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ARTICLE

Effects of Centrifugal Casting and Hot Rolling on Microstructure and Mechanical Properties of Mg-10Gd-3Y-1Sn Alloy

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Abstract: The Mg-10Gd-3Y-1Sn alloys were prepared by centrifugal casting and hot rolling, and their microstructure and mechanical properties were investigated by X-ray diffraction, optical microscope, scanning electron microscope, and tensile tests. Results show that the centrifugal-cast Mg-10Gd-3Y-1Sn alloy consists of α-Mg, $Mg_{24}(Gd, Y)_5$, $Mg_2(Sn, Y)_3Gd_2$, and $Mg_3(Gd, Y)$ phases. With increasing the centrifugal radius and rotation speed, the tensile strength of alloys is increased gradually due to the decreased grain size of alloys. The ultimate tensile strength of as-rolled alloys after centrifugal casting with the rotation speed of 700 r/min is 304 and 296 MPa at room temperature and 300 °C, respectively. The improved tensile strength of Mg-10Gd-3Y-1Sn alloy at elevated temperatures mainly results from the $Mg_{24}(Gd, Y)_5$, $Mg_2(Sn, Y)_3Gd_2$, and $Mg_3(Gd, Y)$ phases with excellent thermal stability.

Key words: Mg-10Gd-3Y-1Sn alloy; centrifugal casting; microstructure; mechanical properties

As a light structural metallic material, the magnesium alloys have great potential for applications in automobiles, aerospace, and computers[1-4]. However, the conventional magnesium alloys cannot be widely applied due to their low strength at room temperature and elevated temperatures[5,6]. Consequently, there is a strong demand for the heat-resistant magnesium alloys with proper cast ability and low cost. It is reported that the addition of rare earth (RE) elements can improve the mechanical properties of magnesium alloys[7-11]. Generally, after the addition of RE elements, the intermetallic compounds with excellent stability are formed, which hinder the dislocation movement at room temperature and elevated temperatures, thereby improving the mechanical properties of alloys. The Mg-Gd-Y alloys have high strength, good ductility, and excellent creep resistance[9,12]. Besides, the Sn addition into Mg-Gd-Y alloys not only enhances the casting fluidity but also improves the tensile strength and creep properties of alloys due to the formation of Mg_2Sn phase with high melting point of 770.5 °C[13,14].

The Mg-Gd-Y alloy is suitable for long-time working parts at 200~300 °C. The precipitates containing RE elements usually have high stability because the diffusion rate of RE elements in the magnesium matrix is slow, which is beneficial to the improvement of elevated temperature strength and creep resistance[15]. Liu et al[16] investigated the high temperature mechanical properties of low-pressure sand-cast Mg-Gd-Y-Zr magnesium alloys, and found that the ultimate tensile strength (UTS) and yield strength of T6-treated Mg-10Gd-3Y-0.5Zr alloy are firstly increased and then decreased with increasing the room temperature to 300 °C. Nodooshan et al[17] investigated the effect of Gd content on the mechanical properties of Mg-Gd-Y-Zr alloy at high temperature, and found that the strength of T6-treated alloys at elevated temperature is gradually improved with increasing the Gd content to 12wt%.

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For the Mg-12Gd-3Y-0.5Zr alloy, the UTS and yield strength are increased with increasing the room temperature to 150 °C. The UTS reaches the maximum value of about 375 MPa at 150 °C. However, with further increasing the temperature to 300 °C, UTS is decreased to about 200 MPa.

Generally, the as-cast MgGd-based alloys exhibit poor mechanical properties due to the coarse α-Mg grains and brittle network eutectic phases. These disadvantages can be overcome by special casting or hot rolling treatments. The centrifugal casting is a direct and effective casting method to improve mechanical properties[18-20] and to obtain homogenous microstructures for the alloys[20]. However, the centrifugal casting is rarely used for Mg alloys. Therefore, the microstructure and mechanical properties of Mg-10Gd-3Y-1Sn alloys treated by the horizontal centrifugal casting followed by hot rolling treatment were investigated in this research, providing a theoretical foundation for the preparation of magnesium alloy parts by centrifugal casting.

1 Experiment

The Mg-10Gd-3Y-1Sn alloys were prepared using commercial pure magnesium (99.9wt%), pure tin (99.9wt%), Mg-30Y master-alloy, and Mg-30Gd master-alloy. Firstly, the pure magnesium, Mg-30Y master-alloy, and Mg-30Gd master-alloy were put into a graphite crucible and then placed in a furnace filled with SF_6/CO_2 gas mixture. Subsequently, the alloy mixtures were heated to 720 °C. After these materials were completely molten, the temperature was decreased to 680 °C, then the pure tin was added into the melt, and the melt was maintained at 680 °C for 20 min. Finally, the melt was poured into a rotated steel mold with different rotation speeds of 0, 300, 750, and 1050 r/min to prepare the centrifugal-cast specimens. The schematic diagram of centrifugal casting process is shown in Fig.1. The specimens for metallographic observation were taken from the inside and outside of the Mg-10Gd-3Y-1Sn alloys along centrifugal radius direction. The minimum and maximum centrifugal radius was 0.12 and 0.21 m, representing the inside and outside parts of specimens, respectively. Before hot rolling, the specimens were heated at 520 °C for 30 min. The initial specimen thickness was 5 mm. The hot rolling was conducted with the reduction per pass of 10% at a rolling rate of 9 mm/min. Finally, the sheets with a thickness of 3.5 mm and a total reduction of 30% were obtained.

The specimens after centrifugal casting and hot rolling treatments for microstructure observation were prepared by metallographic polishing and then etched by 4vol% nital solution. The microstructure was observed by optical microscope (OM) and scanning electron microscope (SEM) coupled with an energy dispersive spectrometer (EDS). The phase composition of the alloys was identified by X-ray diffraction (XRD, Rigaku D/Max2500PC) with a scanning velocity of 5°/min and a scanning angle from 10° to 90°. The tensile tests were conducted at room temperature and 300 °C by SANS GMT-5105 and Gleeble-1500D tensile tester with a displacement speed of 2 mm/min.

2 Results and Discussion

2.1 Microstructure

2.1.1 Microstructure of Mg-10Gd-3Y-1Sn alloys after centrifugal casting

Fig.2 shows XRD patterns of centrifugal-cast Mg-10Gd-3Y-1Sn alloys under different rotation speeds. The results show that the centrifugal-cast alloys mainly consist of α-Mg matrix, $Mg_{24}(Gd, Y)_5$, $Mg_2(Sn, Y)_3Gd_2$, and $Mg_3(Gd, Y)$ phases.

Fig.3 shows the OM microstructures of Mg-10Gd-3Y-1Sn alloys after traditional gravity casting and centrifugal casting under different rotation speeds. It can be seen that the Mg-10Gd-3Y-1Sn alloy is mainly composed of α-Mg matrix and network eutectic compounds distributed at the grain boundaries. As shown in Fig.3a, the α-Mg grains of Mg-10Gd-3Y-1Sn alloy after traditional gravity casting show the dendritic morphology. The grain size of α-Mg is significantly reduced with increasing the rotation speed and centrifugal radius. With increasing the rotation speed, the shape of α-Mg grains becomes regular and the spherical morphology is more obvious.

Fig.4 shows the effect of centrifugal radius and rotation speed on the grain size. It is clear that grain size is gradually decreased with increasing the centrifugal radius and rotation speed. The centrifugal pressure (P_r) can be expressed as

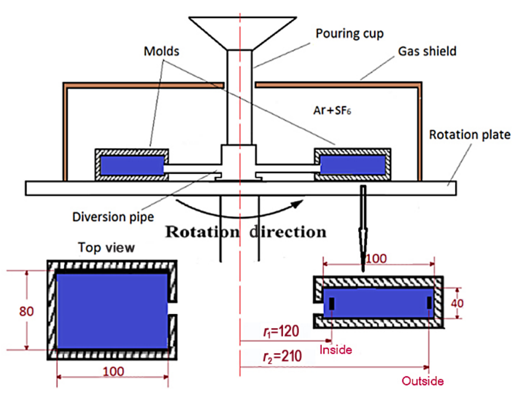

Fig.1 Schematic diagram of centrifugal casting equipment

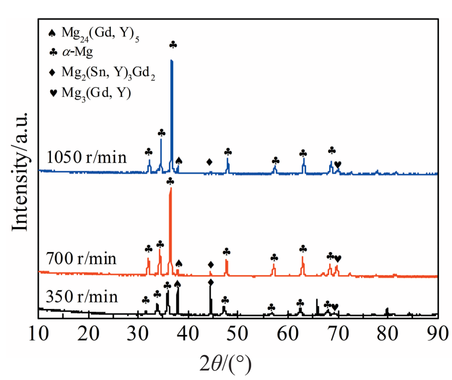

Fig.2 XRD patterns of centrifugal-cast Mg-10Gd-3Y-1Sn alloys under different rotation speeds

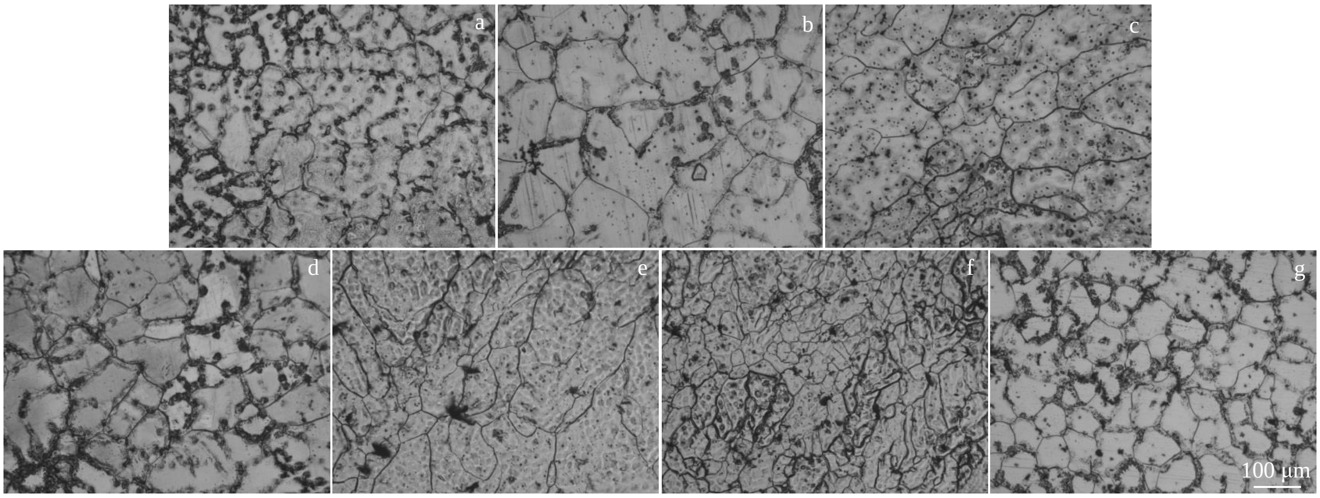

Fig.3 OM microstructures of Mg-10Gd-3Y-1Sn alloys after traditional gravity casting (a) and centrifugal casting (b~g) under different rotation speeds: (b) 350 r/min-inside; (c) 350 r/min-outside; (d) 700 r/min-inside; (e) 700 r/min-outside; (f) 1050 r/min-inside; (g) 1050 r/min-outside

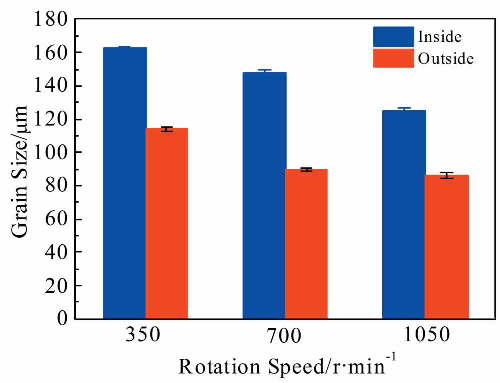

Fig.4 Effects of rotation speed and centrifugal radius on grain size of centrifugal-cast Mg-10Gd-3Y-1Sn alloys

follows:

$$P_r = \rho\omega^2 (r^2 - r_0^2)/2 \quad (1)$$

where ρ is a constant of the density of melt; r is the centrifugal radius; r_0 is the inner surface radius of melt; ω is the rotation angular velocity. Therefore, the centrifugal pressure is increased with increasing the centrifugal radius and rotation speed. On the one hand, the increase in centrifugal pressure leads to the increase in melting point and liquidus temperature, enhancing the undercooling effect during solidification. Thus, the spontaneous nucleation is significantly promoted, leading to the grain refinement. On the other hand, the increase in centrifugal pressure can suppress the atom diffusion, thereby improving the atomic diffusion activation energy and the crystal growth activation energy. Therefore, the increase in centrifugal pressure can inhibit the grain growth and lead to the grain refinement.

In addition, the increase in rotation speed and centrifugal radius leads to the enhancement of the fluid field and vibration, which is beneficial for the break of dendrites on the inner wall of the mold, resulting in the fact that the broken dendrites re-enter the melt. Thus, the detached dendrite arm becomes the nucleation point, improving the grain refinement effect[21] .

Fig. 5 shows SEM images of the Mg-10Gd-3Y-1Sn alloys under different rotation speeds. Under the same rotation speed, the amount of intermetallic phase is increased with increasing the centrifugal radius, because the intermetallic compounds with relatively high melting point are preferentially nucleated during the solidification process. The intermetallic compounds have higher density than the melt does, resulting in the fact that the intermetallic compounds mainly move away from the center during the centrifugal casting.

The solidification rate is reduced with increasing the rotation speed during the centrifugal casting. The prolonged solidification duration promotes the eutectic transformation process in the solidification process, leading to the increase in the amount of intermetallic compound. However, the intermetallic compounds may agglomerate and the macro-segregation is enhanced when the rotation speed is too high. The volume fraction of intermetallic compounds of Mg-10Gd-3Y-1Sn alloy is moderate and their distribution is homogenous under the rotation speed of 700 r/min.

SEM images of centrifugal-cast Mg-10Gd-3Y-1Sn alloys under different rotation speeds are shown in Fig. 6, and EDS results of the points in Fig.6 are summarized in Table 1. It can be seen that the intermetallic phases are significantly changed with increasing the rotation speed. The morphology of intermetallic phases changes from the spherical and small blocks to slender bars and feather-like phases. Several white particles are found in the grain interior. According to EDS results of point C in Fig. 6b, the content ratio of Mg:Gd:Y≈3:1:1, indicating the Mg_3(Gd, Y) phase. However, the point E and F in Fig. 6c consist of less Gd and Y than point C does, suggesting that the phase at point E and F is Mg_{24}(Gd, Y)$_5$, which is in agreement with Ref. [22]. EDS results of point A,

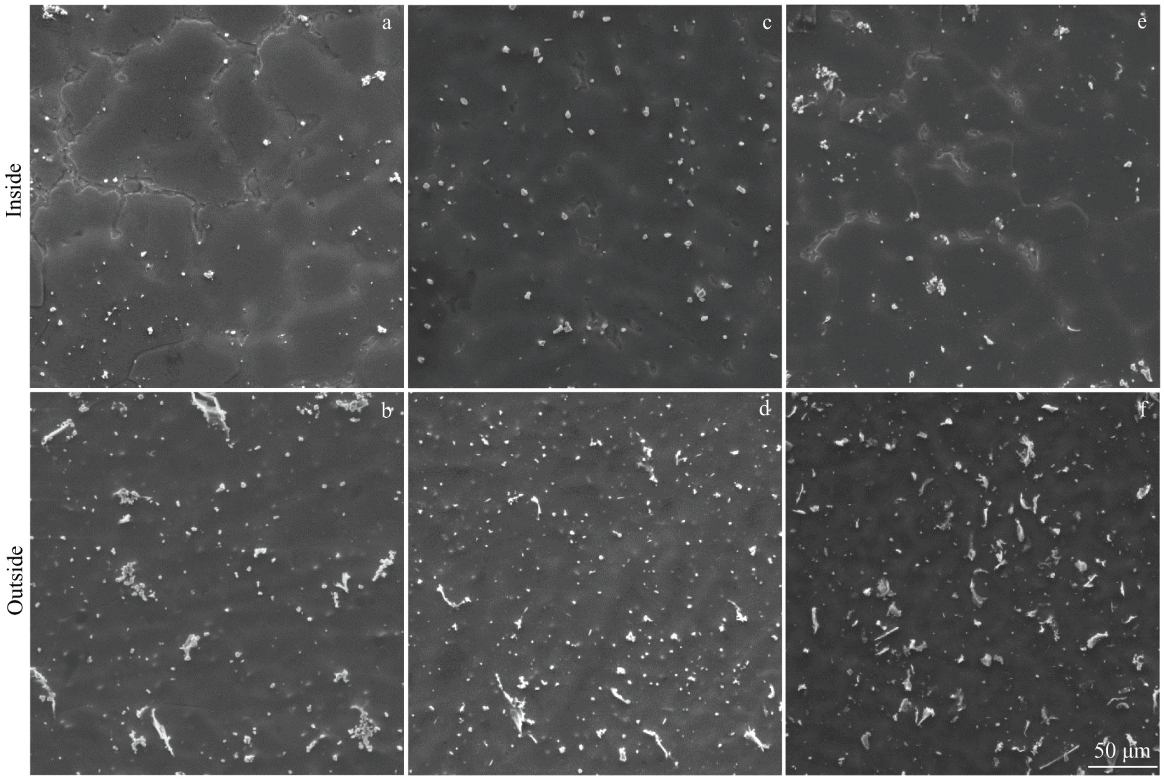

Fig.5 SEM images of Mg-10Gd-3Y-1Sn alloys under different rotation speeds: (a) 350 r/min-inside; (b) 350 r/min-outside; (c) 700 r/min-inside; (d) 700 r/min-outside; (e) 1050 r/min-inside; (f) 1050 r/min-outside

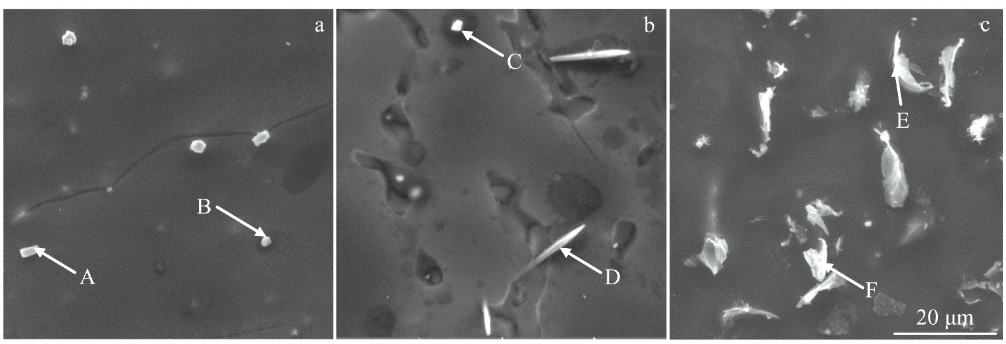

Fig.6 Magnified SEM images of centrifugal-cast Mg-10Gd-3Y-1Sn alloys under different rotation speeds: (a) 350 r/min; (b) 700 r/min; (c) 1050 r/min

Table 1 EDS results of different points in Fig.6 (mol%)

Point	Mg	Gd	Y	Sn
A	56.23	13.89	16.71	13.16
B	76.02	7.79	7.96	8.24
C	62.39	18.00	19.61	0.00
D	49.92	16.65	16.90	17.03
E	93.81	0.00	6.19	0.00
F	92.89	2.09	5.03	0.00

B, and D in Fig. 6 indicate that these phases are quaternary phases containing Mg, Gd, Y, and Sn elements. Combined with XRD results, the quaternary phase is considered as the $Mg_2(Sn, Y)_3Gd_2$, which is also in agreement with Ref.[23].

2.1.2 Microstructure of Mg-10Gd-3Y-1Sn alloys after centrifugal casting followed by hot rolling

Fig. 7 shows OM microstructures of Mg-10Gd-3Y-1Sn alloys after centrifugal casting followed by hot rolling under different rotation speeds. The white α-Mg phase and black flocculent compounds are distributed homogenously in all specimens. During the hot rolling, the deformation storage energy increases, which leads to the increase in driving force for recrystallization nucleation, thereby promoting the dynamic recrystallization. Meanwhile, the accumulated stress promotes the break of compounds, improving the distribution of intermetallic compounds. Particularly, the Mg-10Gd-3Y-1Sn alloy after centrifugal casting followed by hot rolling under the rotation speed of 700 r/min has the most homogenous

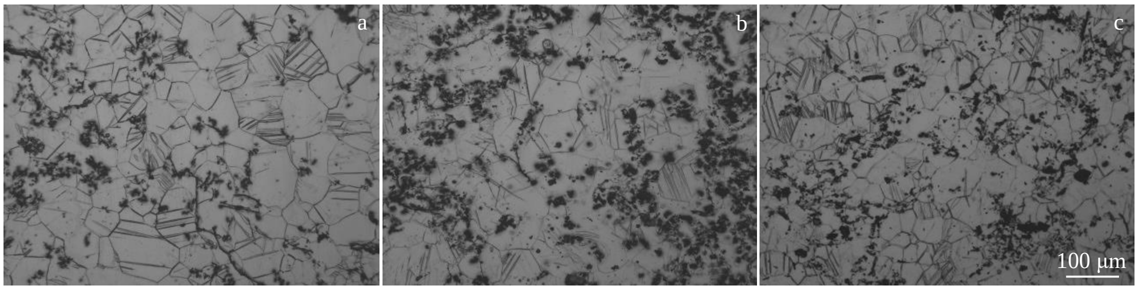

Fig.7 OM microstructures of Mg-10Gd-3Y-1Sn alloys after centrifugal casting followed by hot rolling under different rotation speeds: (a) 350 r/min; (b) 700 r/min; (c) 1050 r/min

distribution of intermetallic compounds, which is related to the initial microstructure of centrifugal-cast alloy. Some deformation twins can also be observed in the as-rolled specimens, which are connected with or parallel to each other in some adjacent grains, indicating that the twins can adjust the grain orientation and release the concentrated stress, leading to the alternative occurrence of cross-slip and twinning. SEM images of Mg-10Gd-3Y-1Sn alloys after centrifugal casting followed by hot rolling are shown in Fig.8, and EDS results of the points in Fig. 8 are summarized in Table 2. Compared with that in the centrifugal-cast specimen, the distribution of intermetallic compounds in the as-rolled centrifugal-cast specimen is improved significantly due to the crushing effect of rolling stress. EDS results of point A and E in Fig. 8 indicate that these long block phases are $Mg_2(Sn, Y)_3Gd_2$. According to EDS results of point B in Fig. 8a, the content ratio of Mg: (Gd+Y) ≈3: 1, indicating the Mg_3(Gd, Y) phase. However, the point C in Fig. 8b consists of less Gd and Y, suggesting that the phase at point C is Mg_{24}(Gd, Y)$_5$. According to EDS results of point D in Fig. 8b, the content ratio of Mg:(Gd+Y)≈2:1, inferring the Mg_3(Gd, Y) phase with some RE-rich phases. EDS results of point F in Fig. 8c indicate that point F is only composed of Gd and Y elements, namely the RE-rich phase.

Fig. 9a~9c show the electron back-scattered diffraction (EBSD) analyses of Mg-10Gd-3Y-1Sn alloys after centrifugal casting followed by hot rolling. The dynamic recrystallization occurs during the hot rolling process, leading to the grain refinement. The twins inside the grains are generally considered as the {1012} tensile twins, which can regulate the anisotropy caused by dislocation glide. When twins intersect with each other, the matrix will be separated, and the twin boundary can react with the moving dislocation, leading to the formation of small angle grain boundaries. The small angle grain boundaries can be transformed into large angle grain boundaries by continuously absorbing dislocations. The dynamic recrystallization caused by twins is the main nucleation mechanism during the hot rolling. The contribution of hot rolling to the grain refinement of different specimens is similar due to the same hot rolling process. However, the increase in rotation speed enhances the undercooling effect during the solidification, which inhibits the grain growth and increases the amount of detached dendrite arm, thereby improving the grain refinement effect. Thus, the grain size of as-rolled specimens is gradually decreased with increasing the rotation speed, which is consistent with the grain size of the initial centrifugal-cast specimens.

The pole figure maps of the as-rolled centrifugal-cast Mg-10Gd-3Y-1Sn alloys under different rotation speeds are shown in Fig.9d~9f. RD, ND, and TD represent the rolling direction, normal direction, and transverse direction, respectively. All as-rolled alloys exhibit typical basal texture with (0001) basal plane of α-Mg parallel to RD. Meanwhile, the basal poles spread broadly along RD and TD and the peak density of

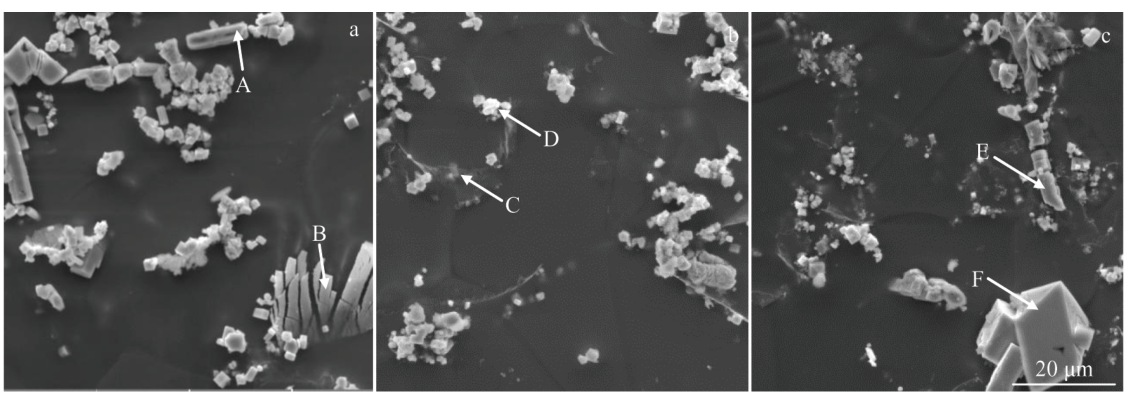

Fig.8 SEM morphologies of as-rolled centrifugal-cast Mg-10Gd-3Y-1Sn alloy under different rotation speeds: (a) 350 r/min; (b) 700 r/min; (c) 1050 r/min

Table 2 EDS results of different points in Fig.8 (mol%)

Point	Mg	Gd	Y	Sn
A	23.63	24.42	16.80	35.16
B	72.17	6.97	20.68	0.00
C	92.24	4.57	2.80	0.40
D	63.60	4.07	30.04	2.29
E	27.41	26.22	20.97	25.40
F	0.00	50.53	49.47	0.00

basal poles is inclined towards TD. The maximum density of the as-rolled specimens under the rotation speed of 350, 750, and 1050 r/min is 11.09, 7.91, and 6.5, respectively. The intensity of basal texture is decreased with increasing the rotation speed probably due to the grain refinement.

2.2 Mechanical properties

Fig. 10 shows the mechanical properties of centrifugal-cast Mg-10Gd-3Y-1Sn alloys under different rotation speeds at room temperature. UTS of specimens is increased, whereas the elongation is basically unchanged with increasing the

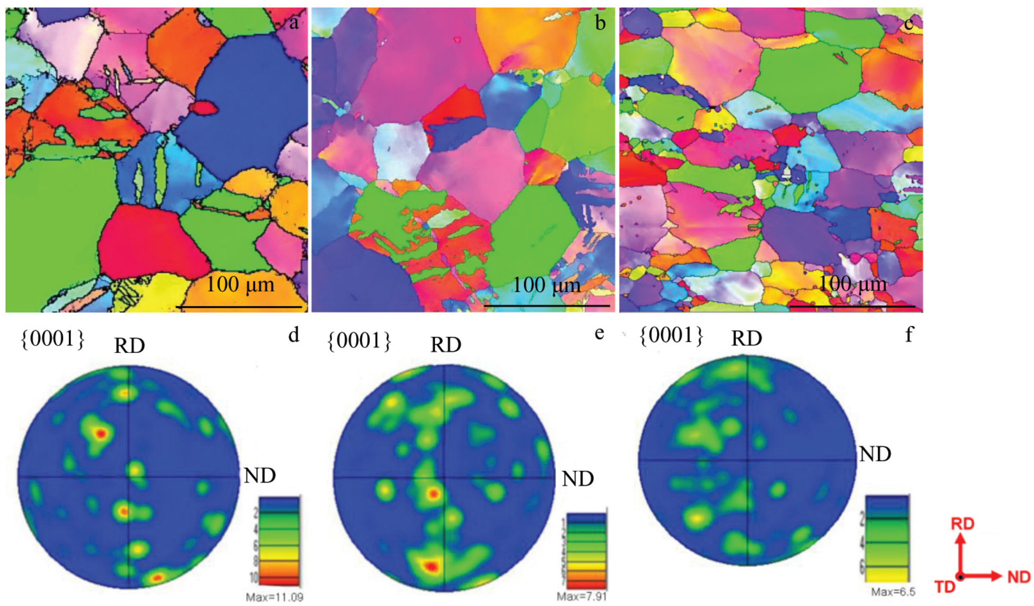

Fig.9 EBSD analyses (a~c) and pole figure maps (d~f) of Mg-10Gd-3Y-1Sn alloys after centrifugal casting followed by hot rolling under different rotation speeds: (a, d) 350 r/min; (b, e) 700 r/min; (c, f) 1050 r/min

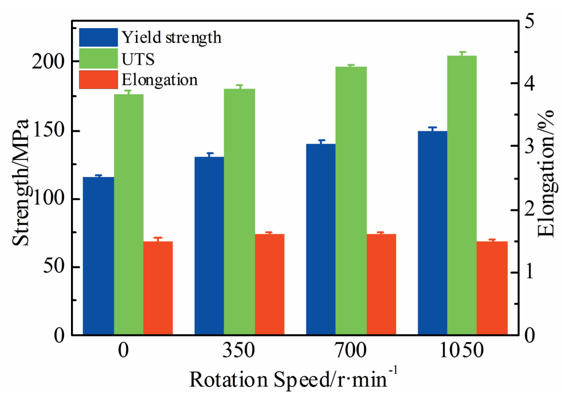

Fig.10 Mechanical properties of Mg-10Gd-3Y-1Sn alloys after traditional gravity casting and centrifugal casting under different rotation speeds

rotation speed. As the rotation speed is increased from 0 r/min (corresponding to the specimen after traditional gravity casting) to 1050 r/min, UTS is increased from 177 MPa to 205 MPa with the increment of 15.8% because of the grain refinement caused by the increasing rotation speed. From this point of view, the rotation speed of 1050 r/min can lead to the best mechanical properties.

Fig. 11 shows the mechanical properties of as-rolled centrifugal-cast Mg-10Gd-3Y-1Sn alloys at room temperature. Compared with that of the centrifugal-cast specimen, the strength of as-rolled alloy is significantly improved due to the

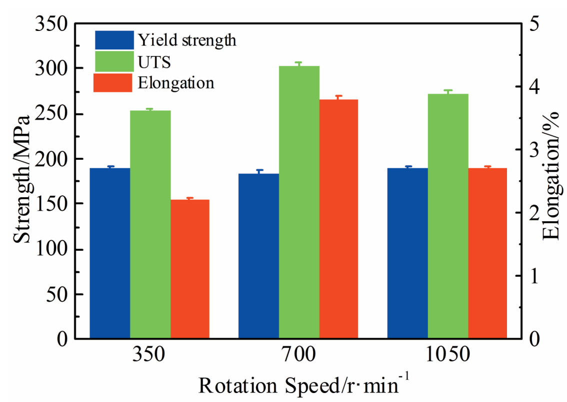

Fig.11 Mechanical properties at room temperature of Mg-10Gd-3Y-1Sn alloys after centrifugal casting followed by hot rolling under different rotation speeds

grain refinement and the more homogenous distribution of the second phase. The Mg-10Gd-3Y-1Sn alloys have a high content of RE elements, which leads to the enrichment of RE solute atoms at the grain boundaries. Thus, a large amount of the second phase precipitates at the grain boundaries, which can effectively hinder the dislocation movement, thereby improving the mechanical properties of alloys. The grain refinement, work hardening effect, and the precipitation strengthening all contribute to the improvement in mechanical properties of alloys[21]. UTS of as-rolled Mg-10Gd-3Y-1Sn alloys under the rotation speed of 350, 700, and 1050 r/min is 254, 304, and 273 MPa, respectively. The elongation of as-rolled Mg-10Gd-3Y-1Sn alloys under the rotation speed of 350, 700, and 1050 r/min is 2.2%, 3.8%, and 2.7%, respectively. The as-rolled Mg-10Gd-3Y-1Sn alloy under the rotation speed of 700 r/min possesses the highest UTS, because it possesses the most homogenous distribution of intermetallic compounds.

Fig. 12 presents the engineering tensile stress-strain curves of as-rolled centrifugal-cast Mg-10Gd-3Y-1Sn alloys at 300 °C. The excellent mechanical properties of the as-rolled centrifugal-cast specimens at elevated temperature are listed in Table 3. UTS at 300 °C of as-rolled centrifugal-cast alloys under rotation speed of 700 r/min reaches 296 MPa, which is even higher than the UTS of AZ31 alloy at room temperature (240 MPa). The superior mechanical properties at elevated temperature is mainly due to the excellent thermal stability of $Mg_{24}(Gd, Y)_5$, $Mg_2(Sn, Y)_3Gd_2$, $Mg_3(Gd, Y)$, and Mg_2Sn compounds. At elevated temperatures, these phases can

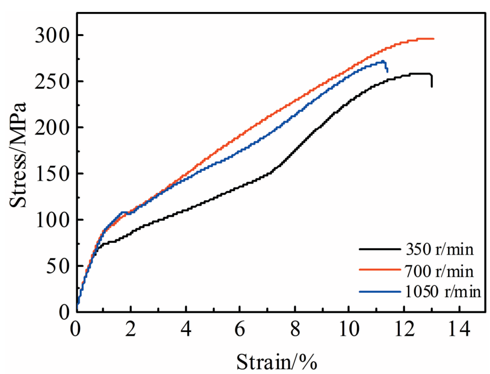

Fig.12 Engineering stress-strain curves of as-rolled centrifugal-cast Mg-10Gd-3Y-1Sn alloys under different rotation speeds at 300 °C

Table 3 Mechanical properties at 300 °C of Mg-10Gd-3Y-1Sn alloys after centrifugal casting followed by hot rolling under different rotation speeds

Rotation speed/r·min⁻¹	Yield strength/ MPa	Ultimate tensile strength, UTS/MPa	Elongation/ %
350	70	258	13
700	83	296	13
1050	87	271	11

effectively hinder the dislocation glide and grain boundary migration, therefore greatly improving the mechanical properties at elevated temperatures.

3 Conclusions

1) The Mg-10Gd-3Y-1Sn alloys after centrifugal casting consist of α-Mg, $Mg_{24}(Gd, Y)_5$, $Mg_2(Sn, Y)_3Gd_2$, and $Mg_3(Gd, Y)$ phases. The grain size of centrifugal-cast alloys is significantly reduced with increasing the rotation speed and centrifugal radius due to the increase in centrifugal pressure, fluid field, and vibration. Correspondingly, the mechanical properties are improved with increasing the rotation speed. Therefore, the optimal rotation speed is 1050 r/min.

2) The hot rolling process promotes the dynamic recrystallization and improves the homogenous distribution of intermetallic compounds. The grain size of as-rolled centrifugal-cast alloys is gradually decreased with increasing the rotation speed, which is consistent with the grain size of the initial centrifugal-cast alloys. The distribution of intermetallic compounds of the as-rolled centrifugal-cast alloys under the rotation speed of 700 r/min is the most homogenous, which leads to the optimal mechanical properties of alloys. The ultimate tensile strength of as-rolled centrifugal-cast alloys under the rotation speed of 700 r/min is 304 MPa at room temperature.

3) The as-rolled centrifugal-cast Mg-10Gd-3Y-1Sn alloy shows optimal mechanical properties with the ultimate tensile strength of 296 MPa at 300 °C due to the excellent thermal stability of intermetallic compounds in the Mg-10Gd-3Y-1Sn alloys.

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离心铸造和热轧对Mg-10Gd-3Y-1Sn合金组织和机械性能的影响

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摘　要：采用离心铸造及热轧工艺制备Mg-10Gd-3Y-1Sn合金，利用X射线衍射、光学显微镜、扫描电子显微镜和拉伸试验对该合金的组织和力学性能进行了研究。结果表明：离心铸造Mg-10Gd-3Y-1Sn合金由α-Mg、$Mg_{24}(Gd, Y)_5$、$Mg_2(Sn, Y)_3Gd_2$和$Mg_3(Gd, Y)$相组成。随着离心半径和离心转速的增大，Mg-10Gd-3Y-1Sn合金的晶粒尺寸逐渐减小，抗拉伸强度逐渐增大。在700 r/min下制备的热轧试样在室温下极限抗拉伸强度为304 MPa，在300 ℃下极限抗拉伸强度为296 MPa。$Mg_{24}(Gd, Y)_5$、$Mg_2(Sn, Y)_3Gd_2$和$Mg_3(Gd, Y)$相具有优异的热稳定性，因而Mg-10Gd-3Y-1Sn合金具有优异的高温抗拉伸强度。

关键词：Mg-10Gd-3Y-1Sn合金；离心铸造；微观组织；力学性能

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