Effects of Y content on microstructure, mechanical and damping properties of Mg–Al–Y alloys

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Abstract

The effect of Y on microstructure, mechanical properties, and damping properties of the extruded and annealed Mg–1Al–xY (x = 4, 6, 8) alloys has been studied. The grain sizes of Mg–Al–Y alloys decreased with the increase of Y. The mechanical properties of Mg–Al–Y alloys improved with increasing Y content. The temperature-dependent damping spectrum could be divided into three parts. The vibration frequency weakly affects the damping capacity of Mg alloys. The result of temperature-dependent damping capacity indicated that the overall trends of the tan δ decreased at first and then increased with the Y Mg–Al–Y alloys at temperatures between 300 K to 675 K. There were two temperature damping peaks P₁ and P₂, which was caused by grain boundary relaxation and grain boundary slip, respectively. Grain boundary slip can significantly affect the damping capacity of the Mg alloys at high temperature. The results of XRD showed that the residual stresses existed in the Mg–1Al–xY (x = 4, 6, 8) alloys after the damping test, which was consistent with the results of damping performance test.

1. Introduction

High damping properties can effectively reduce or eliminate vibration and undesirable noise of materials and play a very important role in the applications and design of engineering structural materials [1–5]. Mg alloys have been attracted significant attentions in aircraft and automobiles industries due to their excellent properties, such as light weight, high specific strength, and environmentally friendly [6–10]. Generally, magnesium alloys with favorable mechanical properties always exhibit poor damping capacities. Thus, finding ways to simultaneously achieve optimal mechanical and damping properties of Mg-based alloys is very important.

In the past decades, there were many researches on damping capacity of Mg alloys [11–13]. Zhao et al developed a novel Mg–Y–Zn–Al–Li alloy with high elastic modulus and damping capacity [14]. Mg–Zr binary alloys have been verified good damping properties [15–17]. Niu et al found that the Y content have greatly influence on damping and mechanical properties of as-cast Mg-0.6Zr-xY ternary alloys. Wang et al [18] reported that the addition of Y in Mg–Zr alloys can effectively improve the mechanical and damping capacity. Ma et al reported that the damping properties of deformed Mg could be promoted by a small amount of Nd and Dy [19]. Wan et al revealed that the addition of Mn could improve the mechanical and damping properties of as-cast Mg-3 wt.%Ni alloy [20]. The influence of some alloying elements on the damping capacity of Mg alloys has been studied. However, the Y content effect on the damping capacity of Mg alloys is still lacking reported. The addition of Al element to Mg-RE alloys could form high modulus and high hardness Al2RE phases, which could increase the modulus of Mg alloys [21–25]. The addition of Y element in Mg–Al alloy can refine the matrix grains and improve the mechanical properties of Mg alloys [26, 27]. The Al3Y phase increased the proportion of the interfaces and improved the mechanical properties of the magnesium alloy. Both the interfaces and the second phase could pin the dislocations, which make the movement of the dislocations difficult and reduce the damping
performance of the magnesium alloy. At present, the influence of Y content and precipitates Al2Y on the mechanical and damping performance of Mg–Al–Y alloy is still lacking reported.

In this work, the microstructure, mechanical and damping properties of Mg–1Al–xY (x = 4, 6, 8) alloys were systematically studied. The effect of Y content on the mechanical and damping properties of as-extruded Mg–1Al–xY (x = 4, 6, 8) alloys with the belief that the parameters provided will be helpful in their applications where simultaneously demanded high mechanical and good damping properties.

2. Experimental

The raw materials for preparing Mg–1Al–xY alloy in the experiment are pure magnesium ingot (99.9 wt %), pure aluminum ingot (99.9 wt %), and Mg–Y master alloy. All raw materials were purchased from Tangshan Weihao Magnesium Powder Co., Ltd P. R. China. A crucible furnace was used to melt the materials, when the crucible was heated to the specified temperature (730 °C), three raw materials ingots were put into the crucible and melt under the protection atmosphere by a mixture of CO2 and SF6. The melts were poured into the steel-mold and cooled by air. The as-cast Mg alloys were processed into a cylindrical specimen of Φ44 × 34 mm. The as-cast Mg–1Al–xY (x = 4, 6, 8) alloys were extruded by using IM-Y300. The used extrusion temperature is 550 °C and the extrusion ratio is 13:1, and the extrusion rate is 0.2 mm min−1. The as-extruded rod-shaped samples covered with Al2O3 powder were put into the muffle furnace and heated at 500 °C for 2 h. The covered Al2O3 powder can make the sample evenly heated and prevent the surface of the sample from being oxidized by direct contact with air during the heat treatment process.

The phases of Mg–Al–Y alloys were analyzed by the X-ray diffraction (XRD, BRUKERXD8AD VANCE-A25). The microstructures and distribution of elements of the alloys were acquired by using scanning electron microscopy (SEM) equipped with Energy Dispersive X-ray (EDX) and electron backscatter diffraction (EBSD). The mechanical properties of Mg alloys were carried out by the universal testing machine. The damping performances of Mg alloys were obtained by the Netzsch DMA 242E dynamic thermomechanical analyzer under protection of argon gas with a flow rate of 80 ml min−1. The temperature–damping relationships of the Mg alloys were tested by the three-point bending method. The magnitude of damping capacity was described by the stress–strain lag angle tan φ. The temperature range is 25°C–400 °C, the absolute target amplitude is 30 μm, and the frequency selected is 0.5 Hz, 1.0 Hz, 5.0 Hz, 10.0 Hz.

3. Results and discussion

Figure 1 shows the X-ray diffraction patterns of as-extruded Mg–1Al–xY (x = 4, 6, 8) alloys. It was found that the α–Mg and precipitate phase Al2Y can be obtained in Mg–Al–Y alloys, and the α–Mg was the main phase. The addition of different Y content has a significant effect on the phases composition of the magnesium alloys. The relative peak altitude of Al2Y phase in the XRD pattern of three Mg alloys increased with the increase of Y, which
means the content of Al$_2$Y phases in the three alloys is increased. The microstructures of Mg-Al-xY (x = 4, 6, 8) alloys were acquired by using the EBSD technique. The grain orientation distribution maps of Mg–Al–Y alloys are shown in figures 2(a)–(c). The grain sizes of the Mg alloys decrease with the increase of Y content, the grain size of Mg-1Al-xY (x = 4, 6, 8) alloy gradually becomes finer. It can be seen from figure 2(d) that the average grain size of the Mg alloy decreased from 14.6 $\mu$m to 8.1 $\mu$m. The grains of three alloys present an equiaxed crystal. Because of the as-extruded Mg alloys were heat treated at 500 $^\circ$C for 2 h, which makes the Mg alloys undergo complete dynamic recrystallization. It was found that the grain size distribution of Mg-1Al-4Y alloy was the most uniform, and there was no obvious extrusion streamline. The grain size distribution of Mg-1Al-6Y alloy and Mg-1Al-8Y alloy were not uniform, but the average grain sizes of two alloys were small, and there have an obvious extrusion streamlines.

The microstructures and elemental mapping of Mg-Al-Y alloys were obtained by SEM. The element distributions of Mg, Al, and Y elements are showed in figure 3. The maximum intensity of Al and Y occurs in the white particles, which confirmed the distribution of precipitates Al$_2$Y observed in the XRD pattern. The element mapping results of as-extruded Mg-Al-Y alloy alloys also indicated that the Al$_2$Y phases presented a weak streamline distribution phenomenon, which was consistent with the experimental result of EBSD. The content of the precipitates Al$_2$Y gradually increases with the increase of Y content, which can significantly pin the movement of dislocations and improve the strength of materials.

The tensile mechanical properties of the extruded-annealed Mg-Al-Y alloys were measured by a universal testing machine at room temperature. It can be seen from figure 4 that the tensile strength, yield strength and elongation of the Mg alloys have been significantly improved with increases of Y. The Mg-1Al-8Y alloy have the best mechanical properties, the tensile strength, yield strength and elongation are 240.85 MPa, 160.51 MPa, and 21.71%, respectively. The grain size decreased with the increase of Y content, which lead to fine-grained strengthening. The amount of the second phases Al$_2$Y increase with the increase of Y content, and dispersedly distributed, which play a role of dispersion strengthening for the Mg alloys. The coarse grains of Mg-Al-Y alloys crushed during intense plastic deformation by extrusion, and the alloys undergo dynamic recrystallization to generate fine grains during the heat treated. Grain boundaries can strongly hinder the movement of dislocations. The finer the grains, the more grain boundaries, the greater the ability to hinder the movement of dislocations, which significantly enhanced the strength of the material. The Al$_2$Y can pin the dislocations and hinder the
growth of cracks, which improved the tensile strength of the alloy. The evenly distributed Al2Y phases in Mg-Al-8Y alloy make the mechanical properties of Mg-Al-8Y alloy superior to two other alloys.

In order to study the fracture mechanism of Mg alloys, the fracture morphologies were analyzed by SEM. It can be seen from figure 5 that there are many dimples left at the fractures features of Mg-Al-Y alloys, which indicate that the fracture modes of the three alloys are ductile fractures. The number of fracture dimples in the alloy increases with the increasing of Y content. Therefore, the plasticity of Mg-1Al-8Y alloy is the best.

Figure 6 is the SEM image of tensile fracture of the Mg-1Al-8Y alloy with an enlarged magnification. The distribution of the Al2Y phase at fracture surface can be obtained from the EDS element mapping analysis. It can be observed from the figure 6 that the Mg alloy directly brittle fracture and produces longitudinal cracks at the coarser second phase. The fine second phase Al2Y was better combined with the Mg matrix than that of coarser Al2Y, resulting in pull out at the second phase when the alloy fractured, which can consume external energy and improve the tensile strength of the alloy. The three Mg-Al-Y alloys have similar fracture morphology. The content of the second phase Al2Y in the Mg-1Al-8Y alloy is the highest, therefore, its mechanical properties are the best.

The influence of different frequencies of Mg-1Al-xY alloys on the damping performance with increase of temperature were obtained by the Netzsch DMA 242E dynamic thermomechanical analyzer (shown in figure 7). The temperature-dependent damping capacity at the strain amplitude of $3 \times 10^{-5}$ m. The selected frequency is
0.5 Hz, 1 Hz, 5 Hz, 10 Hz, respectively. The temperature range is set from 300 K to 680 K, the heating rate is 5 K min\(^{-1}\). Figure 7(a) shows the damping-temperature spectrum of Mg-1Al-4Y alloy with different vibration frequencies. It can be found that the tan \(\phi\) decreased with the vibration frequencies and the difference increases with increasing temperature. The damping-temperature curves of 5 Hz and 10 Hz are basically coincided. The result of temperature-dependent damping capacity indicated that the overall trends of the tan \(\phi\) decreased at first and then increased with the Y addition to Mg-1Al alloys at temperatures between 300 K to 675 K, and the discrepancy was obvious above 550 K. Meanwhile, the tan \(\phi\) of the Mg alloys decreased with the vibration frequencies. When the temperature is lower than 393 K, the damping capacity of the Mg-Al-Y alloys basically do not change with the temperature. There are weak pinning points such as impurity atoms and vacancies on the dislocation line, the dislocation slip from the pinning point is a thermally activated process. The movement of the dislocation inside the material is more difficult at low temperatures, the dislocations cannot get rid of the pinning and need to go through more area to consume energy. Therefore, the damping change of the alloy is small. When the temperature is higher than 393 K, the first damping peak \(P_1\) appeared in the Mg-Al-xY alloy. The damping peak has a wide peak width, the peak temperature of the \(P_1\) damping peak shifts to high

![Figure 5. SEM picture of tensile fracture of the Mg-1Al-xY alloy. (a) \(x = 4\); (b) \(x = 6\); (c) \(x = 8\).](image-url)
Figure 6. The SEM elemental mapping of fractures of Mg-1Al-8Y alloy.

Figure 7. Temperature-dependent damping spectrum of Mg alloys: (a) Mg-1Al-4Y alloy, (b) Mg-1Al-6Y alloy, (c) Mg-1Al-8Y alloy.
temperature with the frequency increases, which conforms to the characteristics of grain boundary relaxation. Therefore, this P1 peak should be a grain boundary relaxation peak. It can be inferred that the distribution of Al2Y in the grain boundaries of the alloy makes the grain boundaries viscoelastic in the Mg-Al-xY alloy, resulting in an inelastic effect and the P1 damping peak. A P2 damping peak appeared at about 632 K. It is believed that grain boundary slip caused this peak.

Figure 8 shows the damping temperature spectrum of alloys with different Y content under the vibration frequency of 1 Hz. It can be clearly seen that the damping curve can be divided into three typical damping-temperature stages (zone I, zone II, zone III). In zone I (298 K–393 K), the damping capacity of different alloys basically did not change with temperature. That was because the dislocation motion satisfies the G-L pinning theory at low temperatures. According to the G-L theory [28–30], solution atoms act as weak pinning points of dislocations, and dislocations are divided into independent fragments by solution atoms. Dislocation fragments can bend between weak pinning points and cause internal friction at low temperatures. The resistance of the dislocation swing between weak pinning points is related to the lattice distortion caused by the solute atoms. The lattice distortion is the main factor affecting the low-strain damping performance of the Mg-Al-Y alloys. In zone I, Mg-1Al-4Y alloy has the largest damping value, and Mg-1Al-6Y alloy has the smallest damping value.

In the II zone (393 K–550 K), the grain boundary damping peak of Mg-1Al-xY (x = 4, 6, 8) alloy makes its the damping performance significantly improved in this temperature range. However, when the temperature was higher than 550 K in zone III, the damping capacity increased rapidly with the temperature elevated. It was found that the Mg-Al-xY alloys have grain boundary slips at 550 K, and the grain boundary slips generate a lot of internal friction. Grain boundary slip is another plastic deformation mechanism in addition to the twinning and the dislocation slip. The damping performance is obviously related to the characteristics of the grain boundaries. Grain boundary slip can significantly affect the damping capacity of the fine-grained Mg alloys. Grain boundary slip plays an important role in improving the damping of Mg-1Al-xY (x = 4, 6, 8) alloy in the high temperature stage. Meanwhile, it can be observed that the temperature of grain boundary slip occurs in Mg-Al-8Y is higher than that of Mg-Al-4Y and Mg-Al-6Y alloy. That is because a large number of Al2Y in Mg-1Al-8Y have an obstructive effect on the sliding of grain boundaries. Due to the coefficient of thermal expansion (CTE) of Al2Y (15 × 10−6 K−1) was smaller than that of magnesium alloy (26 × 10−6 K−1), the thermal mismatch may lead to

![Figure 8. Temperature-dependent damping spectrum of Mg-1Al-xY (x = 4, 6, 8) alloys at 1 Hz. (a) 298–700 K; (b) 298 K–393 K; (c) 393 K–550 K; (d) 550 K–700 K.](image-url)
residual strain or strain accumulation in Mg-Al-Y alloys. When the inter stress near the interface is much higher than the yield strength of the Mg-1Al-xY alloy, the strain induced by thermal mismatch arouse new dislocations at the interface between matrix and Al2Y. Therefore, the increase rate of the damping value of Mg-Al-8Y is higher than that of Mg-Al-4Y and Mg-Al-6Y in the temperature range of 600–650 K. The increasing of the dislocations density is another reason for the high damping peak in Mg-1Al-8Y alloys.

In order to further study the influence of the Al2Y on the damping performance of the Mg-1Al-xY alloy, which need to calculate the damping activation energy of the grain boundary. Zener [31] believed that when the grain boundary is viscoelastic, it will relax when subjected to shear stress. The viscous flow of the grain boundary can convert the mechanical energy into heat energy under the cyclic load, which causes energy loss, thereby generating grain boundary damping. Researches on grain boundary damping shows that the factors that affect grain boundary damping are: temperature, grain size, and the number of impurity atoms on the grain boundary. It can be obtained from figure 7 that the P1 damping peak is related to frequency, and the damping peak temperature increases with the increase of frequency, which indicates that the grain boundary damping peak has a thermal activation relaxation process. Therefore, the relaxation time and activation energy can be determined by the Arrhenius formula [32]:

\[ \tau = \tau_0 \exp \left(-\frac{H}{RT_p}\right) \]  

(1)

In the formula, \( \tau_0 \) is a constant, which is the relaxation time when the formula \( H \rightarrow 0 \) or \( T_p \rightarrow \infty \). \( H \) is the activation energy, \( R \) is the gas constant, and \( T_p \) is the peak temperature. Take the logarithm of both sides of equation (1) to become equation (2):

\[ \ln \tau = \ln \tau_0 - \frac{H}{RT_p} \]  

(2)

It was calculated from figure 9 that the activation energy of Mg-1Al-4Y alloy is 773.9 kJ mol\(^{-1}\), the activation energy of Mg-1Al-6Y alloy is 1303.7 kJ mol\(^{-1}\), and the activation energy of Mg-1Al-8Y alloy is 1688.9 kJ mol\(^{-1}\), which are higher than the self-diffusion activation energy of pure magnesium (134 kJ mol\(^{-1}\)). The grain boundaries sliding lead to the appearance of grain boundary peaks, and its activation energy was close to the self-diffusion activation energy. However, due to the difference in the state of grain boundaries including solute atoms and precipitated phases Al2Y, its activation energy may be higher or lower than the self-diffusion activation energy of pure magnesium. The characteristics of the damping peak are related to the number of solute atoms and precipitated phase Al2Y around grain boundaries. According to the Arrhenius formula, the grain boundary activation energy of Mg-1Al-4Y alloy is the smallest. The grain boundary activation energy of the Mg-Al-xY alloy increased with the increase of Y content, which are much higher than the self-diffusion activation energy of pure magnesium. As the increase of Y content, the grain size of the alloy is refined and the grain boundary increases, and the precipitated phases Al2Y around the grain boundary have a strong effect on the grain boundary. The pinning effect makes the movement of the grain boundary more difficult. The granular Al2Y distributed at the grain boundary have a certain pinning effect on the grain boundary, which delays the appearance of the grain boundary damping peak, and the grain boundary activation energy also increases to a
certain extent. Mg-1Al-8Y alloy has more second phase Al$_2$Y. Such a large number of Al$_2$Y can pin the grain boundary during the vibration of the Mg alloys, which hinder the movement of the grain boundary. Thus, the activation energy required for the grain boundary slip became larger.

There were residual stresses in the Mg-1Al-4Y, 6Y, 8Y alloys after the damping test, which can be analyzed by XRD spectrum. Figure 10 shows the XRD comparison diagram of Mg-Al-Y alloys before and after the damping test. It can be found that the phase peak is slightly shifted to the left and broadened. It was indicated that the lattice distance of Mg-Al-Y alloys increased. The solid solution atoms cause the lattice constant to change, which lead to the lattice distortion and the formation of the macroscopic residual stress in the three Mg alloys. The macroscopic residual stress may cause anisotropic shrinkage of the lattice, and when stress is tensile stress, the diffraction peak shifts to a low angle. It was consistent with the results of damping performance test.

4. Conclusion

The Mg-1Al-xY (x = 4, 6, 8) alloys were prepared by melting and casting. It was found that the grain sizes of the Mg alloys decrease with the increase of Y content and the grains of three alloys present an equiaxed crystal. The mechanical properties and damping capabilities of Mg-Al-Y alloys were obtained. Many dimples left at the fractures features of Mg-Al-Y alloys indicated that the fracture modes of the three alloys are ductile fractures. The mechanical properties of Mg-1Al-8Y alloy is the best. The Y addition has a significant effect on damping capacity of Mg-1Al alloys at temperatures between 300 K to 675 K. The lattice distortion is the dominant factor affecting the low-strain damping capacity of the Mg-Al-Y alloys at low temperature. Grain boundary slip can significantly affect the damping capacity of the Mg alloys at high temperature. According to the Arrhenius formula, the calculated grain boundary activation energy of the Mg-Al-xY alloy increased with the increase of Y content, which were higher than the self-diffusion activation energy of pure Mg. The grain boundaries sliding lead to the appearance of grain boundary peaks, and its activation energy was close to the self-diffusion
activation energy. The macroscopic residual stress in the Mg-1Al-xY (x = 4, 6, 8) alloys after the damping test were verified by XRD.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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