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Effects of Y and Zn on mechanical properties and damping capacity of Mg-Cu-Mn alloy

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Abstract: Optical microscope, X-ray diffractometer, scanning electron microscope, tensile tester and dynamic mechanical analyzer (DMA) were applied to investigate the effects of Y and Zn additions on microstructure, mechanical properties and damping capacity of Mg-3Cu-1Mn (CM31) alloy. The results show that with the increase of Y and Zn contents, the secondary dendrite arm spacing of alloys is reduced; meanwhile, the yield strength is increased. In low strain amplitude, the damping capacity of alloys with Y and Zn addition is lower than that of CM31 alloy. However, in strain amplitude over 5×10^{-3}, the damping capacity of alloy with a trace of Y and Zn addition (1%Y and 2%Zn, mass fraction) increases abnormally with the increase of strain amplitude and is near to that of pure Mg, probably due to the increase of dislocation density caused by the precipitation of secondary phase. The temperature dependence of damping capacity of above alloy was also tested and discussed.

Key words: Mg-Cu-Mn alloy; Y; Zn; magnesium alloys; damping capacity; Granato-Lücke theory

1 Introduction

With the development of modern industry and transportation, noise pollution caused by the vibration has become one of the serious environmental problems. The development and application of high damping materials is one of the effective measures to reduce noise. Magnesium and its alloys are the lightest structural metallic materials with excellent properties, such as high specific strength and high specific elastic modulus[1]. Pure magnesium has the best damping properties among various metallic materials; however, easy-corrosion and poor mechanical properties limit its more widespread applications. Thus, it becomes a continuous subject to develop high damping magnesium alloys[2]. In previous studies, the mechanical properties of damping magnesium alloys can be properly improved by the way of alloying or heat treatment[3−4], but the damping capacity decreases obviously. The as-cast hypoeutectic Mg-Ni alloys exhibit high damping capacity and adequate mechanical properties, but unfortunately it is poor in corrosion resistance[5]. Other Mg alloys such as Mg-Zr[6], Mg-Ca[2], Mg-Si[7−8] were studied in order to develop a promising damping magnesium alloy. Among these researches, the sintered Mg-Cu-Mn alloy developed by NISHIYAMA et al[9] by the method of powder metallurgy (PM) technique had rapture strength of 290 MPa and damping capacity even exceeding that of pure magnesium at strain amplitudes above 4×10^{-5}. However, powder metallurgy technique is complicated and the cost is high. Therefore, a high damping Mg-Cu-Mn alloy with relatively low cost was expected to be developed by adding some alloying elements and using common metallurgical process in this work.

It was reported that Y was an important alloying element which can strengthen magnesium alloys[10−11]. Zn was often chosen in the study of magnesium alloys because of its good solid solution strengthening ability in magnesium matrix. In this work, the influence of Y and Zn additions on the mechanical properties and damping capacity of Mg-Cu-Mn alloys is investigated.

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2 Experimental

In order to obtain the Mg-Cu-Mn alloys, Mg-30%Cu, Mg-4.1%Mn, Mg-30.30%Y (mass fraction) master alloys, pure Zn and pure Mg were melted in an electrical furnace using a mild steel crucible under the argon atmosphere at 850 °C, and then the melt was cooled in air after adequate stirring. The nominal compositions of the alloys are shown in Table 1, and the mass ratio of Y to Zn was kept at about 1:2. Rectangular bending beam specimens for damping measurements with dimensions of 40 mm × 5 mm × 1.2 mm were machined using an electric spark cutting method. Optical microscope, X-ray diffractometer (XRD) and scanning electron microscope (SEM) were applied to observe the microstructure, phase constituent and fracture morphology of alloys. The mechanical properties of samples were tested on a versatile tensile testing machine and the damping capacity of alloys was investigated by a TA Q800 dynamic mechanical analyzer (DMA) with single cantilever vibration mode. The damping capacity was determined by Q^{-1}=tan Φ, where Φ was the lag angle between the applied strain and the response stress. Strain dependent damping capacity measurements were made at various maximum strains (ε) from 1×10^{-5} to 3×10^{-3} at room temperature and vibration frequency (f) of 1 Hz. For the measurements of temperature dependent damping capacity, the test conditions were as follows: the strain amplitude (ε) was 1×10^{-4}, the vibration frequency (f) was 1 Hz, the temperature (T) range was from 35 °C to 400 °C and the heating rate was 5 °C/min.

Table 1 Nominal compositions of prepared Mg-Cu-Mn alloys (mass fraction, %)

Alloy No.	Composition
1	Mg-3Cu-1Mn (CM31)
2	Mg-3Cu-1Mn-1Y-2Zn
3	Mg-3Cu-1Mn-3Y-6Zn

3 Results and discussion

3.1 Microstructure

The optical microstructures of as-cast alloys are presented in Fig.1. The microstructures of these alloys consist of α-Mg matrix grains and compound phase which precipitates along the grain boundary. With the increase of Y and Zn addition, a more continuous distribution of compound phase occurs, and the grain boundaries become finer and closed. Moreover, the secondary dendrite arm spacings of alloys are reduced to about 15, 12 and 9 μm, respectively, for alloys 1, 2 and 3. The grain refinement of alloys is probably caused by two reasons. On one hand, the grain of α-Mg matrix can be effectively refined by Y element. During the growth of α-Mg matrix grains, the solute Y distributing on solid/liquid interface could drag the dendrites growth and finally refine the grains[6]; on the other hand, with the increase of the contents of Y and Zn, more compound phases precipitate along the grain boundaries and pin them, impeding the growth of dendrites. Fig.2 shows XRD patterns of Mg-Cu-Mn alloys. The main phases of alloy 1 are Mg, Mg_2Cu and α-Mn.

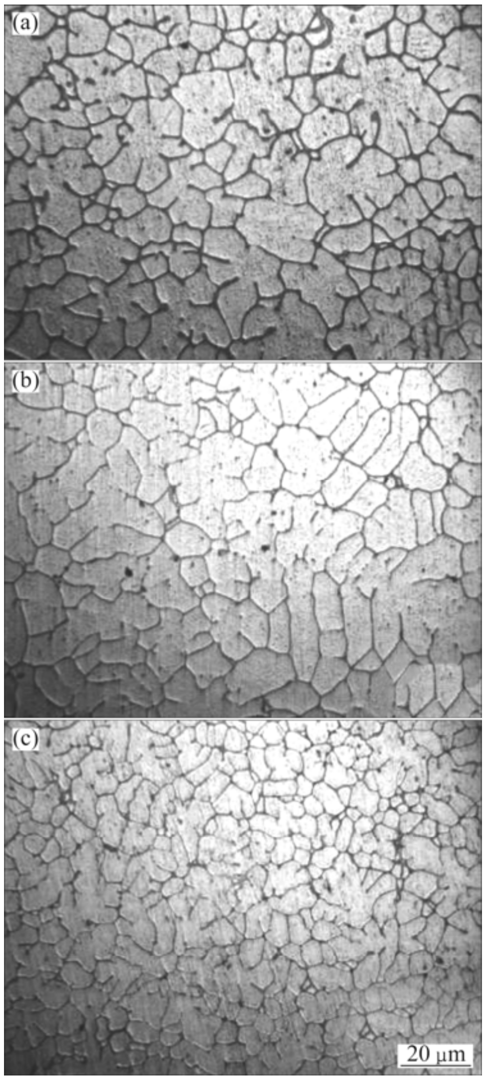

Fig.1 Microstructures of Mg-Cu-Mn alloys: (a) Alloy 1; (b) Alloy 2; (c) Alloy 3

3.2 Mechanical properties

The stress−strain curves of Mg-Cu-Mn alloys are shown in Fig.3. The elastic modulus (E) of alloys increases with the increase of Y and Zn additions. It is indicated that alloys are stiff and brittle after adding Y and Zn, which has been proved by fractographs of alloys shown in Fig.4.

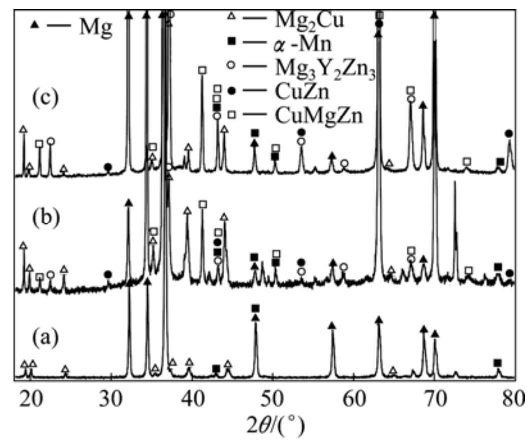

Fig.2 XRD patterns of Mg-Cu-Mn alloys: (a) Alloy 1; (b) Alloy 2; (c) Alloy 3

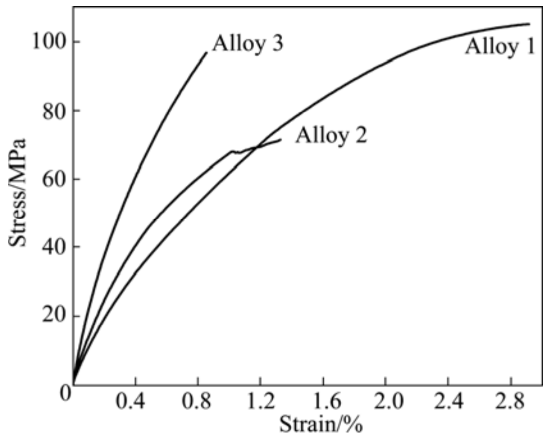

Fig.3 Stress−strain curves of Mg-Cu-Mn alloys

Fig.5 shows the mechanical properties of as-cast Mg-Cu-Mn alloys. With the increase of Y and Zn additions, the yield strength (YS) is gradually improved. The strengthening mechanisms derive from two parts. First, owing to the additions of Y and Zn, α-Mg matrix grains are refined. According to the well-known Hall-Petch formula, the yield strength of alloys could be enhanced when the grain size decreases. Second, some parts of Y and Zn atoms are probably dissolved into α-Mg matrix, which could play a role of solid solution strengthening. However, Alloy 1 without Y and Zn addition exhibits the largest ultimate tensile strength (UTS), and then the ultimate tensile strength of alloy 2 and alloy 3 ascends with the increase of Y and Zn contents. Meanwhile, the elongation of alloys decreases monotonously with Y and Zn additions. After adding Y and Zn into Mg-Cu-Mn alloy, compound phases will precipitate along the grain boundary, which increases with the increase of Y and Zn contents, and they are usually brittle, leading to the intergranular brittle fracture during tension. It is confirmed by the fractographs shown in Fig.4 that, the fracture surface of Alloy 2 and Alloy 3

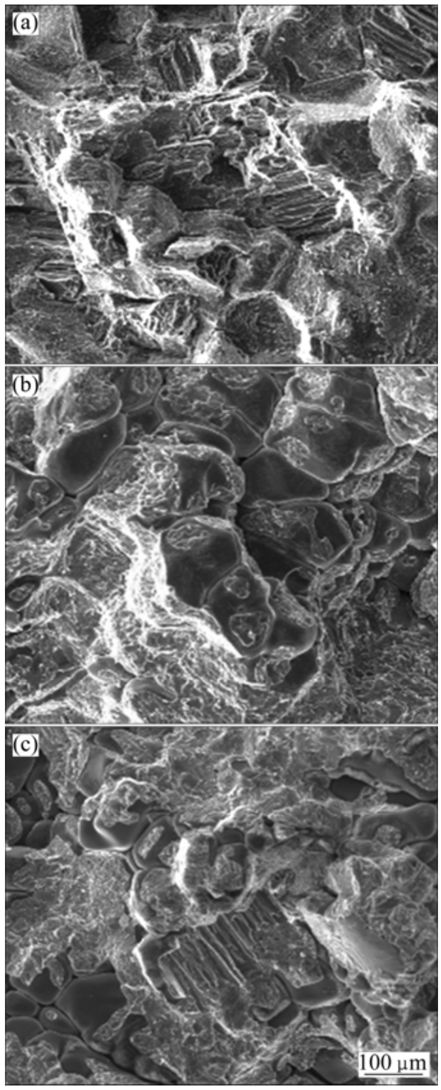

Fig.4 Fractographs of Mg-Cu-Mn alloys: (a) Alloy 1; (b) Alloy 2; (c)Alloy 3

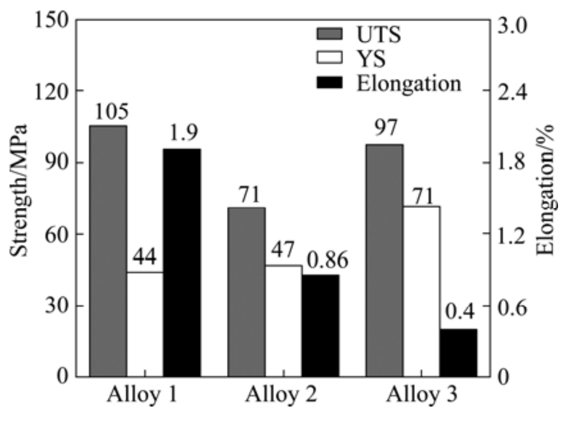

Fig.5 Mechanical properties of Mg-Cu-Mn alloys

are quite smooth, in which even glossy grain can be clearly observed. Alloy 1 without Y and Zn addition has obvious dimples and better plasticity. Furthermore, defects such as pores and entrainment may reduce the ultimate tensile strength and elongation.

3.3 Damping capacity

Strain amplitude dependence of damping capacity in as-cast Mg-Cu-Mn alloys are shown in Fig.6. It can be seen that the curve can be divided into two parts: strain-amplitude weakly dependent part and strain-amplitude strongly dependent part. The turning point of curve corresponds to the critical strain amplitude (ε_c). According to the classic "Granato-Lücke" theory[12], the damping capacity of magnesium alloys can be divided into two components:

$$Q^{-1}= Q_0^{-1}+ Q_H^{-1} \tag{1}$$

$$\begin{cases} Q_0^{-1} \sim L_c^4 \rho \\ Q_H^{-1} = (C_1/\varepsilon)\exp(-C_2/\varepsilon) \end{cases} \tag{2}$$

$$\begin{cases} C_1 = (\rho F_B L_N^3)/(6bEL_c^2) \\ C_2 = F_B/bEL_c \end{cases} \tag{3}$$

where ρ is the dislocation density; L_c is the mean distance of the weak pinning points which refer to solute atom (Zn，Y) and vacancy in dislocation in this work; F_B is the binding force between dislocation and solute atom; b is the Burgers vector of dislocation; E is the unrelaxed modulus; ε is the strain amplitude; L_N is the mean distance of the hard pinning points which refer to precipitates in a dislocation in the present work; Q_0^{-1} is the strain-amplitude weakly dependent damping, which corresponds to damping in the low strain region; and Q_H^{-1} is the strain-amplitude strongly dependent damping, which corresponds to damping in the high strain region.

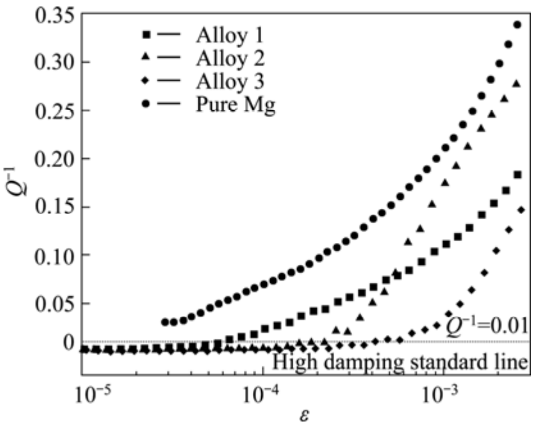

Fig.6 Strain amplitude dependence of damping capacity at room temperature with f=1 Hz for Mg-Cu-Mn alloys

As seen in Fig.6, the critical strain amplitude (ε_c) becomes higher with the addition of Y and Zn, which is 6×10^{-5}, 2×10^{-4} and 7×10^{-4} for Alloy 1, Alloy 2 and Alloy 3, respectively. The interaction between the dislocation and solute atoms is employed to explain this phenomenon. The more the solute atoms distribute among the dislocations, the higher the stress to break away their interaction forces is required, which will cause a large critical strain amplitude[13]. It is easy to understand that more solute atom will dissolve into the magnesium matrix when the contents of Y and Zn increase. By comparing the damping capacity of these three alloys, it is interesting to see that the damping capacity of Alloy 2 exceeds that of Alloy 1 and is even close to that of pure magnesium when strain amplitude is over 5×10^{-4}, exhibiting prominent damping capacity. This is probably caused by the increase of dislocation density in Alloy 2, due to the great difference of thermal expand coefficient (TEC) between magnesium matrix and the precipitating compound phase. The similar case was found in high damping Mg-Si alloys[7]. Moreover, though not very obvious, there is a damping plateau in Fig.6, which has also been observed in high damping Mg-Si and Mg-Ca alloys[7, 13]. Breakaway of different dislocations system (screw-edge system and edge system) from solute atoms can cause this plateau. Currently, it is generally considered that when the damping capacity is larger than 0.01, the alloys exhibit high damping properties[14]. As shown in Fig.6, the damping capacities of three alloys exceed 0.01 under a certain strain amplitude, exhibiting high damping properties. Especially, when the damping capacity of Alloy 1 attains 0.01, the required strain amplitude is only 6×10^{-5}.

According to "Granato-Lücke" theory，the "G-L" plot method is often used to check whether the increase of damping capacity is only caused by dislocation detachment from the solute atoms. The damping could be explained by the dislocation damping model if "G-L" plot is straight. The "G-L" plot of alloys shown in Fig.7 obviously deviates from the straight line. Similar cases have been reported by NISHIYAMA et al[9] in sintered high-damping Mg-Cu-Mn alloy. The deformation twins were found in sintered Mg-Cu-Mn alloys and would play a role in the deviation from straight line of "G-L" plot of alloy, and the deviation from straight line of "G-L" plot shown in Fig.7 is probably related to the twins.

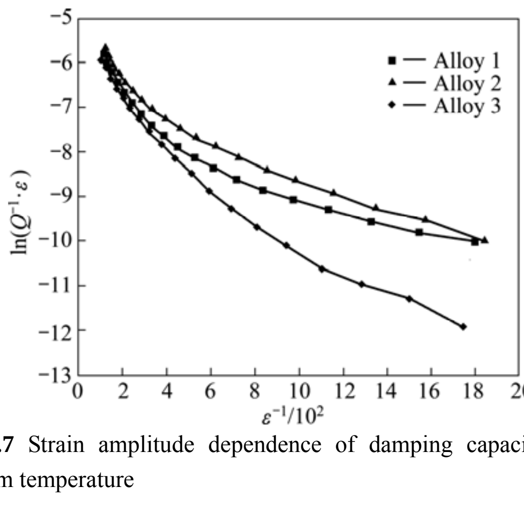

Fig.7 Strain amplitude dependence of damping capacity at room temperature

Fig.8 displays the damping capacity as a function of temperature of Mg-Cu-Mn alloys. It can be seen that beyond a certain temperature which is 175 °C and 275 °C for Alloy 1 and Alloy 2, respectively, with the increase of temperature, the damping capacity of Alloy 1 and Alloy 2 increases monotonously. The increases of damping capacity are mainly caused by the sliding of grain boundary. Generally, the impurity atoms are prone to segregate at grain boundary. Alloy 2 has more impurity atoms segregating at grain boundary than Alloy 1. So, the required activation energy of grain boundary for Alloy 2 is larger and the required temperature for sliding of grain boundary is higher. It is necessary that there is a damping peak P_1 at about 75 °C for Alloy 1, close to 100 °C, which indicates that it should be caused by the movement of dislocations. This damping peak P_1 has been reported in previous work for high damping magnesium alloys[3, 5, 15].

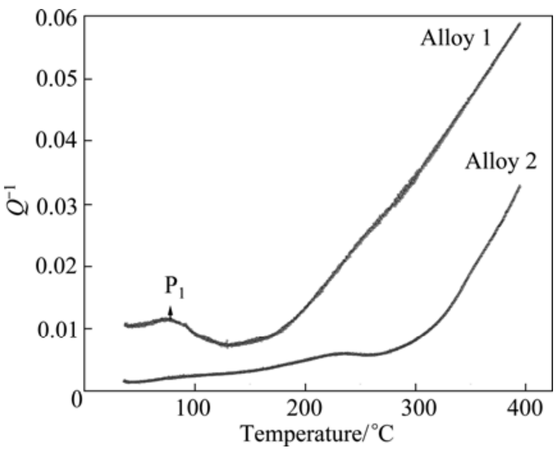

Fig.8 Temperature dependence of damping capacity of Mg-Cu-Mn alloys with f=1 Hz, ε=1×10^{-4} and heating rate of 5 °C/min

4 Conclusions

1) The addition of Y and Zn can reduce the grain size of Mg-Cu-Mn alloys and enhance the yield strength of alloys; with the increase of Y and Zn contents, the compound phases precipitate along the grain boundary, which decreases the plasticity of alloys.

2) The damping capacity of alloys is above 0.01, exhibiting prominent damping property. Especially, when the damping capacity of Alloy 1 attains 0.01, the required strain amplitude is only 6×10^{-5}. In strain amplitude over 5×10^{-4}, due to the increase of movable dislocation density, the damping capacity of Alloy 2 increases abnormally with the increase of strain amplitude and exceeds that of Alloy 1 and even close to that of pure magnesium.

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