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ARTICLE

Quantitative Strengthening Evaluation of Mg-Zn-Y Alloys Containing Icosahedral Quasi-Crystalline Phase

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Abstract: Mg-4.8Zn-0.8Y, Mg-18Zn-3Y, Mg-15Zn-5Y, Mg-30Zn-5Y and Mg-42Zn-7Y (wt%) alloys containing icosahedral quasi-crystalline phases were prepared using the ordinary solidification method. The impact of Mg matrix porosity on the tensile strength and hardness of the alloys was studied. The porosity of the Mg matrix was quantitatively assessed using scanning electron microscope and Image-Pro Plus 6.0 software. Tensile tests were conducted at room temperature. Results show that the maximum tensile strength of the alloy is 175.56 MPa, with a corresponding Mg matrix porosity of 76.74%. Through fitting analysis, it is determined that the maximum tensile strength is achieved when the porosity of the Mg matrix is 64.87%. The microhardness test results indicate a gradual decrease in alloy hardness with increasing the porosity of Mg matrix. This study provides an effective quantitative analysis method for enhancing the mechanical properties of magnesium alloys.

Key words: Mg-Zn-Y alloy; Mg matrix porosity; mechanical properties; quantitative analysis

1 Introduction

Due to its low density, high specific strength, and high specific stiffness[1–4], magnesium alloy possesses broad application prospects in new energy, aerospace, national defense, military, and automotive industries, earning the title of a green engineering material in the 21st century[5]. The rare earth magnesium alloy can form three ternary equilibrium phases[6–8], namely I-phase (Mg_3Zn_6Y, icosahedral quasi-crystal structure), W-phase ($Mg_3Zn_3Y_2$, cubic structure), and long period stacking ordered (LPSO) phase ($Mg_{12}ZnY$). The I-phase exhibits excellent mechanical properties such as high hardness and low surface energy[9–13], while the W-phase is characterized by high elastic modulus and hardness[14–15]. Meanwhile, the mechanical properties of rare earth magnesium alloy are not only related to the volume fraction of the secondary phase[16], but also affected by the content of Mg matrix and the grain size. As the main component of the alloy, Mg matrix will directly affect the strength and hardness of the alloy[17]. However, most studies have concentrated on the qualitative analysis of the secondary phase in magnesium alloy and the microstructure of the Mg matrix[18–21], overlooking the quantitative analysis. Therefore, conducting quantitative analysis using scanning electron microscope (SEM) to understand mechanical properties of rare earth magnesium alloy is of significant importance.

SEM can scan the surface area of samples with electrons through reflection or impact to produce images. Through SEM qualitative analysis, it has been concluded that the influence of different phases on relative mechanical properties in Mg-Zn-Y-Zr alloy follows the order: X-phase>I-phase>W-phase>$MgZn_2$[22]. Its mechanical properties surpass those of traditional magnesium alloys and rare earth magnesium alloys[9]. Nevertheless, to identify the optimal microstructure and improve the mechanical properties, quantitative analysis of the alloy is necessary. Daniel et al[23] studied the four basic structures of the Zn-Al-Mg-Sn alloy system using SEM, and

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performed quantitative analysis with the semi-automatic algorithm in MATLAB for alloys with different Sn contents. Sun et al[24] quantitatively studied the slip/twinning and theoretical critical shear strength of extruded pure Mg and Mg-1Y (wt%) under room temperature tensile deformation through electron backscattering diffraction, SEM, and first-principles calculation of Y addition. Lee et al[16,25] quantitatively analyzed the effects of icosahedral I-phase produced by different Zn/Y mass ratios, and other ternary phases such as cubic W-phase and LPSO-phase on Mg-Zn-Y series alloys[26–27]. At the same time, the strength of Mg-Zn-Y alloy increases with increasing volume fraction of I-phase in the alloy[16]. However, the importance of the Mg matrix in the alloy was overlooked. There are few reports about the influence of Mg matrix on the mechanical properties of Mg-Zn-Y alloy, and the quantitative analysis remains unclear.

In this study, the Mg-Zn-Y alloy was prepared using conventional solidification technique. The microstructure of the alloy was analyzed, and the mechanical properties were evaluated. Image-Pro Plus 6.0 was used to calculate the porosity of the α-Mg matrix, and the impact of Mg matrix porosity on mechanical properties was quantitatively analyzed through linear fitting. This approach offers an effective method for the quantitative analysis and improvement of the mechanical properties of magnesium alloys.

2 Experiment

In this study, Mg-4.8Zn-0.8Y (Alloy I), Mg-18Zn-3Y (Alloy II), Mg-15Zn-5Y (Alloy III), Mg-30Zn-5Y (Alloy IV), and Mg-42Zn-7Y (Alloy V) alloys (wt%) were prepared, and their chemical composition is presented in Table 1. The Mg-Zn-Y alloys were produced using high-purity Mg, high-purity Zn, and Mg-30Y (wt%) intermediate alloy. The alloy constituents were initially melted in an induction melting furnace under a protective atmosphere composed of CO_2 (99vol%) and SF_6 (1vol%), maintaining the molten state at 780 °C for 30 min. Subsequently, the as-cast Mg-Zn-Y alloy was cast into a steel mold measuring 260 mm×110 mm×30 mm at 720 °C.

The microhardness of the samples was assessed using an AHVD-1000XY semi-automatic high-end digital microhardness tester, applying a test force of 1.96 N with a pressure holding time of 10 s. For each sample, 15 test points were selected to calculate the average value. Tensile tests were conducted at room temperature using an MTS810 material testing machine with a displacement rate of 0.5 mm/min, and measurements were taken from three parallel samples in each group.

The microstructure of the alloys, under different composition and conditions, was examined using a field emission-scanning electron microscope (FE-SEM, FEI Quanta 650) equipped with energy dispersive X-ray spectroscope (EDS). A RIGAKU Smartlab 9 kW X-ray diffractometer (XRD, Cu Kα, 40 kV, 100 mA, 10–90 °C, 2 °C/min) was used to analyze the phase composition of the alloy.

Table 1 Chemical composition of Mg-Zn-Y alloys

Alloy	Zn/wt%	Y/wt%	Mg/wt%	Atomic ratio of Zn/Y
I	4.8	0.8	Bal.	8.04
II	18.0	3.0	Bal.	8.14
III	15.0	5.0	Bal.	4.08
IV	30.0	5.0	Bal.	8.17
V	42.0	7.0	Bal.	8.16

3 Results and Discussion

3.1 Characterization of as-cast Mg-Zn-Y alloy

Fig.1 shows XRD patterns of the prepared Mg-Zn-Y alloys. When Zn/Y (at%) is about 8, the alloys are mainly composed of α-Mg, I-phase (Mg_3Zn_6Y), and Mg_7Zn_3, whereas $Mg_{6.58}Zn_{21.84}Y_{7.58}$ with an asymmetric structure is also detected in Alloys I, II, and IV. Additionally, when Zn/Y (at%) is about 4, W-phase ($Mg_3Zn_3Y_2$) is present in Alloy III. Fig.2 shows SEM microstructures of the as-cast Mg-Zn-Y alloys. It can be seen that the as-cast alloy is mainly composed of a low-contrast matrix and a high-contrast secondary phase. The morphology of the high contrast areas from Alloy I to Alloy V transitions from spherical shape to a discontinuous skeletal network, then it evolves into a continuous skeletal network, and ultimately it changes into a lamellar structure.

Fig.3 shows EDS analysis results corresponding to points A–F in Fig.2. Through EDS and the analysis of the Zn/Y atomic ratio[25], it is clear that both the high-contrast spherical or skeletal mesh structures and the lamellar structures are I-phase. Further SEM observations indicate that Alloy I features a large matrix area of low-contrast α-Mg with spherical quasi-crystalline phase. On the other hand, Alloy II and III exhibit a fishbone morphology, transitioning from a discontinuous structure to a continuous network structure. The I-phase is found to be present within the (α-Mg+I-phase) eutectic structure. In Alloy V, α-Mg is nearly enveloped by a continuous lamellar eutectic structure (α-Mg+I-phase), resulting in a significant reduction of α-Mg. Previous investigations into the microstructure of Mg-Zn-Y alloys reveal that the I-phase can form interdendritic eutectic pockets alongside the α-Mg phase[28]. XRD analysis further reveals that an increase in Y content enhances the diffraction peak of the I-phase,

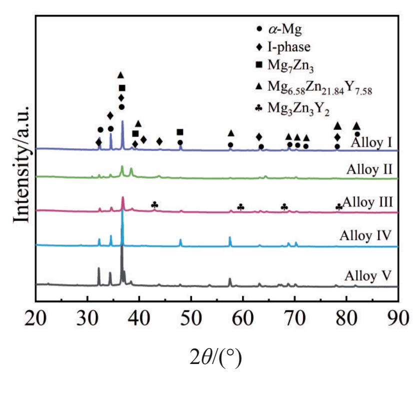

Fig.1 XRD patterns of as-cast Mg-Zn-Y alloys

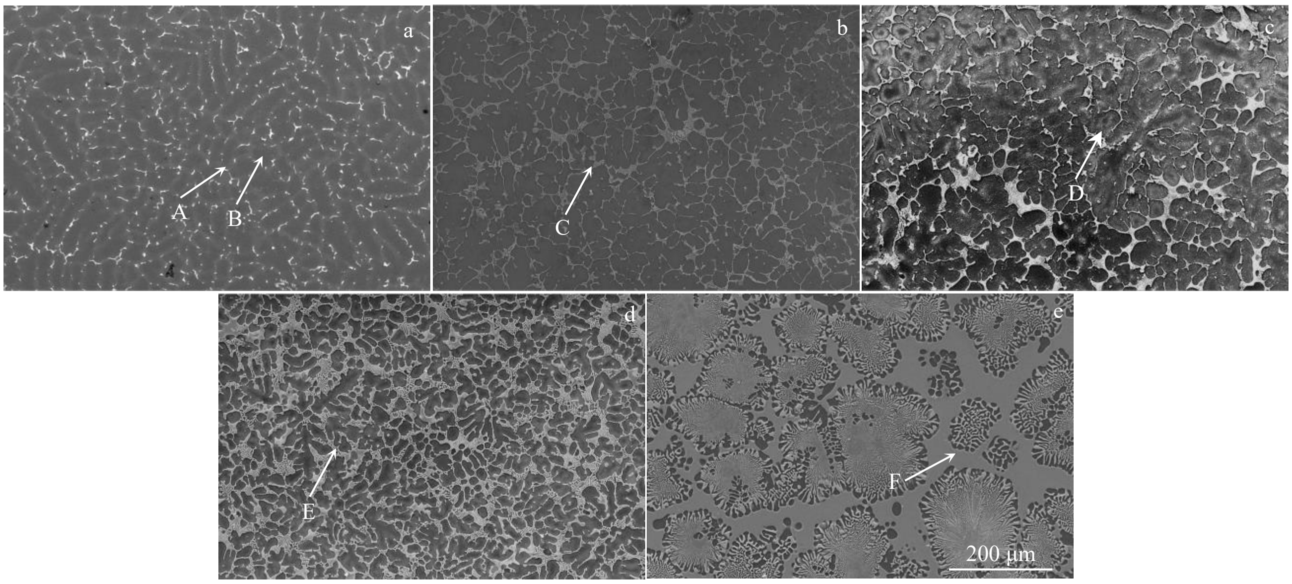

Fig.2 SEM microstructures of as-cast Alloy I (a), Alloy II (b), Alloy III (c), Alloy IV (d), and Alloy V (e)

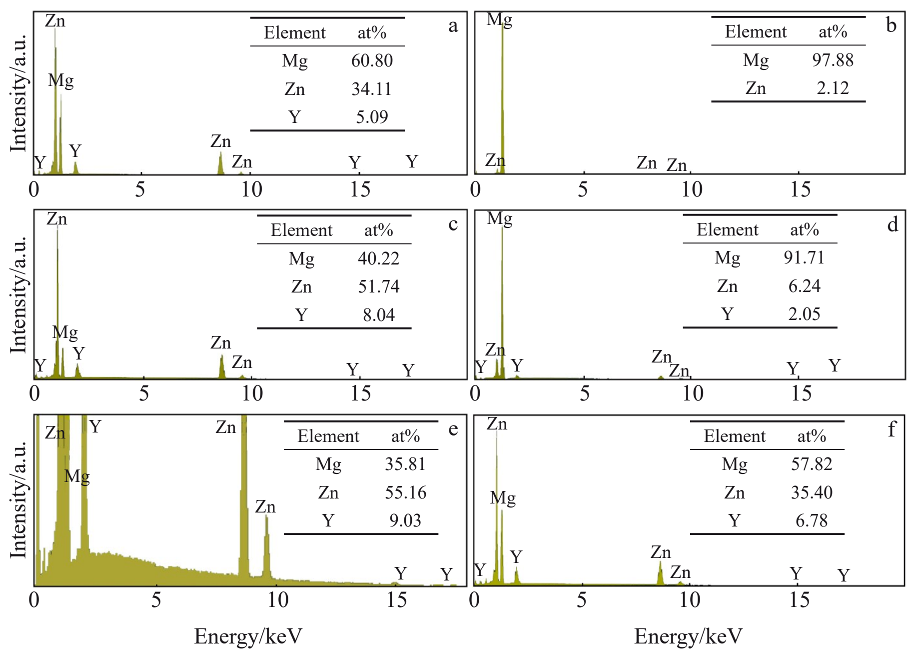

Fig.3 EDS results corresponding to point A (a), point B (b), point C (c), point D (d), point E (e), and point F (f) in Fig.2

indicating a gradual increase in the quasi-crystalline content, which correlates with SEM microstructures in Fig.2.

As shown in Fig. 4, Image-Pro Plus 6.0 software was utilized to calculate the porosity of the α-Mg matrix. Initially, the α-Mg matrix is marked as red area to calculate its area, followed by the calculation of the total area of SEM image using the software. In order to reduce the error of Image-Pro Plus 6.0 software in the calculation of phase content, SEM images with high quality and high contrast should be obtained in the experiment. At the same time, the area of each alloy component should be calculated three times and the average value was used for analysis. The porosity of the Mg matrix in Alloys I–V was calculated to be 95.93%, 85.91%, 76.74%, 70.15%, and 38.79%, respectively.

3.2 Mechanical properties of Mg-Zn-Y alloy and porosity analysis of Mg matrix

Fig.5 shows the engineering stress-strain curves of Mg-Zn-Y alloys at room temperature. It indicates that Alloy III possesses the highest tensile strength, which initially increases before decreasing. Table 2 shows the porosity of the Mg matrix in the alloy as well as the corresponding tensile strength and microhardness values, from which data fitting was conducted, as shown in Fig.6. Fig.6a shows the quadratic polynomial fitting curve of the tensile strength to the porosity of the Mg matrix for Mg-Zn-Y alloy at room temperature. It can be seen that the mechanical properties of the Mg-Zn-Y

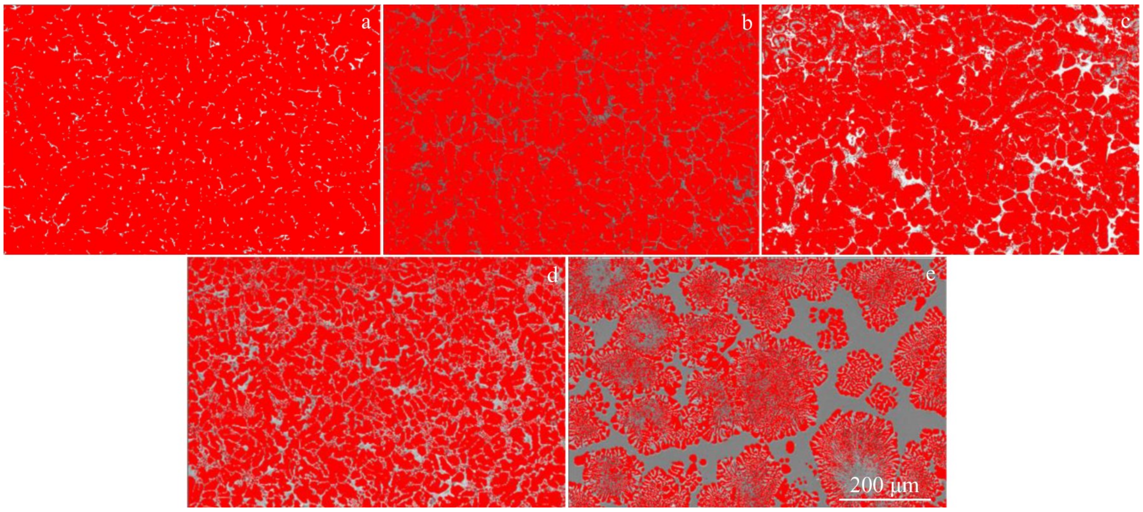

Fig.4 Quantitative analysis of SEM microstructures for as-cast alloys by Image-Pro Plus 6.0: (a) Alloy I; (b) Alloy II; (c) Alloy III; (d) Alloy IV; (e) Alloy V

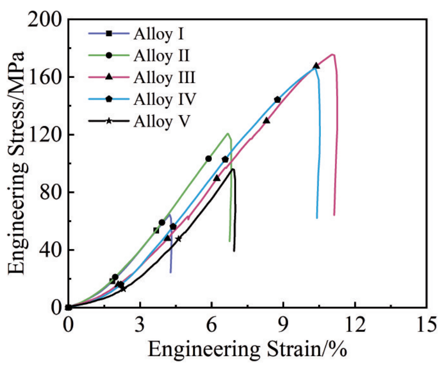

Fig.5 Engineering stress-engineering strain curves of as-cast Mg-Zn-Y alloys

Table 2 Performance of Mg-Zn-Y alloys (wt%)

Alloy	Tensile strength/ MPa	Microhardness/ HV	Mg matrix porosity/%
I	64.39	65.06	95.93
II	120.63	83.57	85.91
III	175.56	83.47	76.74
IV	165.80	131.37	70.15
V	96.12	150.57	38.79

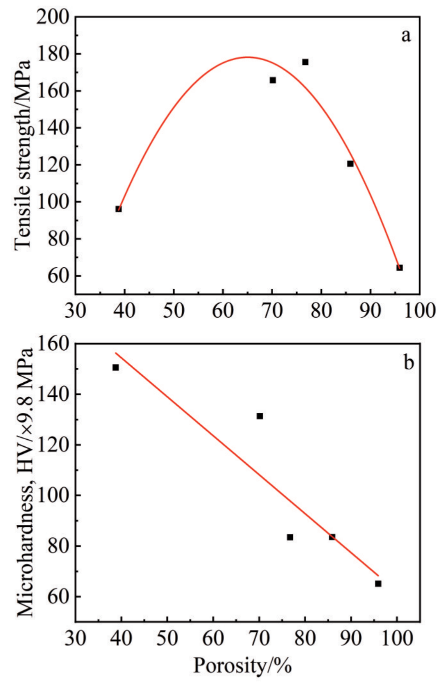

Fig.6 Quadratic polynomial fitting curve of tensile strength to Mg matrix porosity (a); linear fitting of microhardness to Mg matrix porosity (b)

alloy are significantly influenced by the content of Mg, as demonstrated by the polynomial fitting of five points of the Mg matrix porosity. The tensile strength of the Mg-Zn-Y alloy initially rises and then falls as the porosity of the Mg matrix increases. The quadratic polynomial, derived from linear fitting, gets a correlation coefficient (R) of 0.9652. Analysis of the fitting curve shows that the tensile strength is maximum (178.15 MPa) when the porosity of the Mg matrix is 64.87%. When the porosity of Mg matrix is relatively low, due to the high content of I-phase in the alloy, the interface between I-phase and Mg matrix is prone to stress concentration, resulting in crack initiation and propagation[29]. In addition, the excessive accumulation of the secondary phase will also cause the deformation and stress distribution in the loading process, so the tensile strength is lower. With the increase in porosity of Mg matrix, the content of I-phase in the alloy decreases, and the skeleton structure effectively prevents crack propagation, enhances the stability of grain boundaries, and hinders the movement of dislocation[30]. At the same time, the icosahedral quasicrystals have pinning effect on the grain boundary, contributing to the formation of a stable and solid interface between the Mg matrix and the quasi-crystalline phase[31], which also improves the strength of the alloy. When the porosity of Mg matrix in the alloy increases to a certain extent, the content of quasi-crystalline phase in the alloy decreases, so the strength of the alloy decreases.

Fig. 6b shows the linear relationship between the microhardness of Mg-Zn-Y alloy and the porosity of the Mg matrix. This figure shows that the microhardness of the alloy linearly correlates with the Mg matrix porosity, with a correlation coefficient (R) of 0.8488. The microhardness of the alloy progressively decreases as the porosity of Mg matrix increases. It is mainly attributed to the decrease in I-phase and the corresponding increase in Mg matrix porosity. It is known that the I-phase has higher microhardness with the properties of anti-coarsening and brittleness. With the increase in the porosity of Mg matrix in the alloy, the content of I-phase decreases, leading to the decrease in microhardness.

4 Conclusions

1) Mg-4.8Zn-0.8Y, Mg-18Zn-3Y, Mg-15Zn-5Y, Mg-30Zn-5Y, and Mg-42Zn-7Y (wt%) alloys were prepared using the conventional casting method, resulting in the formation of lamellar and porous Mg matrix along with granular and skeletal I-phase.

2) The tensile strength of Alloy III, superior to that of other as-cast alloys, is 175.56 MPa, with the Mg matrix porosity of 76.74%. From the characterization analysis, it can be seen that the mechanical properties of the alloy are optimal when the Mg matrix exhibits a cavity distribution and the I-phase forms a continuous skeletal network structure.

3) The fitting curve indicates that maximum tensile strength of 178.15 MPa is achieved at Mg matrix porosity of 64.87%. As the porosity of the Mg matrix increases, there is a gradual decrease in the microhardness of the alloy. This study provides an effective method for quantitative analysis aimed at enhancing the mechanical properties of magnesium alloys.

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含二十面体准晶相Mg-Zn-Y合金的定量强化评价

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摘　要：采用普通凝固法制备了含二十面体准晶相的Mg-4.8Zn-0.8Y、Mg-18Zn-3Y、Mg-15Zn-5Y、Mg-30Zn-5Y和Mg-42Zn-7Y （wt%）合金，研究了Mg基体孔隙率对合金抗拉伸强度和硬度的影响，并利用扫描电镜和Image-Pro Plus 6.0软件定量分析了镁基体孔隙率。室温拉伸试验表明，合金的最大抗拉伸强度为175.56 MPa，镁基体孔隙率为76.74%。通过拟合分析发现，当镁基体孔隙率为64.87%时，合金抗拉伸强度最大。硬度测试表明，随着镁基体孔隙率的增加，合金硬度逐渐减小。本研究为提高镁合金的力学性能提供了有效的定量分析方法。

关键词：Mg-Zn-Y合金；Mg基体孔隙率；力学性能；定量分析

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