Rare Metal Materials and Engineering
Volume 47, Issue 6, June 2018
Online English edition of the Chinese language journal

Cite this article as: Rare Metal Materials and Engineering, 2018, 47(6): 1655-1661.

ARTICLE

Influence of Hot Extrusion Process on Microstructure and Mechanical Properties of Mg-Zn-Y-Zr Magnesium Alloy

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Abstract: The extrusion experiments at different extrusion parameters were performed; the effects of different extrusion parameters on the microstructure and mechanical property of Mg-4.8Zn-1.2Y-0.4Zr magnesium alloy were described, based on the experimental results and analysis. The result shows that dynamic recrystallization is observed after the hot extrusion process, the alloy grain is refined compared with as-cast alloy. The phase of the extruded alloy is W-phase; there are great differences in morphology and distribution between alloys with different extrusion parameters. The microstructure and mechanical properties of magnesium alloy are affected by extrusion temperature and extrusion ratio in the hot extrusion process. When the extrusion ratio is the same, the number of recrystallization grains increases with the increasing of temperature; meanwhile recrystallization grains also have a tendency to grow up. When the extrusion temperature is 300 °C, the comprehensive mechanics performance of the alloy is the most excellent. The influence of extrusion ratio on the plasticity of the alloy is obvious; when the extrusion ratio is 25, the elongation of the alloy increases significantly.

Key words: hot extrusion; magnesium alloy; microstructure and mechanical property

Magnesium alloy is the lightest metal among common metals, and it has an important role in the development of ligh weight of vehicle[1-6]. Magnesium reserve is high, and the price is cheap[7]. It can be recycled without reducing the performance[8,9]. Magnesium alloy has good dimensional stability and die casting formability, which can be used in the manufacture of many kinds of die casting parts. Currently, the existing magnesium alloy products are mainly obtained through a die casting process. However, there are several defects in the casting process, such as cold shut, shrinkage cavity, porosity. The rate of finished products is low, which reduces the economy of the process.

Wrought magnesium alloy products are produced by extrusion, forging, rolling, or other processes, which have higher strength, better ductility and more varied mechanical properties than cast alloy, and can meet the needs of more structural parts[10-13]. Wrought magnesium alloy has excellent property which cannot be replaced by cast alloy. There is a growing need for the high strength Mg wrought alloys[14-17]. But the plastic deformation of magnesium alloy is difficult because of its close-packed hexagonal structure. Hot extrusion is a kind of common forming process which can effectively enhance the performance of alloy. In the wrought magnesium alloy, the Mg-Zn-Zr-Y alloy has higher strength, better plasticity, heat treatment property and corrosion resistance[18,19]. In this paper, the effects of hot extrusion process on microstructure and mechanical properties of Mg-4.8Zn-1.2Y- 0.4Zr alloy were investigated. It is hoped to find a suitable hot extrusion process to effectively improve the mechanical property of Mg-Zn-Zr-Y alloy.

1 Experiment

The composition of Mg-Zn-Zr-Y alloy used in the experiment is shown in Table 1. There are 4 kinds of extrusion temperatures in the experiment (300, 350, 400, 450 °C) and 3 kinds of extrusion ratios (8, 12, 25). Experimental parameters is shown in Table 2.

The as-cast alloy which had been processed by homo-

Received date: July 25, 2017
Foundation item: International Science and Technology Cooperation Project

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genizing treatment was turned into Φ60 mm×30 mm.

Preheating: The blanks were placed in a resistance furnace after the furnace had been heated to the preset temperature. The temperature was preserved for 20 min or so, while the furnace was heated to 300 °C.

Extrusion: firstly graphite was coated on the preheating mold and the preheating blank was placed into the mold. Due to the small height of sample, the graphite pad was placed. The extruded blank was timely straightened.

After the extrusion had been completed, the metallographic samples were cut from the same part of the extruded bar. The microstructure was observed by an optical microscope, and the phase composition analysis was carried out by X-ray diffraction (XRD). The tensile test specimens were cut from the bar, and the tensile property at room temperature was tested by an electronic universal testing machine.

2 Results and Discussion

Tensile property tests at ambient temperature were carried out to test the mechanical property of alloys at different extrusion parameters. The mechanical properties of extruded alloy are shown in the Table 3. The mechanical properties of the as-cast alloy have been tested (tensile strength is 231 MPa, yield strength is 105.1 MPa and elongation is 13.67%).

In order to study the influence of extrusion temperature and extrusion ratio on the mechanical properties of the alloy, the relationship between the properties of the alloy with different extrusion ratios and the extrusion temperatures is established (Fig.1).

As shown in Fig.1a, the influence of extrusion temperature at different extrusion ratios on the tensile strength of the alloy is consistent, namely the alloy extruded at 300 °C has the highest tensile strength and the strength decreases afterwards. When the extrusion temperature is 400 °C, the strength exhibits the second peak. When the temperature is 350 or 450 °C, the strength of the alloy is lower.

Generally, the plasticity of the alloy increases with the increase of the extrusion temperature, which is mainly due to the differences of the microstructure and the morphology and distribution of the second phase.

On the whole, when the extrusion temperature is 300 °C, the alloy has the best performance. When the extrusion ratio is 25, the plasticity of the alloy is the best.

The comprehensive mechanical properties of the alloy are not only related to the grain size and uniformity, but also to the number, shape and distribution of the second phase[20,21]. After extrusion deformation, there occur the dislocation pile-up, recrystallization grain refinement, second phase dispersively and granularly distributed in the alloy. All these have different effects on the mechanical properties of the alloy. In this paper, the effects of extrusion temperature and extrusion ratio on the microstructure and properties of the alloy are analyzed in two aspects.

2.1 Influence of extrusion ratio on the microstructure and mechanical properties of magnesium alloys

During the process of hot extrusion, not only tissue deformation, but also dynamic recrystallization in the alloy happens. The dynamic recrystallization in the alloy is mainly affected by the stacking fault energy of the material and the lattice diffusion rate. Stacking fault energy is generally easier to cause dynamic recovery, and stacking fault energy of the material usually causes dynamic recrystallization. The stacking fault energy of magnesium is only 78 mJ·m^{-2} which is easier to cause dynamic recrystallization. After the extrusion deformation, under a certain extrusion stress and extrusion temperature, the deformation structure forms subgrain structure along the grain boundary firstly[22,23], and then the structure turns to high-size and high-angle subgrain through subgrain combination mechanism. Followed by the grain boundary migration, further consolidation and rotation of subgrain happens, and ultimately forms small large angle grains. The different deformation temperatures and deformation degrees provide different driving forces for dynamic recrystallization, and the recrystallization degree of the alloy is also very different.

Table 1 Composition of cast alloy（wt%）

Zn	Zr	Y	Mg
4.761	0.367	1.160	Bal.

Table 2 Combination of the extrusion parameters

Code	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#	11#	12#
λ	8	8	8	8	12	12	12	12	25	25	25	25
T/℃	300	350	400	450	300	350	400	450	300	350	400	450

Note: λ-extrusion ratio; T-extrusion temperature

Table 3 Mechanical properties of extruded alloy at ambient temperatures

Code	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#	11#	12#
δ/%	11.2	12.4	13.9	14.4	10.7	11.5	17.4	17.0	16.9	13.9	16.2	22.4
σ_s/MPa	249	226	248	218	249	242	247	221	234	230	241	228
σ_b/MPa	317	290	311	305	315	304	309	297	311	303	312	304

Note: δ-elongation; σ_s-yield strength; σ_b-tensile strength

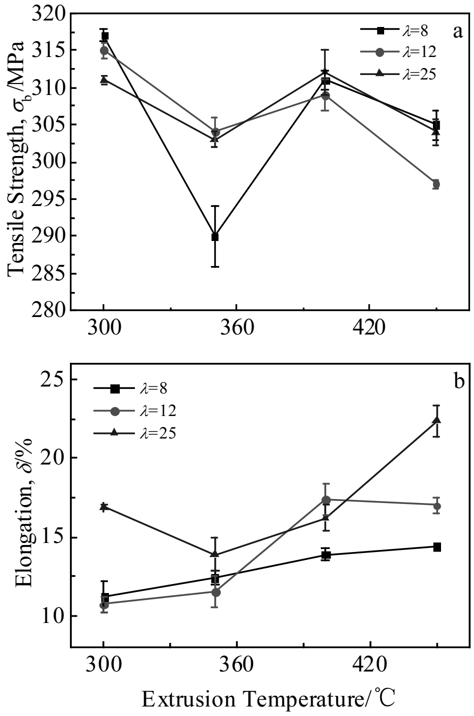


Fig.1 Mechanical properties of the alloys with different extrusion parameters: (a) tensile strength and (b) elongation

Fig.2 is the microstructure of the different extrusion ratios at 300 °C. When λ=8, since the deformation is small, the deformation driving force is also small, a large number of coarse and elongated grains can be observed in the alloy metallographic structure, and the fine crystalline grains are less. It can be seen from the cross-section of the alloy and scanning electron microscope (SEM) images that part of second phases are granularly distributed in the grain, and some fish-bone-shaped phases concentrate in the triangular grain boundary. These two kinds of phases are in favor of improving the strength of the alloy; so although the grain is relatively coarse, the strength of the alloy is higher. In addition, there are a small number of second phases, which are long-rod-shaped and distributed along the grain boundary, and not conducive to the plasticity of the alloy.

When λ=12, with the deformation increasing, the compressive zones in alloy appear to be more slender, the coarse and elongated grains become smaller and thinner. At the same time, due to the increase of deformation, the recrystallization driving force of the alloy is enhanced, and the fine grains obviously increase. But the fine grains and the original coarse grains are mixed together, the mixed crystal phenomenon occurs, which is harmful to the plasticity of the alloy. Compared with λ=8, the amount of second phase decreases and the crystal boundary becomes thinner. Through SEM image, the precipitated phase in the alloy mainly presents coarse irregular herringbone shape and it is of uneven distribution. It will have adverse effects on the mechanical properties of the alloy. But the precipitated second phase decreases, and the solid solution in alloy increases, which can increase solid solution strengthening effect, enhance the resistance of dislocation movement and improve the alloy strength. Therefore, the strength of the alloy is good and the plasticity is very poor.

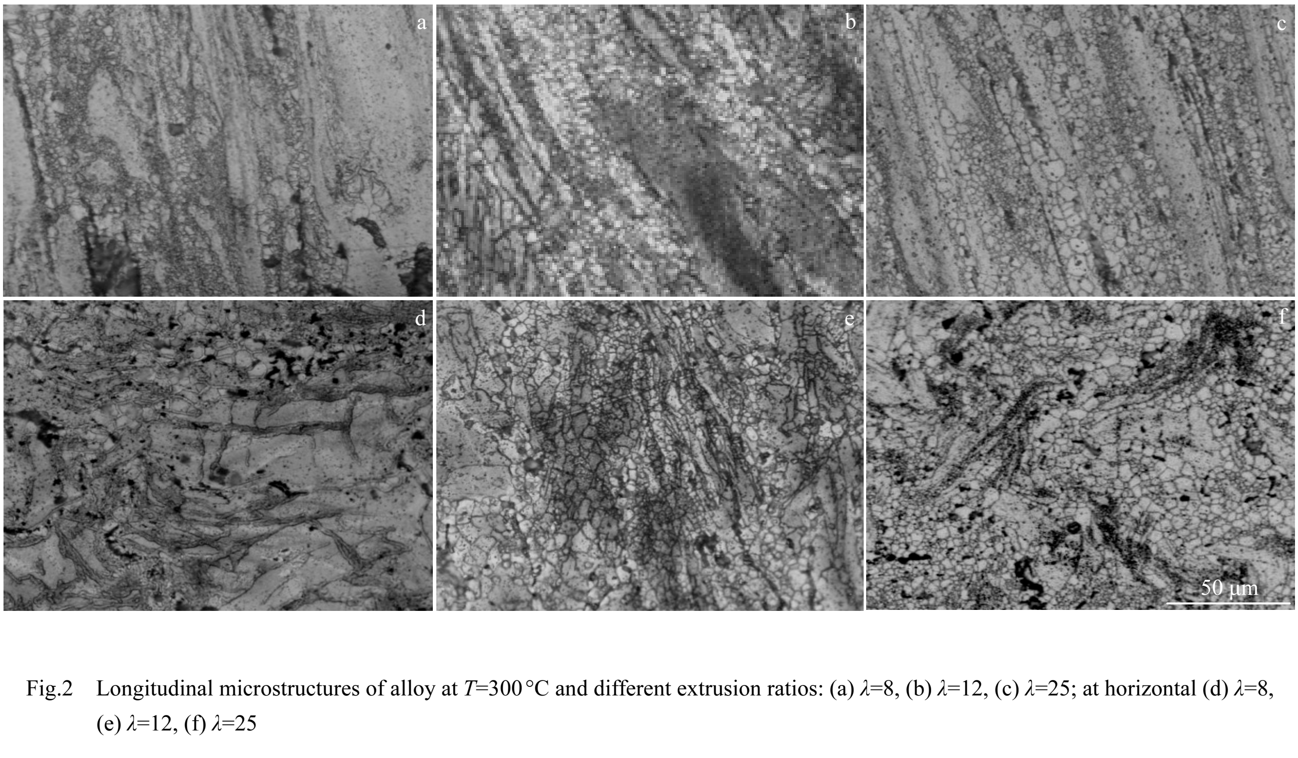


Fig.2 Longitudinal microstructures of alloy at T=300 °C and different extrusion ratios: (a) λ=8, (b) λ=12, (c) λ=25; at horizontal (d) λ=8, (e) λ=12, (f) λ=25

When λ increases to 25, the recrystallization of the alloy has been provided a great power by the large extrusion deformation, so the recrystallization is obvious. There are only a small amount of coarse compressive zones in the microstructure; the grain size is small, which can improve the plasticity of the alloy. The precipitated phases are fragmented sufficiently and the quantity of precipitated phase increases much more. The second phases in the grain boundaries are mostly thin rods and a small of phases are in fishbone shape. The second phases in the grain are uniform granular, which is beneficial to improving the strength of the alloy.

Conclusively, when the extrusion ratio is 25, the plasticity of the alloy is the best. The increase of plasticity mainly due to the tiny grains and tiny distributed precipitated phases. The thin precipitations distributed along the grain boundary weaken the pinning effect of grain boundary, which effectively increases the plasticity of the alloy.

The influence of different extrusion ratios on the type, shape and distribution of precipitated phase was analyzed through Fig3 , Fig4 and Fig.5. As shown in Fig.3, with the increase of the extrusion ratio, the quantity, shape and distribution of the precipitated phases change obviously. The precipitated phases are fishbone-, rod-shaped or granulated. According to the back scattering principle, the brightness indicates different phases. The zones of EDS analysis for alloys at different extrusion ratios are shown in Fig.4a, 4b and 4c. Dark parts are Mg matrix and the bright parts are precipitated phases. There are three kinds of precipitated phases at 300 °C of extrusion temperature: Mg-Zn-Y ternary phase (zone A), Mg-Zn phase (zone B) and Mg-Zn-Zr phase (zone C). The EDS results of three phases are shown in Fig.4a_1, 4b_1 and 4c_1. Considering the accuracy of instrument

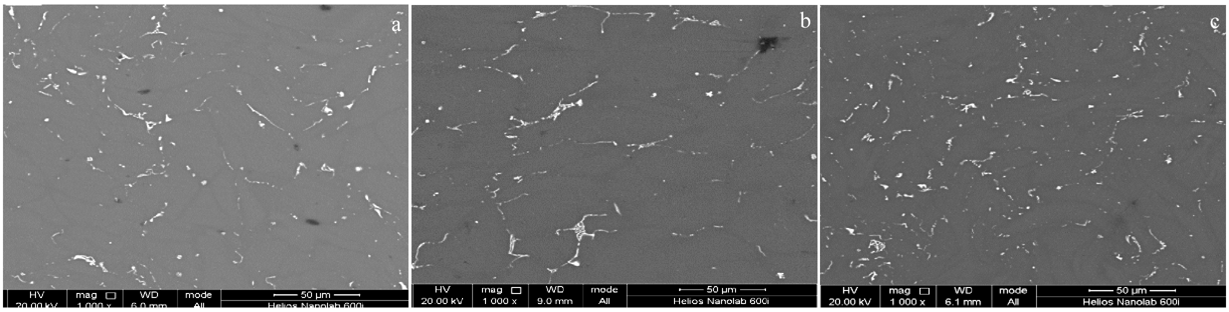
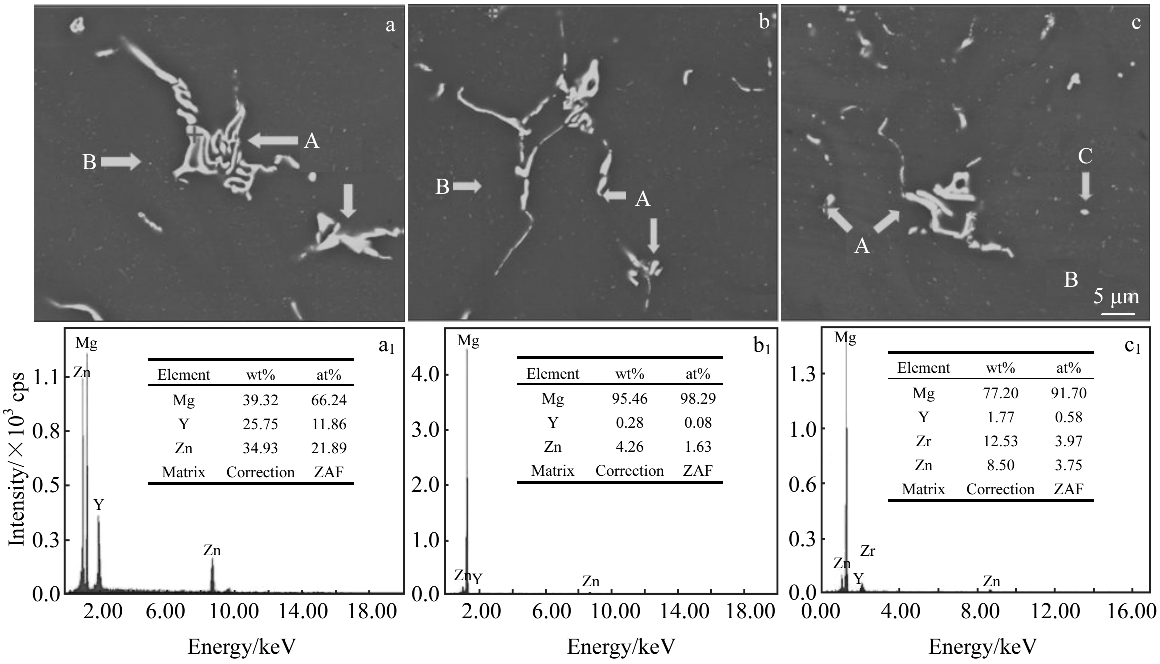


Fig.3 SEM images of alloy at T=300 °C and different extrusion ratios: (a) λ=8, (b) λ=12, and (c) λ=25



Element	wt%	at%
Mg	39.32	66.24
Y	25.75	11.86
Zn	34.93	21.89
Matrix	Correction	ZAF

Element	wt%	at%
Mg	95.46	98.29
Y	0.28	0.08
Zn	4.26	1.63
Matrix	Correction	ZAF

Element	wt%	at%
Mg	77.20	91.70
Y	1.77	0.58
Zr	12.53	3.97
Zn	8.50	3.75
Matrix	Correction	ZAF

Fig.4 EDS analysis zones (a~c) and corresponding EDS spectra (a_1~c_1) of the alloy at T=300 °C and different extrusion ratios: (a, a_1) λ=8, (b, b_1) λ=12, and (c, c_1) λ=25

detection and composition segregation, the atomic contents in the three alloys are different, but the element ratios are almost similar. So there is only one group of EDS results. Mg-Zn-Y ternary phase is fish-bone shaped with high brightness. From XRD results in Fig.5, it may determine the content of phase which is W phase ($Mg_3Zn_3Y_2$) with cubic system. Mg-Zn binary phase contains a small amount of Zn elements and the brightness is very close to the matrix. It may be $Mg_{0.97}Zn_{0.03}$ phase. The X-ray diffraction peak of the phase is almost exactly coincident with Mg. Considering the low solid solubility in magnesium, XRD test results show that the Mg-Zn-Zr phase is Mg-Zn with a small amount of Zr Element which is formed by segregation. Because of the element diffusion and dynamic recrystallization during hot extrusion process, I phase (Mg_3Zn_6Y) in original as-cast microstructure disappears and the main precipitated phase is W phase.

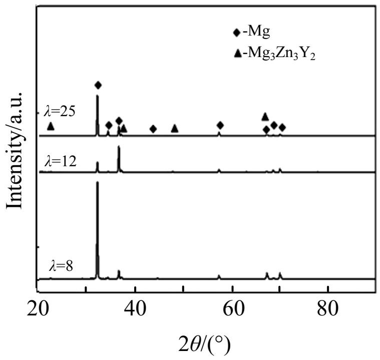


Fig.5 XRD patterns of alloy at different extrusion ratios and T=300 °C

2.2 Influence of extrusion temperature on the microstructure and mechanical properties of magnesium alloys

Fig.6 shows the microstructure along the extrusion direction. Fig.7 is the corresponding SEM image of the extrusion ratio (λ=25). As shown in Fig.6a, when the extrusion temperature is 300 °C, the compressive zones are coarse because the deformation temperature is lower, and the energy provided to alloy recrystallization is less, and finally there are still a small amount of coarse compressed zones without complete recrystallization. And due to lower deformation temperature, the crystal grains do not grow obviously. The second phases of the alloy are mainly distributed in the grain or centrally in triangular grain boundary. As for the extrusion alloy at 350 °C in Fig.6b, the remaining compressive zones are thinner and smaller, the recrystallization grains grow slightly and the boundary is more clear. The granular precipitated phases in grain decrease, centralize towards the grain boundary, and are mainly distributed along the grain boundary grain. There are too much precipitated phases in grain boundary to form reticulate precipitates. When the temperature is 400 °C (Fig.6c), the remaining extrusion belts are not obvious and the recrystallization grains grow a little. The second phases in the grain boundary are relatively massive but not in a continuous mesh. At 450 °C, the alloy has been completely recrystallized without obvious extrusion direction, and the equiaxed grains have been obtained (Fig.6d). At the same time, the amount of the second phase increases, the shape becomes smaller, and the distribution is more uniform.

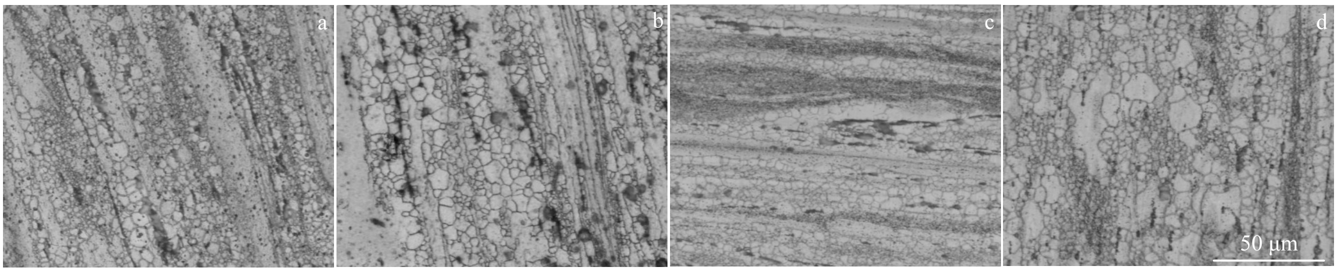


Fig.6 Microstructures of alloy at λ=25 and different temperatures along the extrusion direction: (a) T=300 °C, (b) T =350 °C, (c) T =400 °C, and (d) T =450 °C

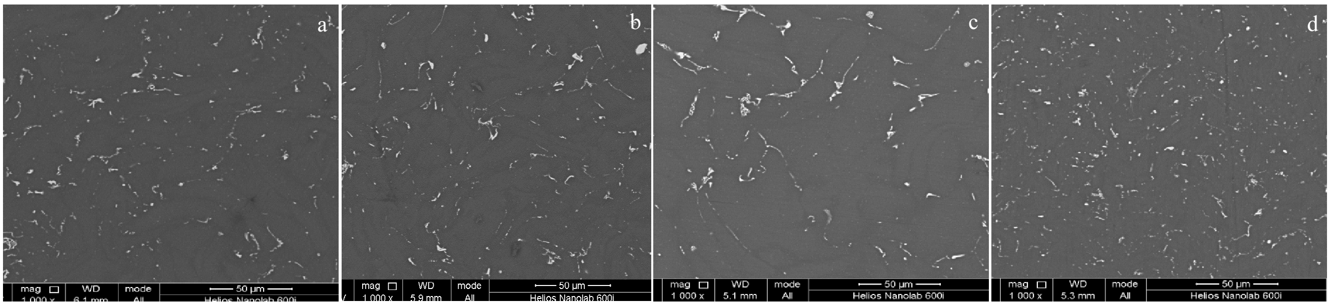


Fig.7 SEM images of alloy at λ=25 and different temperatures: (a) T=300 °C, (b) T =350 °C, (c) T =400 °C, and (d) T =450 °C

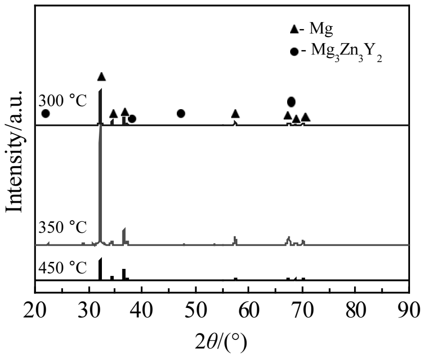


Fig.8 XRD patterns of alloy at λ=25 and different temperatures along the extrusion direction

On the whole, with the increase of extrusion temperature, the grain grows not obviously. Only when the extrusion temperature is 450 °C, the grain grows most significantly, and the massive grain reduces the strength of alloy.

The results show that the mechanical property is significantly affected by the shape, size and distribution of the precipitates. Firstly, the precipitates dispersed in the grain have the effects of dispersion strengthening; on the other hand, massively precipitates distributed along the grain boundary can enhance the pinning effect of grain boundary. Both kinds of precipitates can improve the strength. So there are two strength peaks at 300 and 400 °C. Reticular precipitates may cause the stress concentration during tensile process[24,25], so the mechanical property of alloy at 350 °C is low. On the whole, when the extrusion temperature is 300 °C, the as-extruded alloy has the best combined properties.

According to the XRD results of the alloy with different extrusion temperatures (Fig8) , it can be concluded that although the change of extrusion temperature affects the quantity of precipitation and the morphology of second phase, it does not affect the phase type. With the extrusion ratio, the precipitated phase in the alloy is mainly W phase.

3 Conclusions

1) The phase of extruded alloy is mainly W-phase after extrusion process. Dynamic recrystallization occurs in the microstructure; meanwhile the grain of alloy is refined. At last the comprehensive performance of the alloy is significantly improved.

2) When the extrusion temperature is the same, the influence of extrusion ratio on the strength of the alloy is not obvious, and the strength of the alloy changes little. While the influence of extrusion ratio on the plasticity of the alloy is obvious; when extrusion ratio is 25, the elongation of the alloy increases significantly.

3) The performance of the alloy is influenced by many factors. When the extrusion ratio is the same, the number of recrystallization grains increases with the increasing of temperature; meanwhile recrystallization grains also have a tendency to grow up. Overall, it has an adverse effect on the intensity of the alloy with the increasing of extrusion temperature. On the other hand, because of the influence of the precipitated phase, there are two strength peaks at 300 and 400 °C. The plasticity of alloy increases with the rise of temperature. When the extrusion temperature is 300 °C, the as-extruded alloy has the best combined properties.

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热挤压工艺对 Mg-Zn-Y-Zr 合金组织性能的影响

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摘　要：对合金进行不同挤压参数的挤压试验，通过对实验结果的分析，来探究挤压工艺参数对镁合金的组织性能的影响规律。研究表明，合金在热挤压过程发生了明显的动态再结晶，与铸态组织相比晶粒得到了细化，力学性能也有了明显提升。合金中的第二相是 W 相，第二相在不同热挤压条件下，形态和分布差别较大。合金的组织和力学性能在挤压过程中受挤压温度和挤压比影响，随着挤压温度提高，合金的再结晶晶粒数量增加，但有长大的趋势，挤压温度为 300 ℃时，合金强度最高；挤压比对合金塑性影响较大，挤压比为 25 时，合金的塑性显著提升。

关键词：热挤压；镁合金；组织性能

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