non-weld zones in the AZ31 alloys formed by multi-channel porthole extrusion at different extrusion ratios, and the extrusion temperatures are 340 ℃: (a) extrusion ratio of 25; (b) extrusion ratio of 14; (c) extrusion ratio of 9.

3.4 Effect of extrusion temperatures on the microstructures of the non-weld zones

Fig. 6 (a-c) shows the microstructures of AZ31 alloys extruded with an extrusion ratio of 14 at extrusion temperatures of 340, 380, and 420 ℃, respectively. The average grain sizes were 8.3, 12.1, and 15 μm for alloys formed at 340, 380, and 420 ℃, respectively. The grain sizes of the non-weld zones gradually increased with decreased extrusion ratios. When the extrusion temperature was 340 ℃, the grains of the non-weld zones were the most uniform and fine. Thus, similar to the weld zones, increased extrusion temperatures result in decreased average grain sizes of the non-weld zones. At a constant extrusion ratio, increased extrusion temperatures result in increased atomic diffusion rates, increased dislocation slip, and increased dynamic recrystallization nucleation rate. Therefore, increased extrusion temperatures can increase the likelihood that dynamic recrystallization will occur and can also enhance grain boundary migration, resulting in the formation of coarser grains. Secondary recrystallization occurs in some of the grains and leads to coarser grains and deteriorated alloy properties.

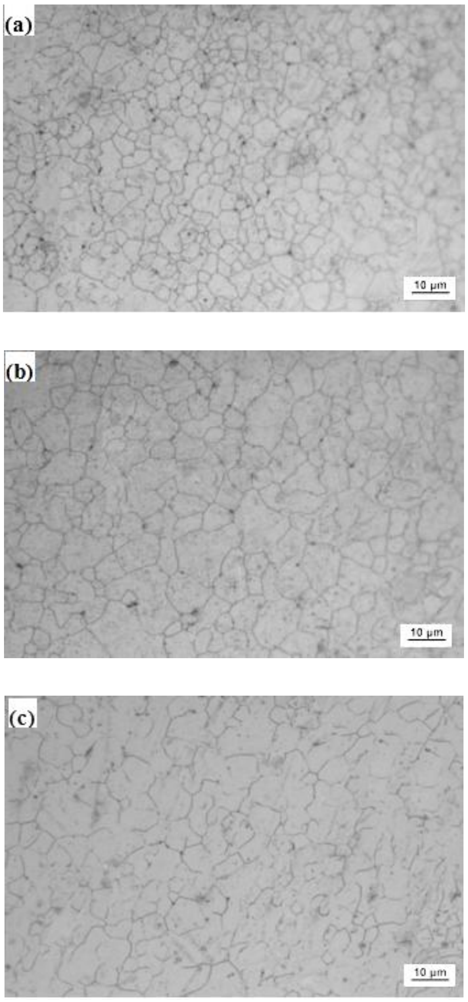


Figure 6. Microstructures of the non-weld zones of AZ31 alloys formed by multi-channel porthole extrusion at different extrusion temperatures, and the extrusion ratios are 14: (a) extrusion temperature of 340 ℃; (b) extrusion temperature of 380; (c) extrusion temperature of 420 ℃.

Fig. 7 shows the microstructures of as-cast AZ31 magnesium alloy. As can be seen from Fig. 7, the matrix of as-cast AZ31 alloy is α-Mg, the dendritic crystal is coarse and the average grain sizes (large than 100 μm) of as-cast AZ31 alloy are much larger than the average grain sizes of AZ31 alloys formed by multi-channel porthole extrusion. In addition, a small amount of second phases ($\beta\text{-Mg}_{17}\text{A1}_{12}$), which are bone shaped phase and distribute in interdendritic and grain boundaries. Due to the segregation in the grain boundaries and the second phases ($\beta\text{-Mg}_{17}\text{A1}_{12}$) between the dendrite, the thermoplastic of the as-cast AZ31 alloy is bad. So, the as-cast AZ31 alloys should be homogenized before extrusion.

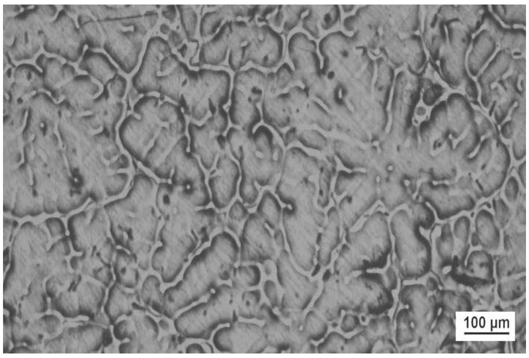


Figure 7. Microstructure of as-cast AZ31 magnesium alloy.

3.5 Effect of extrusion parameters on the mechanical properties of the as-extruded AZ31 alloys

Improvement of the mechanical properties of the as-extruded magnesium alloys can be mainly attributed to two factors. One factor is that hot extrusion can shrink cavities, tiny holes, and other weld defects, thus improving the density and continuity of the alloys. The second factor is that the process of dynamic recrystallization causes the original coarse grain to form equiaxed grain and significantly reduces the average grain sizes [17]. The Hall-Petch formula characterizes the relationship between grain sizes and the mechanical properties of the alloys. Finer grain sizes yields improved mechanical properties of the alloys [18]. The Hall-Petch constant term for magnesium alloys is larger than that for other non-ferrous alloys; therefore, magnesium alloys have a more pronounced effect on grain refinement. Alloys with finer grain are less likely to form tensile stress cracks, and the cracks do not easily expand; thus, fine-grained materials have improved mechanical properties compared to coarse-grained materials.

Fig. 8 and 9 show the tensile strength and elongation of nine AZ31 alloys produced by multi-channel porthole extrusion. Fig. 8 and Fig. 9 show that when the extrusion ratio is unchanged, an increased extrusion temperature results in a decrease in the tensile strength and elongation of the alloy, whereas when the extrusion temperature is unchanged, an increased extrusion ratio results in an increase in the tensile strength and elongation of the alloy. Among the nine alloys, we found that an extrusion temperature of 340 °C and an extrusion ratio of 25 produced an AZ31 alloy with the maximum tensile strength (290 MPa) and elongation (20.8 %). When the extrusion temperature is unchanged, increased extrusion ratios produced finer alloy grains, resulting in higher tensile strength and elongation of the alloys. When the extrusion ratio is unchanged, higher extrusion temperatures result in coarser alloy grains and decreased tensile strength and elongation of the alloys. Therefore, lower extrusion temperatures and higher extrusion ratios produce as-extruded alloys with higher tensile strength. Reasonable extrusion ratios and extrusion temperatures can effectively improve the tensile strength and elongation of AZ31 magnesium alloys, thereby improving the overall mechanical properties of the alloys. The tensile strength and elongation of as-cast AZ31 magnesium alloy are 139 MPa and 6.5 %, respectively. The minimum tensile strength and elongation of AZ31 alloy formed by multi-channel porthole extrusion in this experiment are 245 MPa and 12.7 %, respectively. Obviously, the comprehensive mechanical properties of AZ31 magnesium alloy are improved significantly by multi-channel porthole extrusion.

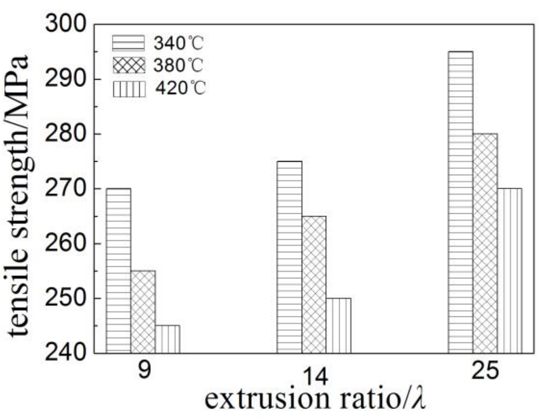


Figure 8. Tensile strength of the AZ31 alloys formed by multi-channel porthole extrusion.

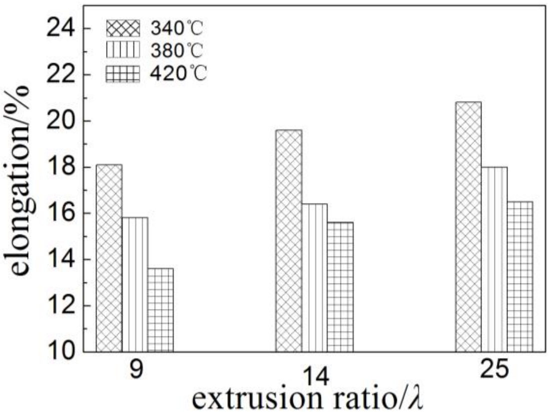


Figure 9. Elongation of the AZ31 alloys formed by multi-channel porthole extrusion.

3.6 Fracture morphology analysis of the AZ31 alloys

Analysis of the microstructures of the nine AZ31 alloys produced by multi-channel porthole extrusion showed that the alloy produced at an extrusion temperature of 340 °C and an extrusion ratio of 25 possessed the highest tensile strength. Fig. 10 (a) shows a SEM image of the fracture morphology of this alloy (extrusion temperature of 340 °C and extrusion ratio of 25). Fig. 10 (b) shows the fracture morphology of the weld zone shown in Fig. 10 (a). Fig. 10 (c) shows the fracture morphology of the non-weld zone shown in Fig. 10 (a). Fig. 10 (b) and Fig. 10 (c) reveal the presence of many tiny dimples and torn edges, which suggest that the plasticity and tensile strength of the alloy were greatly enhanced. In addition, the cleavage-river patterns and the tiny dimples imply that the mode of tensile fracture of the as-extruded alloy was ductile fracture.

Fig. 11 shows a SEM image of the fracture morphology of as-cast AZ31 magnesium alloy. Fig. 11 (a) shows the whole fracture morphology of as-cast AZ31 alloy. As is seen in Fig. 11 (a), there exist casting defects, such as slag， inclusion and gas cavity in the as-cast AZ31 alloy specimen，these casting defects are hard to be avoided in the casting process and can seriously reduce the comprehensive mechanical properties of the as-cast alloys. Fig. 11 (b) shows enlarged fracture morphology of the central zone in the alloy, there are obvious river patterns, cleavage planes, cleavage steps and torn edges due to large plastic deformation in the process of fracture process, and these characteristics indicate that the fracture mode of as-cast AZ31 alloy is quasi cleavage fracture.

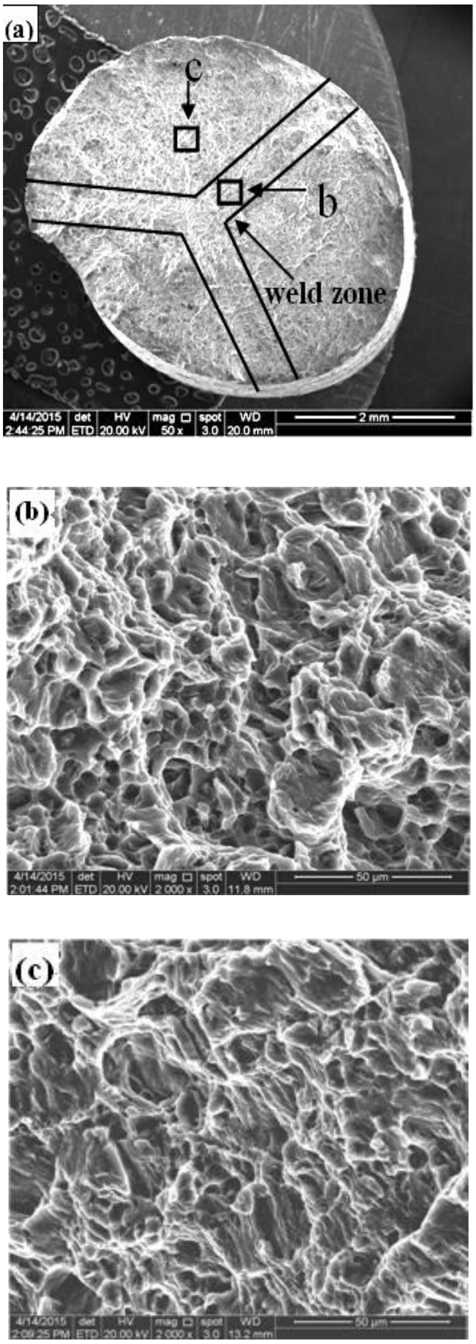


Figure 10. Fracture morphology of the AZ31 alloys formed by multi-channel porthole extrusion: (a) the whole fracture morphology of the alloy at an extrusion temperature of 340 ℃ and an extrusion ratio of 25, (b) the fracture morphology of the weld zones (c) the fracture morphology of the non-weld zones.

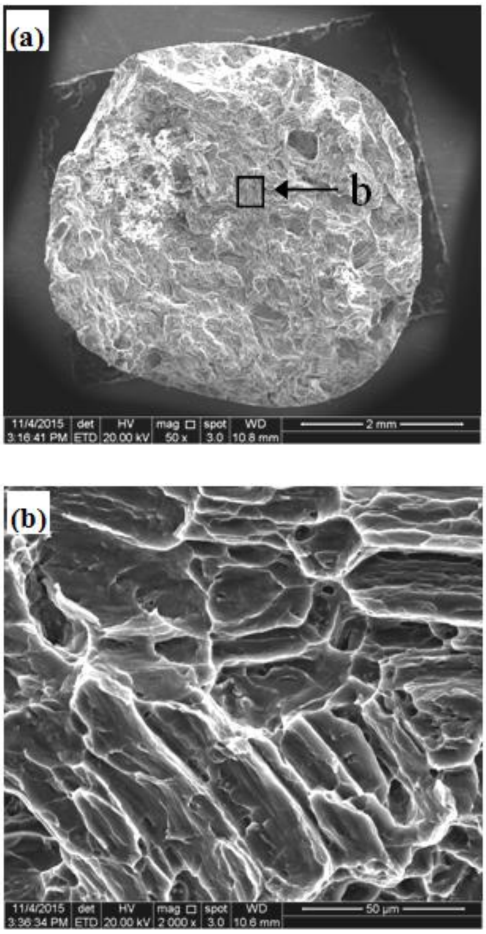


Figure 11. Fracture morphology of as-cast AZ31 alloy: (a) the whole fracture morphology of as-cast AZ31 alloy, (b) enlarged fracture morphology of the central zone.

4 Conclusions

1) In this experiment, the strengthening mechanism of the as-extruded alloys is grain refinement mechanism. When extrusion temperatures are from 340 ℃ to 420 ℃ and extrusion ratios are from 6.25 to 25, if the extrusion temperature was unchanged, higher extrusion ratios will result in AZ31 magnesium alloys with finer grain and higher tensile strength and elongation, if the extrusion ratio was constant, higher extrusion temperatures resulted in alloys with coarser grain and decreased tensile strength and elongation.
2) When extrusion temperature is 340 ℃ and extrusion ratio is 25, the AZ31 alloys formed by multi-channel porthole extrusion have the finest grains, the average grain sizes of the weld zone and non-weld zone of AZ31 alloys are only 1.1 μm and 5.1 μm, respectively; under the condition， the tensile strength and elongation of AZ31 alloys formed by multi-channel porthole extrusion reached the maximum, 290 MPa and 20.8 %, respectively.
(3) The innovation point in my research work is the design of a new extrusion device, namely the multi-channel portable extrusion device. As we know, the grains of forward extruded alloy core are coarse and not uniform, which seriously affect the mechanical properties of the alloys. Multi-channel portable extrusion device is designed on the basis of the forward extrusion device. A multi-channel porthole mould is added to the device, and it increases the deformation of the alloys and promotes the dynamic recrystallization of the alloys core greatly, making the microstructures of the alloys a little finer and more uniform. Compared with other portable extrusion devices, the advantages of the multi-channel portable extrusion devices in this experiment are simple operation and low cost. It needs only to change either the multi-channel porthole mould or the single channel concave mould to get different sizes of specimen, and the microstructures and the comprehensive mechanical properties certainly ought to be good.

Acknowledgements

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