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Effects of Y on mechanical properties and damping capacity of ZK60 magnesium alloys

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Abstract: The microstructure, mechanical properties and damping capacity of ZK60-*x*Y (*x*=0, 1.5%, 2.5%, 4.0%, mass fraction) magnesium alloys were investigated by using the optical microscope (OM), X-ray diffractometer (XRD), universal tensile testing machine and dynamic mechanical analyzer (DMA). The mechanisms for damping capacity of referred alloys were discussed by Granato-Lücke theory. The results show that Y additions remarkably reduce grain size (the average grain size is 21.6, 13.0, 8.6 and 4.0 μm, respectively), and the tensile properties are enhanced with grain refining (the yield tensile strength increases to 292 MPa from 210 MPa and ultimate tensile strength increases to 330 MPa from 315 MPa). For the ZK60-*x*Y (*x*=0, 1.5%, 4.0%) alloys, the damping capacity decreases with the increase of Y content. However, for the ZK60-*x*Y (*x*=2.5%) alloy, the damping capacity improves abnormally, which is possibly related to the formation of $Mg_3Y_2Zn_3$ (W) FCC phase in this alloy.

Key words: magnesium alloys; microstructure; mechanical property; damping capacity; Granato-Lücke Theory

1 Introduction

Vibration and noise pollution has seriously bad effects on people's work and living environment. Therefore, the application of high damping materials which aim to reduce or eliminate vibration and noise plays an increasingly important role in modern structural design[1]. Pure magnesium has excellent damping capacity, high specific strength and stiffness, good cutting and polished performance, but the mechanical strength of pure magnesium is low, which cannot serve as structural material and be widely used[2−3]. ZK60 is a kind of high-strength wrought magnesium alloy, whose strength is close to that of high-strength 7075 aluminum alloy, and has broad application prospects. However, the contradiction between mechanical properties and damping capacity of ZK60 magnesium alloy confines its more widespread applications. Therefore, the balance optimization of mechanical properties and damping capacity of ZK60 magnesium alloy was attempted by using the ordinary methods such as processing and heat treatment, and some positive effects were gained[4−5]. The attempt that adding rare earth element into ZK60 magnesium alloy to improve its performance has caused extensive concerns since the 20th century[6]. The current concerns mainly lay on the influence of the addition of Y on microstructure and mechanical properties[7−9], but rarely damping capacity. Consequently, in this work, the influence of the addition of Y on mechanical properties and damping capacity of ZK60 magnesium alloy was systematically investigated by designing ZK60 magnesium alloys containing 0, 1.5, 2.5, 4.0 (mass fraction, %) contents of Y; meanwhile, the mechanism of Y additions on damping capacity of ZK60 magnesium alloy was also studied.

2 Experimental

Experimental ZK60 magnesium alloys with Y content of 0, 1.5%, 2.5% and 4.0% (mass fraction) were prepared from commercial pure magnesium (99.95%), zinc (99.95%), Mg-30Zr master alloy and Mg-25Y master alloy in electrical resistance furnace with the

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protection of 0.2%SF_6+CO_2 mixed gas. The chemical compositions of the designed ZK60-*x*Y alloys are listed in Table 1. The ingots were homogenized at 400 ˚C for 29 h then extruded in a 2 500 t of LXJ-horizontal extruder (the extrusion ratio was 25, and the extrusion temperature was 450 ˚C).

Table 1 Chemical composition of test alloys ZK60+*x*Y (mass fraction, %)

Alloy No.	Mg	Zn	Zr	Y
1	93.8	6.0	0.2	0
2	92.4	5.7	0.4	1.5
3	91.6	5.5	0.4	2.5
4	90.3	5.3	0.4	4.0

The microstructure of specimens was examined with the Olympus optical microscope. The phase analysis was carried out by Rigaku D/MAX2500PC X-ray diffractometry (XRD) with copper target. Tensile testing at ambient temperature was performed in a Shimadzu CMT-5105 material testing machine. Damping capacity was tested using dynamic mechanical analysis (TA- DMA Q800) in single cantilever vibration mode at a test frequency of 1 Hz. The samples for damping were machined with dimension of 45 mm× 5 mm×1 mm on electric spark cutter and damping capacity was evaluated by the loss tangent (tan φ). Measurements of damping capacity at ambient temperature were made at various strain amplitudes from 1×10^{-5} to 8×10^{-3}. For the measurements of temperature dependence of damping capacities, the testing conditions were as follows: the strain amplitude 5×10^{-3}, the temperatures range from −100 to 400 ˚C and the heating rate 5 ˚C/min.

3 Results and discussion

Fig.1 shows transverse sectional microstructures of the extruded ZK60-*x*Y (*x*=0, 1.5%, 2.5%, 4.0%) alloys. In ZK60 alloy without Y, it is observed that a clean, fine and equiaxed grain structure with an average grain size of 21.6 μm (Fig.1(a)). But with the increase of Y content, the grain size becomes smaller with an average grain size of 13.0 μm, 7.6 μm and 4.0 μm, respectively (Figs.1(b), (c) and (d)). The additions of Y have the well distributed grain and the cleaned grain interior. There is no obvious precipitate appeared in the grain interior with increasing content of Y except the Alloy 3. This also suggests that Y element can properly solve in the ZK60 magnesium alloys.

Fig.2 shows the XRD patterns of the alloys. The main phases of the ZK60-*x*Y (*x*=0, 1.5%, 2.5%, 4.0%) are α-Mg, Mg-Y-Zn-Zr and Mg_7Zn_3 phase, and there is a new phase $Mg_3Y_2Zn_3$(*W*-phase) in Alloy 3. In microstructure, the dispersion of the black dispersed precipitates in Fig.1(c) may be this phase[10]. The $Mg_3Y_2Zn_3$ is face-centered cubic crystals with high melting point and high thermal stability, and it is difficult to grow up and will cause more slip system[11].

During the deformation, the extruded ZK60-*x*Y (*x*=0, 1.5%, 2.5%, 4.0%) alloys have no obvious yield

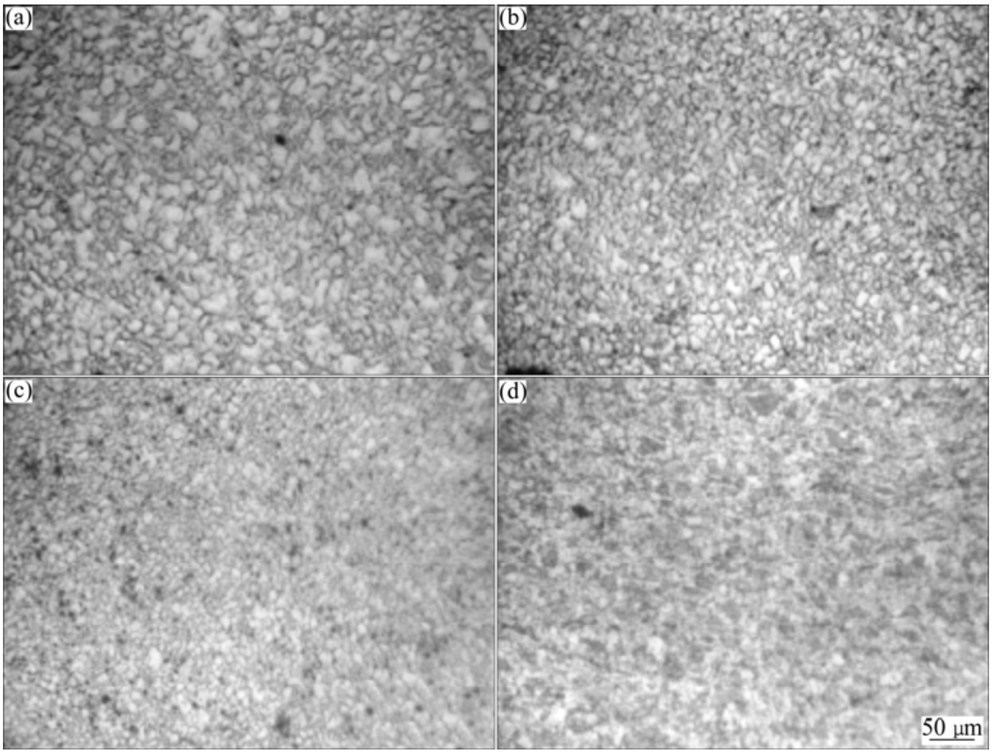

Fig.1 Microstructures of as-extruded ZK60+*x*Y magnesium alloys: (a) ZK60; (b) ZK60+1.5%Y; (c) ZK60+2.5%Y; (d) ZK60+4.0%Y

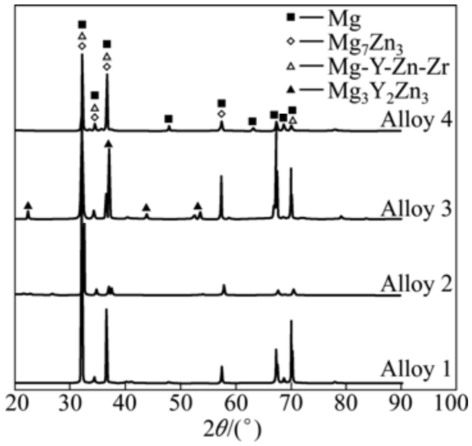

Fig.2 XRD patterns of as-extruded ZK60-xY (x=0, 1.5%, 2.5%, 4.0%) magnesium alloys

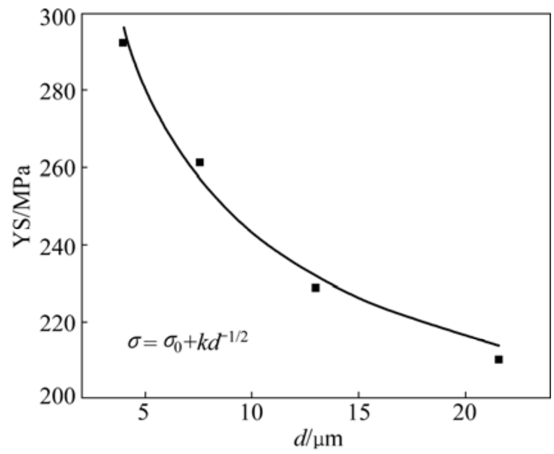

Fig.3 Fitting curve of relation between YS and grain size of alloys

point from elastic deformation to plastic deformation. The strain of the elastic deformation process is small. After yielding, materials enter the stage of homogeneous plastic deformation. With the increase of strain, stress keeps stable. Table 2 shows the influence of different extrusion process on mechanical properties of ZK60-xY alloys.

Table 2 Mechanical properties of as-extruded ZK60-xY(x=0, 1.5%, 2.5%, 4.0%) magnesium alloys

Alloy No.	UTS/MPa	YS/MPa	Elongation/%
1	315	210	19
2	313	229	16
3	313	261	18
4	330	292	21

With the addition of Y, the ultimate tensile strength (UTS) of ZK60-xY (x=0, 1.5%, 2.5%, 4.0%) alloys increases from 315 to 330 MPa, the yield strength (YS) increases from 210 to 292 MPa and the elongation increases from 19% to 21%. In all, with the increase of Y content, the mechanical properties of alloys are improved, because of the grain refinement of Y. With the increase of Y content, the role of the refinement is more obviously. And the finer the grains are, the higher the strength of alloys is. Then, the strength of alloys is increased by the solid solution strengthening of Y, but the elongation of the alloys is decreased slightly.

The quantitative relation between the average recrystal grain size d and the yield strength σ is fitted by

$$\sigma = 151.4 + 290 d^{-1/2} \quad (1)$$

This formula fits well with the Hall-Petch equation $\sigma=\sigma_0+kd^{-1/2}$. According to this equation, yield strength is inversely proportional to the square root of grain size of alloys[12]. Fig.3 shows the fitting curve.

Fig.4 shows the strain dependence of damping capacity of ZK60-xY alloys. From Fig.4, it is clear that the curves can be divided into two areas: in the first area, the amplitude of strain is small, and damping parameter Q^{-1} has almost nothing to do with the amplitude of strain and shows a straight line. When the amplitude of strain reaches to a certain value—larger than the critical value of strain[13], with the increase of amplitude of strain, the Q^{-1} increases rapidly. Therefore, damping capacity of alloy Q^{-1} can be expressed with Q_0^{-1} and Q_h^{-1}, respectively, as:

$$Q^{-1}(\varepsilon) = Q_0^{-1} + Q_h^{-1}(\varepsilon) \quad (2)$$

It can be seen that in the small strain amplitude, the damping capacity of each sample is small and changes little with the increase of strain amplitude. But when the strain exceeds a certain critical value, the damping capacity begins to increase rapidly with the increase of strain. The curves show that in high strain amplitude region, the damping capacities of Alloys 1, 2 and 4 decrease with the increase of strain, but the damping

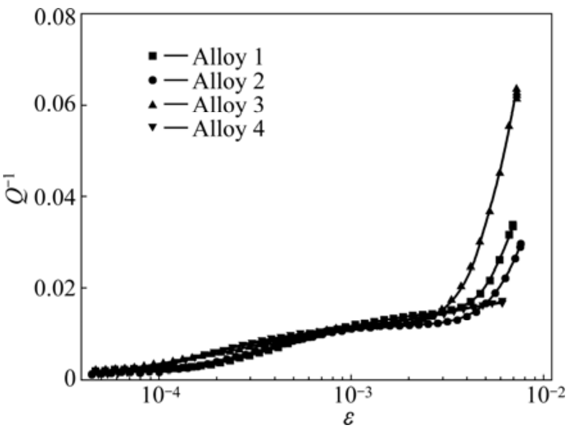

Fig.4 Damping—strain amplitude curves of ZK60-xY (x=0, 1.5%, 2.5%, 4.0%) magnesium alloys

capacity of Alloy 3 increases rapidly. The properties of Alloys 1, 2 and 4 fit well with the rule that mechanical properties and damping capacity are contrary, but the property of Alloy 3 is excellent. The possible reason is the appearance of the $Mg_3Y_2Zn_3$ (W-phase) new phase.

W-phase has been reported in Refs.[14−16]. It appears when the molar ratio of Zn to Y achieves to a certain value, but there is no report about the effect of this phase on the damping capacity of alloy. The damping capacity of Alloy 3 increases more than that of Alloys 1, 2 and 4. It is maybe due to two reasons. First, new phase purifies the matrix and decreases pinning effect of dislocation. Second, the thermal expansion coefficients of new phase are different with the matrix. So, it makes the mobile dislocation density increased, and the damping capacity is increased too. The damping capacity of Alloys 2 and 4 is lower than that of Alloy 1 because of the addition of Y can make the lattice of grain distort. It causes the aggregation of the element atoms to dislocation line nearby. The pinning effect of element atoms will make the dislocation line curve, and then decrease the damping capacity of alloys by decreasing the mobile dislocation density and effective dislocation length. Y can refine the grain size significantly, and the smaller the grain size is, the more quantity the grain boundaries have. The grain boundaries are effective hindrances of dislocation motion; dislocations move difficultly and cannot unpin even under the large strain, so damping capacity is low.

In addition, the measurement of temperature dependence of damping capacities of Alloy 1 and Alloy 3 was carried out (Fig.5). It can be seen that the damping capacity of Alloy 3 is higher than that of Alloy 1 below 100 ˚C. But above 200 ˚C, both the dislocation damping and the boundary damping take effect simultaneously and the main effect is from the grain boundary. With decreasing the temperature, the elements in Alloy 3 begin to distribute along the grain boundary uniformly. The segregation hinders the moving of grain boundary, and the boundary damping depends mainly on the moving between the grain boundaries. This moving can consume energy and bring out the internal friction. So, at high temperature, the damping capacity of Alloy 3 is lower than that of Alloy 1.

The damping capacity mechanism of alloy is dislocation damping mainly at room temperature. So, G-L theory is used to explain the damping capacity of alloys. According to G-L dislocation pinning model[17], at low temperatures the damping of magnesium alloys is made by moving dislocations and the point defects. At high amplitude of strain, when the additional stress increases, dislocation breaks away at weak points. This phenomenon is called “avalanche form” and Expressed by[18]

$$Q_{\mathrm{h}}^{-1}=\frac{C_1}{\varepsilon}\exp(-\frac{C_2}{\varepsilon}) \tag{3}$$

where $C_1=\Omega\Lambda L_{\mathrm{N}}^3 K\eta\alpha/(\pi^2 L_{\mathrm{C}}^2)$, $C_2=K\eta\alpha/L_{\mathrm{C}}$, ε is the amplitude of strain, Ω is the orientation factor, Λ is the densities of mobile dislocation, K is the factor related with the elasticity coefficient of anisotropy and sample orientation, η is the mismatch coefficient of solute and solvent atoms, α is the lattice constants, L_{N} is the length between strong pinning points, and L_{C} is the length between weak pinning points. This equation can be rewritten as

$$\ln(\varepsilon\cdot Q_{\mathrm{h}}^{-1})=\ln C_1-C_2\varepsilon^{-1} \tag{4}$$

It can be seen that $\ln(\varepsilon\cdot Q_{\mathrm{h}}^{-1})$ and $1/\varepsilon$ should be of a linear relationship, and the intercept is ln C_1, the slope is $-C_2$. The larger the intercept, the better the damping capacity. And the smaller the slope, the better the damping capacity. Fig.6 shows G-L curves of ZK60-*x*Y (*x*=0, 1.5%, 2.5%, 4.0%) alloys. The linear relation in Fig.6 shows the damping capacity of the alloys in this work fits the G-L model well.

It is obvious that the intercept of Alloy 3 is the

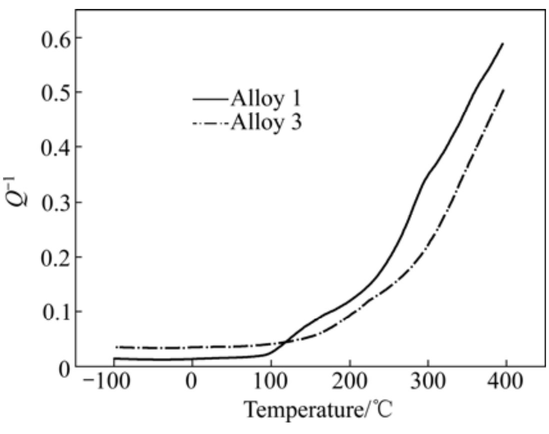

Fig.5 Damping—temperature curves of ZK60-*x*Y (*x*=0, 2.5%) magnesium alloys

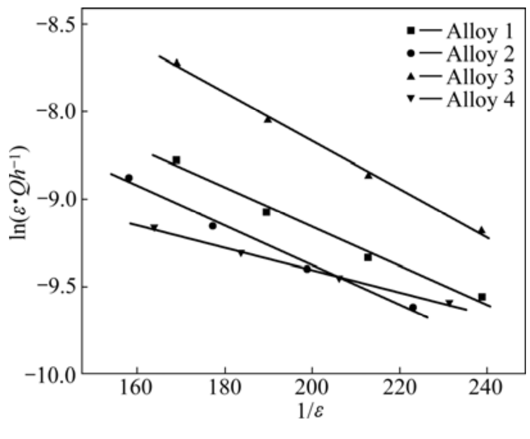

Fig.6 G-L plots of ZK60-*x*Y (*x*=0, 1.5%, 2.5%, 4.0%) magnesium alloys

largest, so the damping capacity is the best. The slope of Alloy 1 is the same as that of Alloy 2, but the intercept of Alloy 1 is larger than that of Alloy 2, so the damping capacity of Alloy 1 is larger than that of Alloy 2. Although the slope of Alloy 4 is smaller than others, its intercept is the smallest, so the damping capacity of Alloy 4 is the smallest. So, these all can be explained by G-L model.

4 Conclusions

1) The addition of Y reduces the grain size of ZK60-*x*Y (*x*=0, 1.5%, 2.5%, 4.0%, mass fraction) alloys. The more the Y content is, the finer the grain size will be, and the better the mechanical property of alloy is. This is consistent with the Hall-Petch equation.

2) The mechanical properties of alloys increase, meanwhile the damping capacities decrease unfortunately. But the damping capacity of alloy with the content of 2.5%Y addition is excellent because of appearance of the $Mg_3Y_2Zn_3$ (*W*) phase.

3) The damping capacity of the alloys can be well explained by Granato-Lücke theory.

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