Influence Of LPSO Phase On Elastic Modulus And Casting Performance In Mg-Y-Ni Alloys

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Abstract: Mg alloys are widely used as lightweight structural materials in aerospace and other fields, but their low modulus of elasticity limits engineering applications. In this study, the effect of relative elastic modulus, flow and hot tearing properties of long period stacked ordered (LPSO) is investigated by modulating the Y content in Mg-Y-Ni alloys. The results showed that the volume fraction of LPSO phase significantly increased and the Mg_2Ni phase decreased with the increase of Y content, and the elastic modulus increased from 47.29 GPa to 50.24 GPa. The flowability test showed that the spiral filling length increased from 226.4 mm to 323.4 mm with the increase of Y content from 1.5 at. % to 4.5 at.%, and the flowability was significantly improved. However, the high Y content (4.5 at. %) resulted in increased thermal tearing susceptibility, as evidenced by wider extension of the restraining rod cracks. The results provide a theoretical basis for the composition design and process optimisation of high-modulus cast magnesium alloys.

Keywords: Mg-Y-Ni alloy, LPSO, Metal fluidity, Hot tearing mechanism, Elasticity modulus

1 Introduction

Mg alloys have gained popularity as the lightest metal structural materials due to the growing need for lightweight materials in aerospace, military, and other fields [1, 2]. However, they lack adequate elastic modulus to meet engineering requirements. Elastic modulus is an important measure of a material's ability to resist deformation and is one of the most critical properties of structural materials [3]. A high modulus of elasticity results in increased stability and a longer service life for the material. The value of E for Mg alloys is ~45GPa, which is about 3/5 of Al alloys and less than 1/5 of steels [4]. In practice, this means that magnesium alloy components have a shorter service life and are more prone to failure. Because elastic modulus is an intrinsic property for Mg-based materials, which is insensitive to heat treatment and manufacturing process. Although it is possible to create intermetallic compounds or solid solution structures with a high modulus in alloys, the enhancement is limited [5-7]. Therefore, enhancing the elastic modulus of Mg-based materials has been considered a critical challenge in recent decades for the development of new high-performance Mg-based materials.

The Mg-rare-earth (RE)-Zn/Ni alloys, which contain a long-period stacking ordered (LPSO) phase, exhibit superior mechanical properties compared to other commercial Mg alloys [8, 9]. The LPSO phase is a novel strengthening phase in Mg alloys, with a modulus of elasticity of 70 GPa, surpassing the Mg matrix's 40 GPa. The coherent phase boundary between the LPSO phase and the Mg matrix facilitates perfect load transfer [10]. Thus, Therefore, the introduction of the LPSO phase in Mg alloys can increase the overall modulus of elasticity.

Compared to the element Zn, the element Ni is more favourable to promote the formation of the LPSO phase at a given solute content [11]. Therefore, this work aims to elucidate the effect of LPSO on the modulus of elasticity of Mg-Y-Ni alloys. In addition, since the casting process is necessary for magnesium alloy extrusion, die casting, stretching and other plastic forming parts, and the fluidity and HTS are the key to determine the casting quality and yield, the role of LPSO phase in the fluidity and hot tearing susceptibility (HTS) of Mg-Y-Ni alloys is discussed. Thus far, the specific influence of secondary phases in Mg-Zn-based alloys on thermal conductivity remains unclear.

2 Experimental section

2.1 Material compositions

The original alloy ingots with nominal compositions of Mg-1.5Y-3Ni, Mg-3Y-3Ni and Mg-4.5Y-3Ni in at. % were fabricated in an electric-resistant furnace under an argon atmosphere by melting high-purity Mg, Y and Ni at 750 °C. The melt was purified by bubbling argon gas, with a controlled gas flow to ensure the integrity of the melt surface. Subsequently, the molten metal was maintained at 750 °C for 20 min before removing any slag. The melts were then cast into a preheated mold at 200 °C. The resulting cast alloys had a diameter of 42 mm and a height of 150 mm.

2.2 Alloy fluidity and hot tearing mechanism testing

For the metal fluidity test, another part of the Mg-Y-Ni melt was cast into a preheated spiral mold. As shown in Fig. 1(a), the size of the spiral test mold was 224 × 224 × 130 mm^3, and it included spiral grooves with a width of 10 mm and a depth of 5 mm.

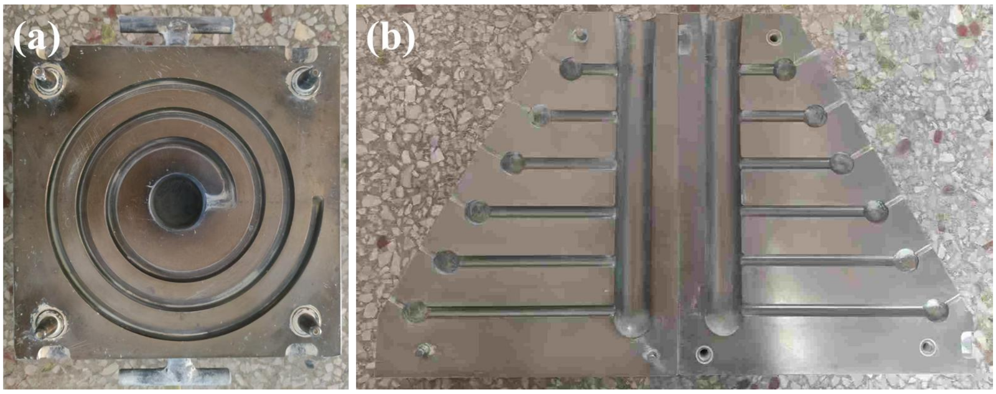

Fig. 1 The Mg-Y-Ni alloy casting properties test molds: (a) fluidity and (b) hot tearing mechanism

In the hot tearing test, a constrained-rod casting (CRC) mold was used to evaluate the HTS of the alloy. As shown in Fig. 2(b), the length of the constrained rods varied from the shortest to the longest at 51 mm (rod A), 75 mm (rod B), 95 mm (rod C), 121 mm (rod D), 143 mm (rod E) and 165 mm (rod F), respectively. The diameter of the restrained rods in the CRC mould was 9.5mm. a 19mm diameter ball end was fitted at the end of each rod.

2.3 Microstructure characterization and mechanical performance test

The microstructures of the Mg-Y-Ni alloys in the as-cast condition were detected by optical microscopy (OM) and scanning electron microscopy (SEM), respectively. Phase identification was carried out by transmission electron microscopy (TEM). The specimens for OM and SEM imaging were etched by using 4% nitric acid-alcohol mixture after a traditional mechanical polishing. The elastic modulus of samples was measured using the impulse excitation of vibration technique. The elastic modulus was calculated according to:

$$E = \frac{0.9465 \cdot \rho \cdot f_f^2 \cdot L^4}{t^2} \cdot T_1 \quad (1)$$

where E is damping elastic modulus, ρ is the density of the samples, f_f is the fundamental flexural resonant frequency, L and t are the length and thickness of the samples, respectively. T_1 is a correction factor which is a function of the dimensions.

3 Results and discussion

3.1 Mg-Y-Ni alloys microstructures

The as-cast optical microscopy image of the Mg-Y-Ni alloys are shown in Fig. 2. It reveals that the as-cast microstructure is constituted with a course α-Mg matrix phase (white contrast), block phase (gray contrast) and eutectic phase (black contrast). In addition, the volume fraction of the bulk phase increases with increasing Y-element content and becomes networked along the grain boundaries. At the same time, the eutectic phase gradually decreases. According to the literature that has been reported, the bulk and eutectic phases are LPSO and

Mg_2Ni phases, respectively [12].

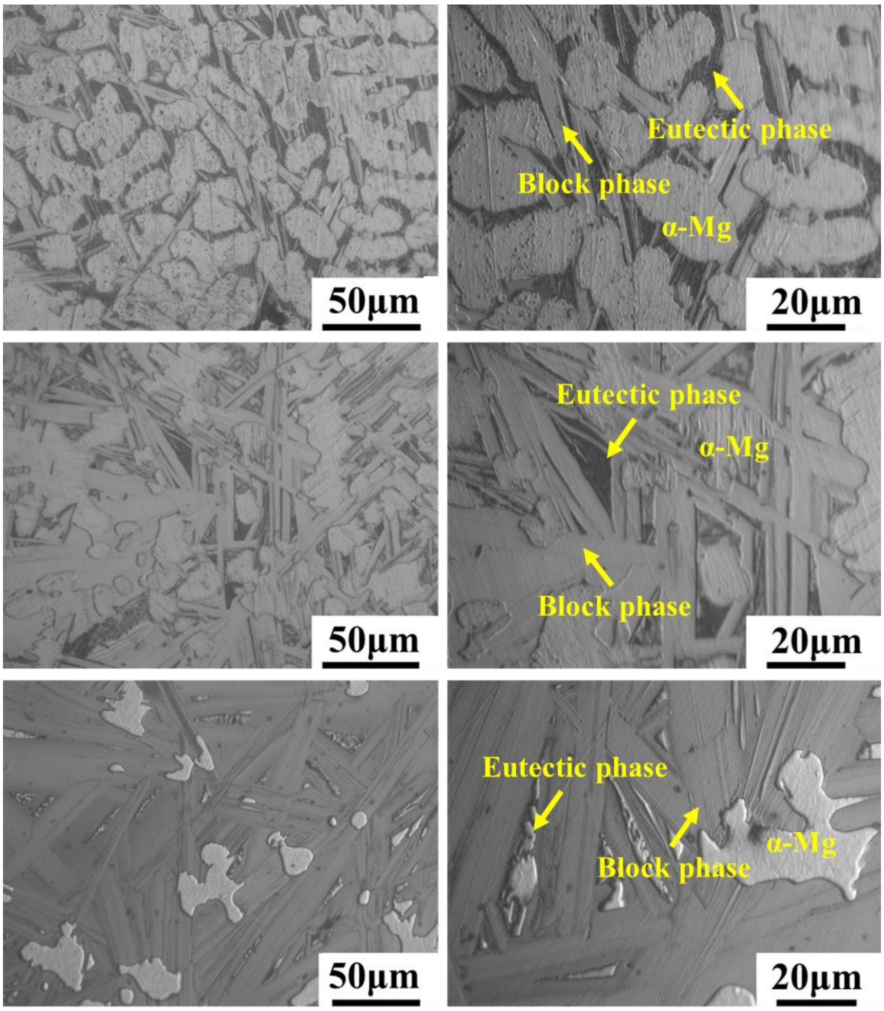

Fig. 2 OM images of as-cast Mg-Y-Ni alloys： (a, b) Mg-1.5Y-3Ni, (c, d) Mg-3Y-3Ni and (e, f) Mg-4.5Y-3Ni

To further identify the different secondary phases, the microstructures of the Mg-3Y-3Ni alloy are examined by SEM and TEM, as shown in Fig. 3. Positions A and B in Fig. 3(b) have been studied by EDS energy spectroscopy. Among them, the continuous bulk phase contains 3.7 at. % of element Y and 4.1 at. Its atomic ratio of Y to Ni is consistent with that of the LPSO phase studied by Zhu et al [13]. The ratio of Mg to Ni in the white eutectic phase is about 2:1, which is similar to the composition of the Mg_2Ni phase [12]. This is in agreement with our conclusions above. In addition, the type of LPSO phase was determined by selected area electron diffraction (SAED), and in Figure 3(d) five additional diffraction points appear at the n/6 position (n is an integer) of the (0002)α diffraction (α is the Mg matrix), confirming that the LPSO phase is of type 18R [13].

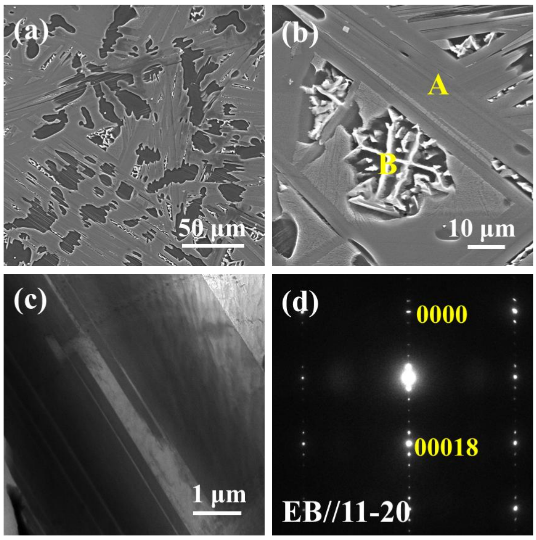

Fig. 3 SEM and TEM images of as-cast Mg-3Y-3Ni alloy: (a) Low magnification SEM, (b) High magnification SEM, (c) 18R-LPSO bright-field image and (d) The SAED pattern corresponding to 18R-LPSO

3.2 Mg-Y-Ni alloy fluidity and hot tearing mechanism

Figure 4 shows the filling lengths of cast Mg-Y-Ni alloys with different levels of Y content in a spiral test mold. Corresponding physical drawings of these four alloys are presented in the inset of this figure. It can be seen that the filling length increases from 263 mm to 304 mm to 365 mm as the Y content increases from 1.5 at. % to 3 at. % to 6 at. %. This result indicates that Y addition can effectively improve the metal fluidity of Mg alloys.

Figure 5 displays the cast produced from the CRC mold. It can be seen that cracks occur only at the gated end of each rod of the Mg-Y-Ni alloy. The Mg-.5Y-3Ni alloy shows the smallest tear among all the alloys. Both Mg-3Y-3Ni and Mg-4.5Y-3Ni alloys exhibit severe hot tearing. They even have much large tears than Mg-1.5Y-3Ni alloy. The Mg-1.5Y-3Ni alloy was not completely fractured, with large cracks occurring only at the gated end of the D rod. As the Y content increased, the C, D and E bars of the Mg-3Y-3Ni alloy fractured. In the Mg-4.5Y-3Ni alloy, which has the highest Y content, in addition to the fracture of the C, D and E bars, cracks were also observed at the gate end of the B bar. Thus, the HTS of the Mg-Y-Ni alloy decreases with increasing Y content.

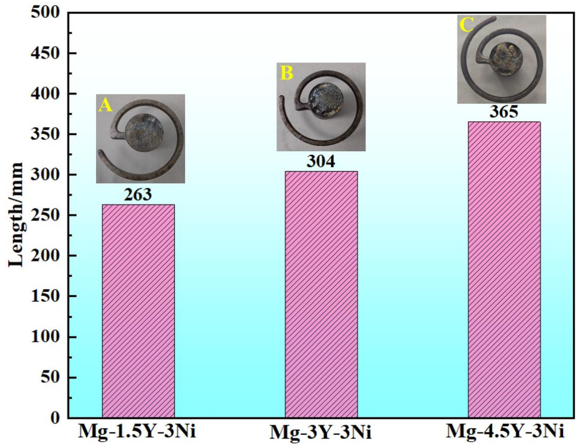

Fig. 4. Comparison of the filling length between fluidity samples of the Mg-1.5Y-3Ni, Mg-3Y-3Ni and Mg-4.5Y-3Ni alloys. (A)-(C) Fluidity casting samples corresponding to the Mg-1.5Y-3Ni, Mg-3Y-3Ni and Mg-4.5Y-3Ni alloys, respectively

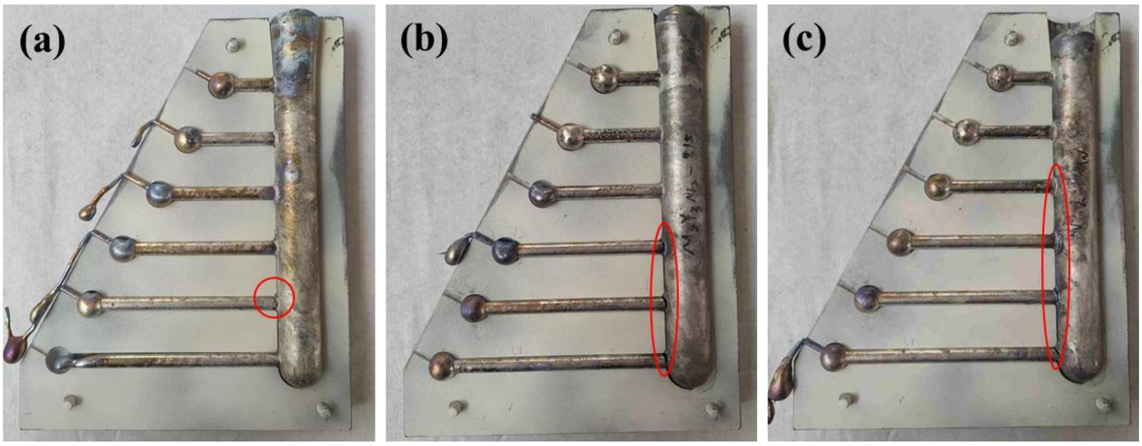

Fig. 5 Macrocracks pictures of hot tear mechanical in castings: (a) Mg-1.5Y-3Ni, (b) Mg-3Y-3Ni and (c) Mg-4.5Y-3Ni.

Hot tearing behavior is affected by many factors, which are mainly categorized into two kinds: material and cast parameters. Numerous studies proved that HTS is composition dependent. Different alloys may lead to various susceptible temperature ranges, grain size, residual liquid fraction, second phase, and dendrite coherency temperature which eventually result in different hot tearing behaviors [14-17]. In this study, the HTS of the Mg-Y-Ni alloy is only influenced by the alloy composition by using the same casting parameters. As the Y content increases, the α-Mg matrix in the Mg-3Y-3Ni and Mg-4.5Y-3Ni alloy transforms into the 18R-LPSO phase [18]. The alloy with 18R-LPSO phase exhibited low HTS due to the short solidification range, while the Mg-1.5Y-3Ni alloy with Mg_2Ni phase exhibited high HTS.

Furthermore, in Figures 3 and 4, the fluidity and hot tear mechanism of Mg-Y-Ni alloys have been tested using spiral and CRC molds respectively. It is noteworthy that the flowability and HTS of Mg-Y-Ni alloys show opposite trends with increasing Y element content. Most studies have showed that good fluidity of the alloy normally leads to low HTS because the residual liquid with good fluidity facilitates tear refilling and healing [19-21].

3.3 Mg-Y-Ni alloy elasticity modulus

The histogram of the modulus of elasticity (E) of the cast

Mg-Y-Ni alloys with different Y contents is shown in Fig. 6. It is apparent that the E significantly increases from 47.29GPa to 48.56GPa to 50.24GPa, corresponding to the Mg-1.5Y-3Ni, Mg-3Y-3Ni and Mg-4.5Y-3Ni. In general, the modulus of elasticity of magnesium alloys usually depends on the modulus of elasticity and the volume fraction of its matrix and second phase. As can be seen in Figure 2, only a small amount of 18R-LPSO phase and Mg_2Ni phase are present in the Mg-1.5Y-3Ni alloy. With increasing Y content, the volume fraction of 18R-LPSO phase increases while the volume fraction of Mg_2Ni phase decreases in Mg-3Y-3Ni alloy and Mg-4.5Y-3Ni alloy.

Luo et al. [22] calculated the elastic moduli of the α-Mg matrix and the 18R-LPSO phase in Mg-Y-Ni alloys to be about 43 GPa and 62 GPa, respectively, based on first-principles density functional theory (DFT). It can be seen that the conversion of α-Mg to 18R-LPSO phase in the alloys can effectively improve the overall Young's modulus of the alloys by modulating the Y element content.

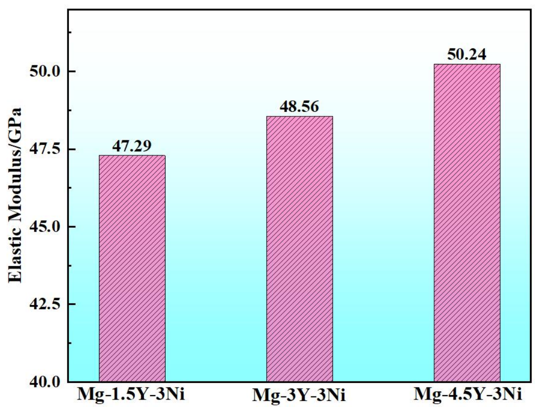

Fig. 6 Histograms of elastic modulus of cast Mg-Y-Ni alloys with different Y element contents

4 Conclusions

• This work investigates the effect of relative modulus, fluidity and hot tear tearing of long period stacking ordered (LPSO). The results show that increasing the volume fraction of the LPSO phase favours the improvement of the modulus and flowability, but also leads to an increase in the hot tear sensitivity.

• Optimization of the LPSO phase matrix synergies through the right amount of Y elements (3 at.%) increases the modulus and fluidity while controlling the risk of hot tearing.

• A further exploration is required into the effect of LPSO structural parameters on the elastic modulus and casting properties of magnesium alloys.

Acknowledgments

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Conflicts of interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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