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Journal of Alloys and Compounds 230 (1995) 109–114

Journal of ALLOYS AND COMPOUNDS

Strengthening effects of rare earths on wrought Mg–Zn–Zr–RE alloys

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Received 2 September 1994; in final form 9 May 1995

Abstract

The strengthening effect of rare earths (REs) on wrought Mg–Zn–Zr–RE alloys has been studied. It has been shown that the RE elements have a pronounced strengthening effect on the Mg alloys. Homogenization of the cast ingots and the quenching-plus-aging treatment of the extruded bars decreased the strength, whereas aging of the extruded bars increased the strength. It is proposed that the strengthening mechanism is due to RE-containing particles that are able to suppress the dynamic recrystallization during the hot extrusion process, and to promote the dispersive strengthening effect of RE-containing particles in these materials.

Keywords: Mg–Zn–Zr–RE alloys; Strengthening effect of rare earths

1. Introduction

As structural materials Mg alloys have certain advantages, such as low density, relatively high specific strength and specific elastic modules. However, their strengths are limited. In order to improve the strength of Mg alloys Rare Earth (RE) elements have been added to Mg alloys since the early 1960s [1]. However, there have been very few microstructural studies of RE-containing Mg alloys up to now. We have recently reported the phase constitutions of high-strength Mg–Zn–Zr–RE alloy systems [2,3]. This paper deals with the strengthening effects of RE on wrought Mg–Zn–Zr–RE alloys.

2. Experimental procedures

The materials were melted in a 30 kg electric furnace and water-cooled in a semi-continuous manner. Their chemical compositions (wt%) were Mg–(5.56–5.78)Zn–(0.47–0.60)Zr–(0.89–1.72)Y and Mg–(5.60–5.92) Zn–(0.35–0.64)Zr–(0.60–1.36) Y-rich mischmetal (MM). A Mg–5.65Zn–0.50Zr alloy without RE was also used in these experiment for comparison. The entire heat treatment procedure may be represented as follows: cast ingots are homogenized at 360–400°C for 8 h, followed by extrusion at 350°C to bars of 25 mm diameter, then quenching at 510°C for 1.5 h and aging at 170°C over 10 h. The individual heat treatment conditions are covered below. After these treatments the bars were used to make standard tensile specimens and tested at room temperature in a universal Instron machine. An optical microscope was used for general microstructural examinations, and structural analyses were conducted in an H-800 transmission electron microscope (TEM) at 200 kV.

3. Experimental results

3.1. Tensile properties

The tensile properties of the extruded bars of the three kinds of alloy are shown in Fig. 1. It was found that the Mg–Zn–Zr–RE alloys with Y or MM elements have similar strengths, these being 30 MPa higher than that of the Mg–Zn–Zr alloy without RE elements. Clearly, the RE elements have a pronounced strengthening effect on the Mg alloy.

The effect of various heat treatments on the tensile properties was also investigated for the Mg–Zn–Zr–Y alloys. Fig. 2 shows the effects of homogenization treatment of cast ingots on the tensile properties. It

0925-8388/95/$09.50
SSDI 0925-8388(95)01893-X

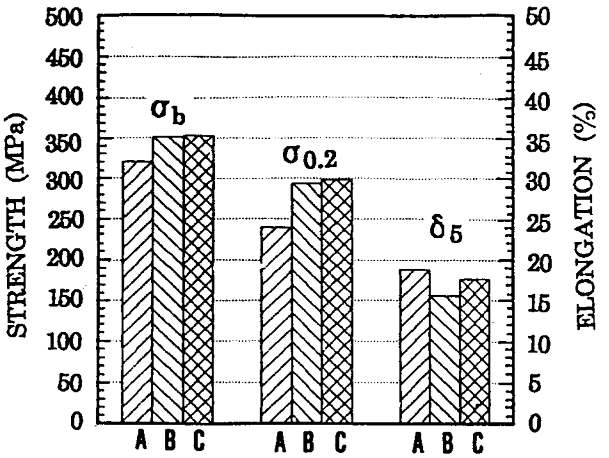

Fig. 1. Tensile properties of extruded bars. (A) Mg–Zn–Zr; (B) Mg–Zn–Zr–Y; (C) Mg–Zn–Zr–MM.

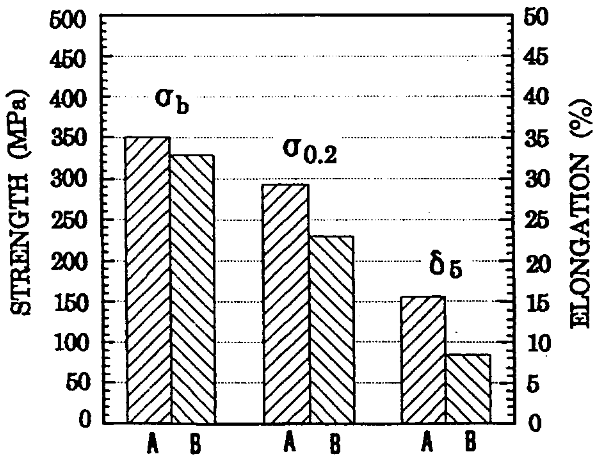

Fig. 2. Effect of homogenization of cast ingots on the tensile properties of Mg–Zn–Zr–Y alloy. (A) Without homogenization; (B) homogenized at 400°C for 8 h.

was found that both the strength and plasticity decreased after the homogenization treatment of the cast ingots, while after the aging treatment of the extruded bars both the strength and plasticity were increased, as shown in Fig. 3. After the quenching-plus-aging treatments of the extruded bars both the strength and plasticity were decreased, as shown in Fig. 4.

3.2. Changes of grain size

The optical micrographs of the extruded bars of Mg–Zn–Zr–MM and Mg–Zn–Zr alloys without homogenization treatment of the cast ingots are shown in Fig. 5. The Figs. 5(a–d) show micrographs in the radial direction, while 5(e–h) are in the axial direction. For the Mg–Zn–Zr–MM alloy it was found that some of fine grains (white regions) appear except in the strip structure along the extrusion direction, as shown in

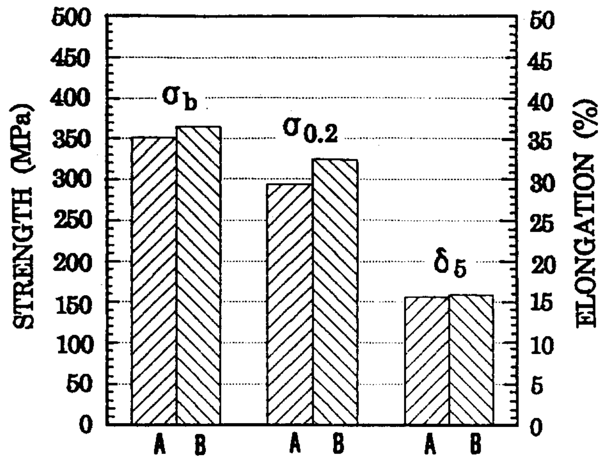

Fig. 3. Effect of aging treatment of extruded bars on the tensile properties of Mg–Zn–Zr–Y alloy. (A) Extruded state; (B) extruded and aged at 170°C for 10 h.

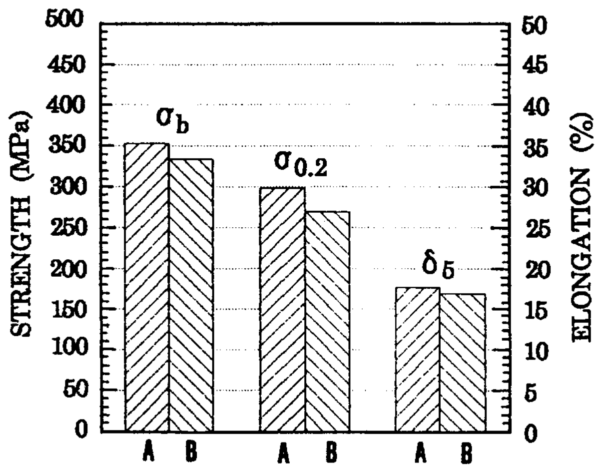

Fig. 4. Effect of quenching plus aging treatments of extruded bars on the tensile properties of Mg–Zn–Zr–Y alloy. (A) Extruded state; (B) quenched from 510°C and aged at 170°C for 10 h.

Figs. 5(a) and (e) in the extruded state. This means that a certain degree of dynamic recrystallization has occurred during the process of hot extrusion. After the aging treatment the optical micrograph shows no clear change, as shown in Figs. 5(b) and (f), while after the quenching-plus-aging treatments the grain size is clearly increased, as shown in Figs. 5(c) and (g). It is obvious that the quenching treatment from 510°C speeds up the recrystallization process, thus producing coarser grains. For the Mg–Zn–Zr alloy without RE elements we observed that the grains were very coarse even in the extruded condition, as shown in Figs. 5(d) and (h), and some deformation twins were also present. This indicates that the dynamic recrystallization process occurs completely during the hot extrusion process for this alloy. Therefore, it can be concluded

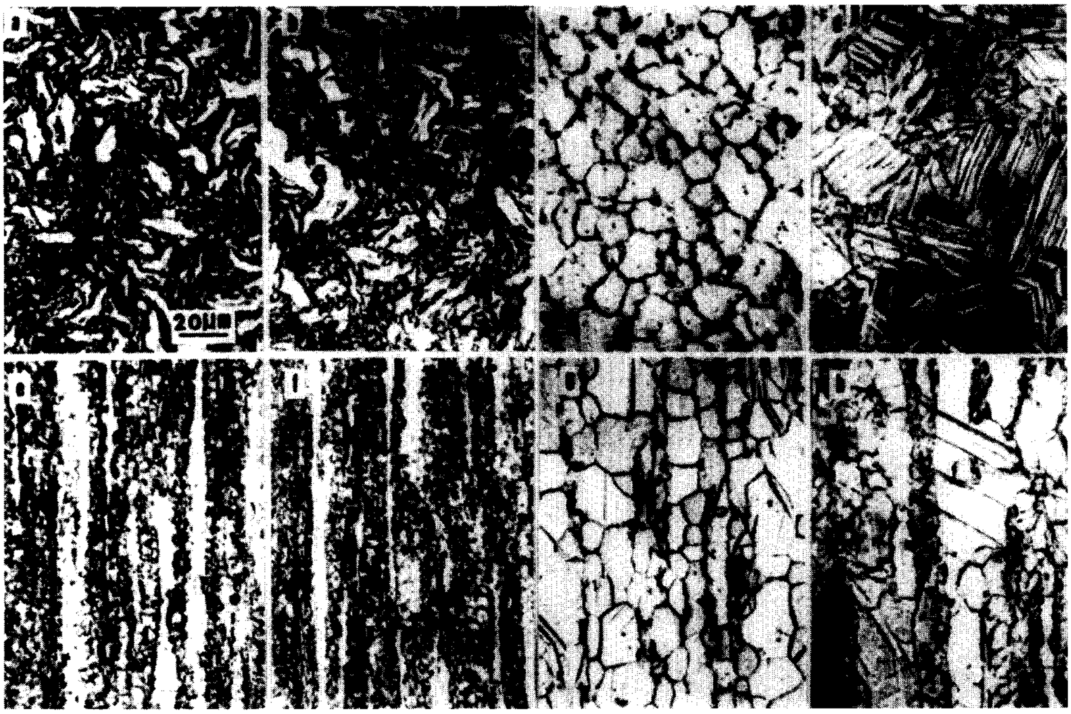

Fig. 5. Optical micrographs of the extruded bars without homogenization of cast ingots. (a) and (e) Mg–Zn–Zr–MM alloy, extruded; (b) and (f) Mg–Zn–Zr–MM alloy, extruded and aged; (c) and (g) Mg–Zn–Zr–MM alloy, extruded, quenched and aged; (d) and (h) Mg–Zn–Zr alloy, extruded.

that RE elements have the effect of suppressing the dynamic recrystallization process during hot extrusion, which makes the crystal grains less likely to coarsen.

Fig. 6 shows the microstructures of the extruded bars of the Mg–Zn–Zr–MM alloy formed from homogenized cast ingots. Compared with Figs. 5(a) and (e) a large number of small grains appeared clearly in the extruded condition, as shown in Fig. 6(a) and (d). It was reported previously that some of the grain boundary phases were dissolved during the process of homogenization of the cast ingots [4]. Thus the dragging effect of RE elements in the dynamic recrystallization process in the form of RE-containing particles during hot extrusion is reduced. This is the reason why the homogenization treatment of cast ingots decreases the strength. After the aging treatment the grain size is not changed, as shown in Figs. 6(b) and (e), whereas after the quenching-plus-aging treatment the grains get very coarse, as shown in Figs. 6(c) and (f). The grain size is larger than that obtained without homogenization (Figs. 5(c) and (g)).

3.3. Structural analysis

In the as-cast condition there are three frequently observed phases: quasicrystal, W phase and $MgZn_2$-type C14 Laves phases. All of these phases contain RE elements, as proved by the energy dispersive X-ray (EDX) spectra in our previous report [2]. TEM analyses of these extruded materials show that those phases with large size in the cast ingots are broken up and distributed along the deformation strip, as shown in Fig. 7. A detailed electron diffraction study of these particles showed that the quasicrystal is still present in the extruded material, as shown in Fig. 8, while small W phases and $MgZn_2$ phases are also observed, as shown in Fig. 9. Inevitably, these phase particles are obstacles to dislocation movement during deformation and have a dispersive strengthening effect on the materials. As may be seen in Fig. 10, after the aging treatment the aging precipitate particals of $MgZn_2$ phase are more plentiful and the high density dislocations are tangled around the $MgZn_2$ particles, which causes the strengthening effect observed for the aged materials.

It is necessary to point out that although plentiful research has been carried out on the quasicrystals [5] since their first discovery by Shechtman et al. [6] in 1984, very little use has been made of quasicrystals up to now. The quasicrystal studied here has a good strengthening effect on Mg alloys. Although the quasicrystals in these alloys had not been discovered before, they have produced the strengthening effect for many years.

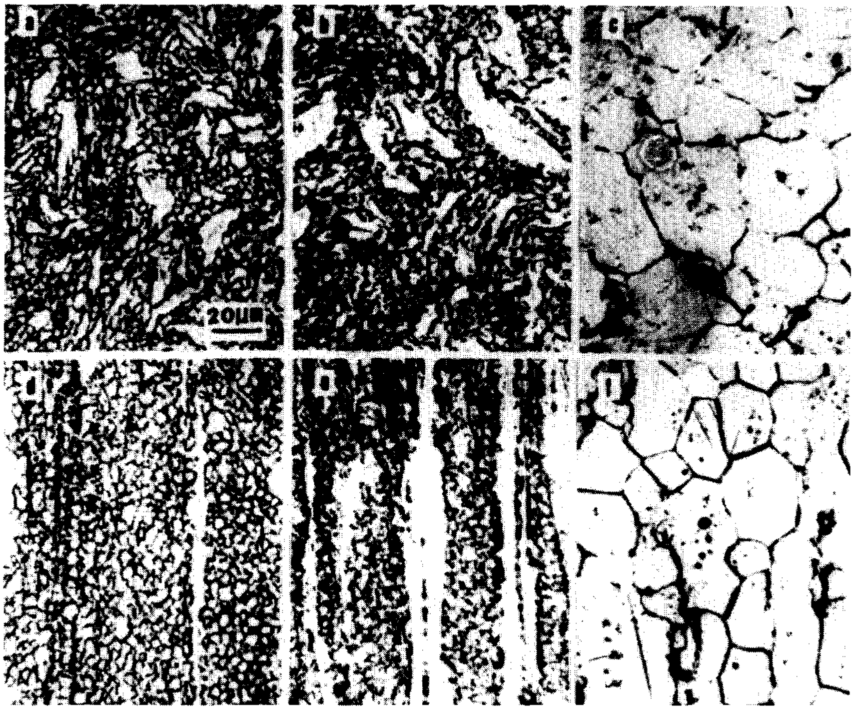

Fig. 6. Optical micrographs of the extruded bars of Mg–Zn–Zr–MM alloy with homogenization of cast ingots. (a) and (d) extruded; (b) and (e) extruded and aged; (b) and (e) extruded and aged; (c) and (f) extruded, quenched and aged.

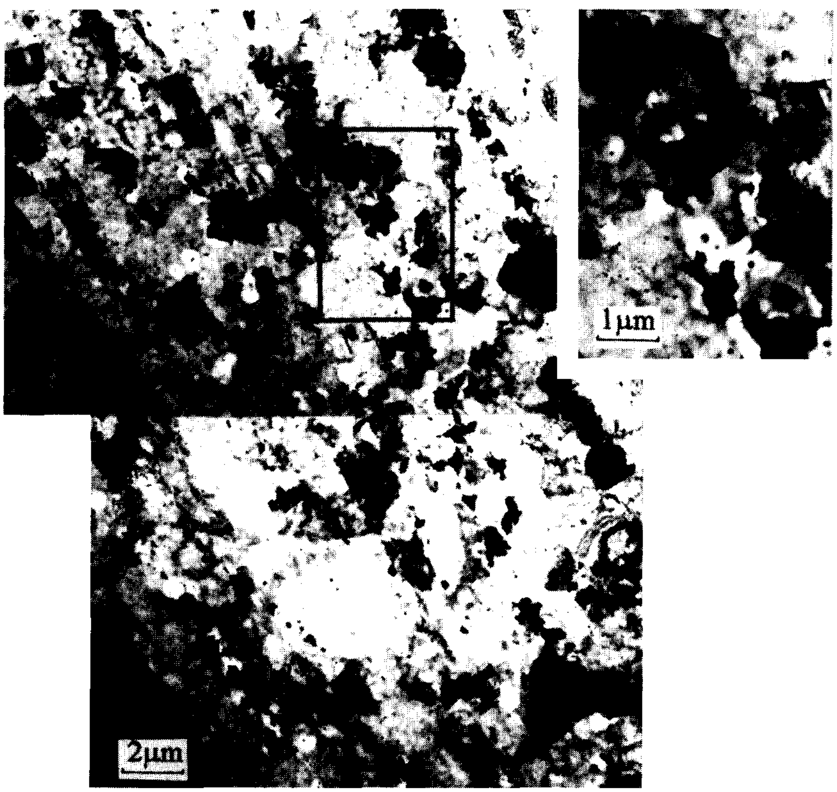

Fig. 7. Phase particles in the extruded bars of the Mg–Zn–Zr–Y alloy.

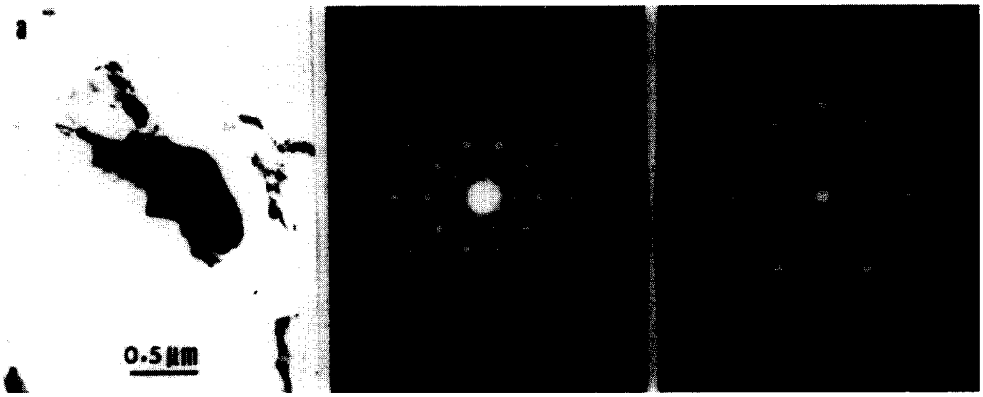

Fig. 8. Small quasicrystal particle in the extruded bar (a) and its electron diffraction patterns with (b) five-fold and (c) two-fold symmetries.

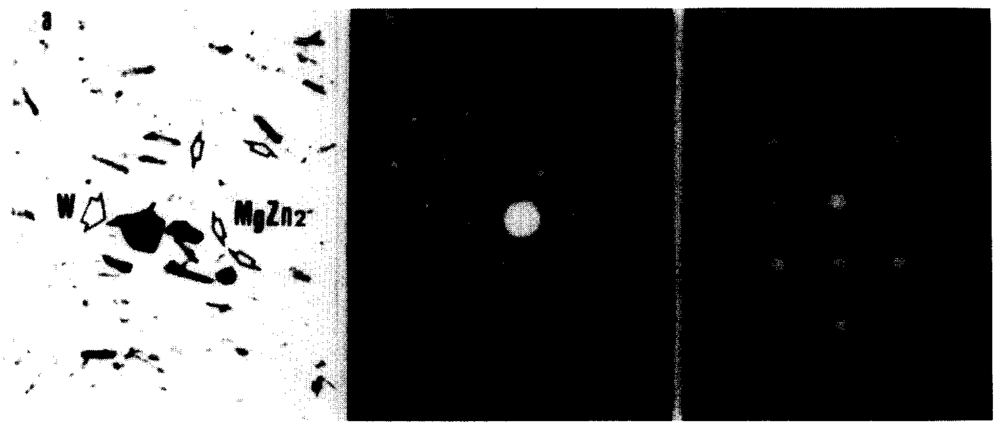

Fig. 9. Small W and $MgZn_2$ phases in the extruded bar (a) and their corresponding electron diffraction patterns (b,c).

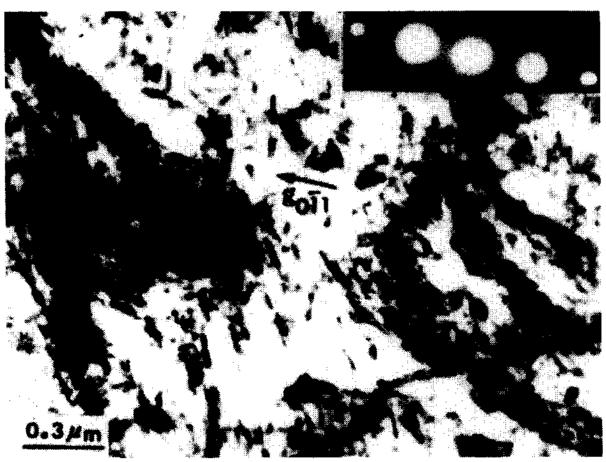

Fig. 10. Dislocation tangling around a $MgZn_2$ phase particle in the aged specimen after tensile deformation.

4. Discussion

4.1. The grain-refining effect of RE elements

Some researchers have reported that the RE elements have a grain-refining effect in Al alloys [7]. For this reason we measured the grain size of cast Mg–Zr, Mg–Zn, Mg–Zn–Zr and Mg–Zn–Zr–RE alloys. Table 1 gives the quantitative results. It is shown that only the Mg–Zn alloy without Zr has the coarse grains, while the others are very similar. It is widely accepted that the grain-refining effect of Zr, which was first discovered by Sauerwald (1937) [8], is due to the peritectic reaction at 653.6 ± 0.5°C for the Mg–Zr binary alloy [9,10]. From the ternary diagrams of Mg–Zn–Y [11] the formation temperatures of RE phases are lower than that for the peritectic reaction. Thus, during the solidification process the peritectic reaction should occur first. The Mg matrix was found to solidify around the Zr particles. Owing to the nonequilibrium distribution the solute atoms of Zn and RE are pushed to the front of the liquid / solid interface, thus various Zn- and RE-rich phases are

Table 1
Grain size of cast alloys (μm)

Alloy	Mg–Zr	Mg–Zn	Mg–Zn–Zr	Mg–Zn–Zr–RE
Grain size	46.6	96.7	43.6	44.5

formed along the grain boundaries while in the interior of the grains only the Zr-rich zone is present. This is in good agreement with experimental observations [2,4]. According to this analysis, the grain-refining effect of RE elements is minor in Zr-containing Mg alloys.

4.2. The solid-solution strengthening effect of RE elements

The atomic diameters of Fe and Al are 0.2482 and 0.2863 nm, respectively [12], which differs greatly from that of the RE elements. For example, the atomic diameter of Y is 0.3554 nm, thus a solution of Y in Fe and Al would cause 43.2% and 24.1% lattice distortion, respectively. Therefore, the solid-solution strengthening effect of RE elements in Fe and Al based materials is considerable, especially for the Fe-based materials. While Mg has a bigger atomic diameter of 0.3197 nm [12], dissolution of Y in Mg causes 11.2% lattice distortion. The EDX analysis shows that the peak due to RE elements in the matrix of extruded materials did not appear in the spectrum, which indicates that the concentration of RE elements in the matrix was very low. Thus, we deduce that the solid-solution strengthening effect by RE elements of these Mg alloys is small.

From the experimental results and discussions above we conclude that the strengthening of the wrought Mg–Zn–Zr–RE alloys by RE elements is due to their capacity to suppress the dynamic recrystallization during the hot extrusion process, and to then dispersive strengthening effect of RE-containing particles in these materials.

5. Conclusions

(1) The RE elements have a pronounced strengthening effect on wrought Mg–Zn–Zr–RE alloys. The homogenization of the cast ingots and the quenching-plus-aging treatments of the extruded bars decreases the strength, but aging of the extruded bars increased the strength.

(2) The strengthening of the alloys by RE is due to the RE-containing particles that suppresses the dynamic recrystallization during the hot extrusion process and leads to a dispersive strengthening effect of RE-containing particles in these materials.

Acknowledgments

This work was supported by the Aeronautical Sciences Foundation of People's Republic of China. The authors would like to thank Mr. L.Q. Lu and Mr. G. Wei for their assistance.

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