A Novel High-Strength and High Modulus $Mg_{90}Y_4Zn_2Ni_4$ Alloy

Wenyu Liu[1], Wei Liu[1], Hua Hou[1,2], Yuhong Zhao[1*]
1.School of Materials Science and Engineering, Collaborative Innovation Center of Ministry of Education and Shanxi Province for High-performance Al/Mg Alloy Materials, North University of China, Taiyuan, Shanxi 030051, PR China.
2. School of Materials Science and Engineering, Taiyuan University of Science and Technology, Taiyuan, Shanxi 030024, PR China.
*Corresponding address: e-mail: zhaoyuhong@nuc.edu.cn

Abstract: A novel high strength, high modulus hot extruded Mg90Y4Zn2Ni4 alloy is reported here with an ultimate yield strength of 380MPa, elongation at break of 10% and modulus of elasticity of 51.3 GPa. The excellent strength of the hot-extruded alloy is primarily attributed to the combination of grain refinement, long-period stacking ordered (LPSO) strengthening, and precipitation strengthening induced by stacking fault and 14H LPSO phase, among which the LPSO strengthening is dominant. The significant increase in elastic modulus is then attributed to the high-volume fraction of the high modulus 14H LPSO phase. This study can enhance specific theoretical references for the development of high modulus, high strength, and tough deformed magnesium alloys needed for engineering applications.

Keywords: Magnesium, LPSO, Plastic deformation, Elasticity modulus, Mechanical testing

1 Introduction

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. The value of E for Mg alloys is ~45 GPa, which is about 3/5 of Al alloys and less than 1/5 of steels[1]. 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[2]. 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 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. Thus, Therefore, the introduction of the LPSO phase in Mg alloys can increase the overall modulus of elasticity. In addition, through plasticity processes such as hot extrusion, rolling and equal channel angles, LPSO short-fiber strengthening, LPSO kink band strengthening and refinement strengthening by recrystallisation (DRX) can be introduced into Mg alloys, which significantly improves the strong plasticity of the Mg alloy[3].

2 Experimental procedure

Ingots of $Mg_{90}Y_4Zn_2Ni_4$ alloy (atom percent, at. %) were prepared in a resistance furnace under an Ar_2 protective atmosphere. Then, the as-cast was subsequently homogenized at 500 ℃ for 12 h and subsequently water quenched. Finally, the specimen was extruded at 400 ℃ with extrusion ratio of 25 under extrusion speed of 0.4mm/s. After hot extrusion, the sample is immediately cooled with water. The microstructure of the hot-extruded alloy was observed using scanning electron microscopy (SEM). The metallographic specimens were etched with a magnesium alloy etching solution. Determination of the modulus of elasticity using the Buzz-o-sonic 5.6 Modulus of Elasticity Tester. Tensile results were calculated from the average values of three repeated tests to ensure reliability.

3 Result and discussion (Bold, 10 pt., Arial)

3.1 Mechanical performance of the $Mg_{90}Y_4Zn_2Ni_4$ alloys

Table. 1. Elastic modulus and tensile property of the $Mg_{90}Y_4Zn_2Ni_4$ alloys at different conditions.

Alloy	E/GPa	TS/MPa	YS/MPa	ε/%
Cast	50.85±0.5	211±8	104±6	6.3±0.4
Extruded	51.32±0.7	434±11	362±10	10.2±0.8

The elastic modulus (E) values of the $Mg_{90}Y_4Zn_2Ni_4$ alloys were 50.36 GPa and 51.32 GPa at the as-cast and hot-extruded states, respectively. Figure. 1 depicts the tensile stress-strain curves of as-cast and hot-extruded $Mg_{94}Y_4Zn_2Ni_4$ alloys at room temperature. Table. 1 lists their tensile strength (TS), yield strength (YS) and elongation to failure (ε). The results show that the TS, YS and ε of the as-cast $Mg_{90}Y_4Zn_2Ni_4$ alloy are only 219 MPa, 104 MPa and 6.3%, respectively. After hot extruded, the TS, YS and of the $Mg_{90}Y_4Zn_2Ni_4$ alloy significant increase. The hot-extruded $Mg_{90}Y_4Zn_2Ni_4$ alloy has an outstanding strength-ductility balance with TS=434 MPa, YS=362 MPa and ε=10.2%.

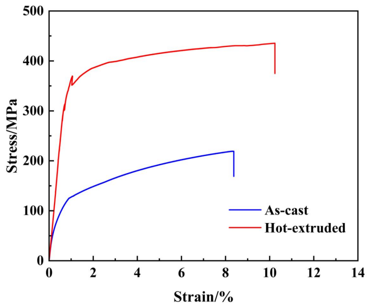

Fig. 1. Tensile properties of the as-cast and hot-extruded Mg94Y4Zn2Ni4 alloy.

3.2 Microscopic structure of the hot-extruded $Mg_{90}Y_4Zn_2Ni_4$ alloy

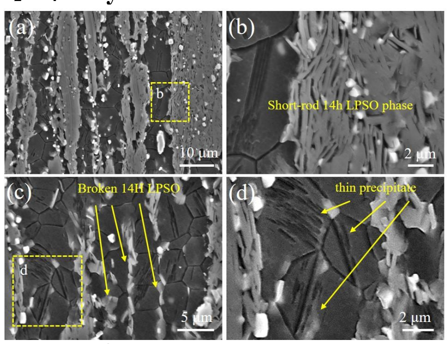

Fig. 2. SEM results of the hot-extruded Mg90Y4Zn2Ni4 alloy along the extrusion direction (ED).

The SEM image of hot-extruded Mg94Y4Zn2Ni4 alloy along the ED direction is presented in Fig. 2. It can be found that, the hot-extruded Mg90Y4Zn2Ni4 alloy exhibit an elongated microstructure in the ED. The hot extruded $Mg_{90}Y_4Zn_2Ni_4$ alloy comprises the 14H LPSO phase, diffusely distributed white granular phase and dynamically recrystallized grains, among which the 14H LPSO phase is dominant. Its volume fraction is about 65 %. The relatively high modulus of elasticity of 14H LPSO results in a significant increase in the overall modulus of elasticity of the $Mg_{94}Y_4Zn_2Ni_4$ alloy[4]. In addition, the LPSO phases display two morphologies: a block LPSO phase elongated along the extrusion direction and a fine, short-rod LPSO phase interspersed with each other. Fig. 2(b) shows a region with a dense distribution of short-rod LPSO phases, which are randomly distributed in different directions and are pinned together, resulting in better staple fibre reinforcement. It is observed in Fig. 2(c), a significant amount of completely fragmented LPSO phases were found to be distributed along the DRX grain boundaries in the region with a higher number of DRX grains. The broken LPSO has a better Particle Stimulated Nucleation (PSN) effect due to the increased number of nucleation sites, thus promoting DRX behavior. Furthermore, the precipitation of the SF and 14H LPSO phases was observed within partially recrystallised grains, which resulted in a strengthening effect on the precipitation.

4 Conclusion

The microstructure and mechanical properties of a novel high-strength and high modulus hot-extruded $Mg_{90}Y_4Zn_2Ni_4$ alloy. The main conclusions drawn from the results are as follows:

(1) The hot-extruded $Mg_{90}Y_4Zn_2Ni_4$ alloy has an outstanding modulus-strength-ductility balance with YS=362MPa, ε=10.2% and E=51.32GPa.

(2) The excellent mechanical properties of the hot-extruded $Mg_{90}Y_4Zn_2Ni_4$ alloy mainly originate from the combination of the combination of grain refinement, LPSO strengthening, and precipitation strengthening induced by stacking fault and 14H LPSO phase, among which the LPSO strengthening is dominant.

(3) The high-volume fraction (65%) of the high modulus 14H LPSO phase significantly increases the overall elastic modulus of the alloy.

5 Acknowledgments

This work was supported by National Natural Science Foundation of China (Nos. 52375394, 52074246, 52275390, 52205429, 52201146, 52305429), National Defense Basic Scientific Research Program of China (JCKY2020408B002), Shanxi Scholarship Council of China (No. 2021-125), Natural Science Foundation of Shanxi Province (No. 20210302124631), and Key Research and Development Program of Shanxi Province (Nos. 202102050201011, 202202050201014)

References

[1] Gu Z, Zhou Y, Dong Q, et al. Designing lightweight multicomponent magnesium alloys with exceptional strength and high stiffness[J]. Materials Science and Engineering: A, 2022, 855: 143901.

[2] Shi H, Xu C, Hu X, et al. Improving the Young's modulus of Mg via alloying and compositing–a short review[J]. Journal of Magnesium and Alloys, 2022, 10(8): 2009-2024.

[3] Liu W, Zhao Y, Zhang Y, et al. Deformation-induced dynamic precipitation of 14H-LPSO structure and its effect on dynamic recrystallization in hot-extruded Mg-Y-Zn alloys[J]. International Journal of Plasticity, 2023, 164: 103573.

[4] Tane M, Suzuki S, Yamasaki M, et al. Insignificant elastic-modulus mismatch and stress partitioning in two-phase Mg–Zn–Y alloys comprised of α-Mg and long-period stacking ordered phases[J]. Materials Science and Engineering: A, 2018, 710: 227-239.