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High damping capacities of Mg-Cu based alloys

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Abstract: The dynamic mechanical analyzer (DMA) was applied to investigate the damping properties of Mg-Cu based alloys. The results show that the as-cast hypoeutectic Mg-Cu binary alloys exhibit ultra-high damping capacities, while the eutectic Mg-Cu alloy exhibits low damping capacity. The strain amplitude dependent damping performance reveals that the dislocation damping mainly dominates in Mg-Cu alloys. Furthermore, the influence of eutectic phase on damping mechanisms of Mg-Cu binary alloys was discussed in detail and the effect of Si addition on the damping of Mg-1%Cu based alloy was also reported. Two damping peaks are observed on the temperature dependent spectrum of Mg-Cu based alloys. One is located at room temperature, which is dislocation related peak; and the other is located at moderate temperature, which is caused by the grain boundary sliding.
Key words: Mg-Cu based alloys; high damping; microstructure; damping peaks; damping mechanism

1 Introduction

In various fields of industry, high acceleration of mechanically moving parts may cause undesirable vibrations in those parts. Hence, vibration control has become an important subject in many industrial areas [1−3]. The development and application of high damping material is one of the effective and direct measures to control the vibration. Magnesium alloys are the lightest structural materials with promising damping properties. Pure magnesium has the best damping properties among various metal materials; however, easy-corrosion and poor mechanical properties limit its more widespread application. Thus, it is necessary to develop novel high damping magnesium alloys to meet the needs of modern industrial engineering[4−7].

A high damping magnesium alloy, named MCM (Mg-Cu-Mn alloy) was reported by NISHIYAMA et al [8], which was prepared successfully by powder metallurgy. Subsequently, the damping behaviour of Mg-Cu-Mn alloy processed by equal channel angular pressing was reported by ZHENG et al[9]. However, the damping properties of Mg-Cu binary alloys are rarely studied. As we know, the Mg-Cu binary alloy is a good system to reveal the damping mechanisms due to its simple microstructures. Hence, in this work, the damping properties of Mg-Cu based alloys are systematically studied. Furthermore, a novel high damping of Mg-Cu-Si ternary alloy was reported and the study of temperature dependent damping was carried out.

2 Experimental

The compositions of prepared alloy are Mg-1%Cu, Mg-5%Cu, Mg-30%Cu, Mg-1%Cu-0.5%Si and Mg-1%Cu-1%Si (mass fraction), respectively. The alloys were prepared by melting pure Mg (99.99%), Mg-30%Cu and Mg-30%Si (mass fraction) master alloys in an electrical furnace under SF_6+CO_2 protective atmosphere and then poured into the steel mould at 700 ˚C which was preheated at 300 ˚C. The samples were cut by electric sparking forming with a size of 50 mm×5 mm×1 mm. Dynamic mechanical analyzer (DMA) was employed to investigate the damping properties of Mg-Cu based alloys. The test-pieces for damping measurement were properly installed in the DMA clamping heads. The resulting sinusoidal force and deflection data were recorded and the damping capacities were evaluated by the loss tangent ($\tan\phi$), which was

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calculated from

$$Q^{-1} = \tan\phi = \frac{E''}{E'} \quad (1)$$

where E'' is the loss modulus and E' is the storage modulus[10].

The vibration frequency was held at 1 Hz at room temperature damping measurement; while a heating rate of 5 ˚C/min and strain amplitude of 4×10^{-5} were applied during the damping measurement at high temperature. Furthermore, influence of frequencies on damping at high temperature was examined with frequencies ranging from 0.5 to 10 Hz.

3 Results

3.1 Microstructure observation

According to the Mg-Cu binary alloy phase diagram [11], at the first eutectic point, Cu content is 30.7%, so the tested Mg-1%Cu and Mg-5%Cu have the composition within hypoeutectic composition and Mg-30%Cu is very close to the eutectic composition, which could be considered as eutectic alloy. Fig.1 shows the microstructures of as-cast Mg-Cu binary alloys. With respect to the microstructure of hypoeutectic Mg-Cu alloys, the as-cast microstructure consists of α-Mg dendrite and inter-dendrite composition, which is made up of α-Mg and β-Mg_2Cu phase. As shown in Figs.1(a) and (b), with the increase of Cu contents, the dendrite size of primary α-Mg becomes smaller and the volume fraction of the eutectic phase increases. Meanwhile, as shown in Fig.1(c), the microstructure morphology of Mg-30%Cu is lamellar, which is typical eutectic phase morphology.

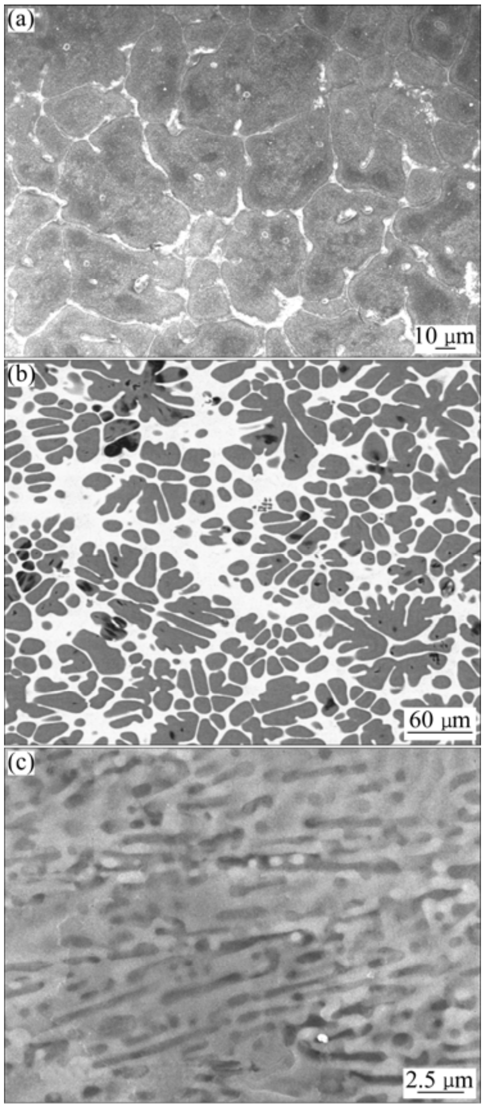

Fig.1 Microstructure of as-cast Mg-Cu binary alloys: (a) Mg-1%Cu; (b) Mg-15%Cu; (c) Mg-30%Cu

3.2 Damping capacities of Mg-Cu based alloys

Fig.2(a) shows the damping capacities of Mg-Cu binary alloys at room temperature as a function of strain amplitude. It is seen that the damping curves of hypoeutectic alloys can be mainly divided into two parts, including strain amplitude weakly dependent part at low strain amplitude and strain amplitude strongly dependent part at high strain amplitude. The turning point of the curve is corresponding to the critical strain amplitude. The damping capacity of eutectic alloy is lower than that of the hypoeutectic alloys and is very weakly dependent on the strain amplitude even at much higher strain amplitude. Recently, it is considered that when damping value $\tan\phi > 0.01$, the material exhibits high damping capacity. Accordingly, when the strain amplitude is higher than 5×10^{-5}, the damping value of the hypoeutectic alloys is greater than 0.01, which belongs to the high damping materials. However, in terms of eutectic alloy, the damping value basically maintains around 0.006 even at high strain amplitude. Therefore, the tested Mg-Cu binary alloys all exhibit high damping properties except for eutectic alloy. Moreover, it is necessary to note that the strain amplitude dependent damping performance of hypoeutectic alloy is different from that of the eutectic alloy, which is mainly due to its different microstructure.

It is known that the solubility of Si in magnesium is very low[11], which makes it a promising alloying element for high damping magnesium alloys. A ternary Mg-1%Cu-1%Si alloy was prepared and its damping properties were tested. As shown in Fig.2(b), it is found that the damping capacity of Mg-1%Cu-1%Si is basically the same as Mg-1%Cu. However, in the whole range of strain amplitude, the damping property of Mg-1%Cu-1%Si is still lower than that of Mg-1%Cu alloy, which is mainly due to the extremely trace amount of Si dissolving into the matrix and pinning dislocations.

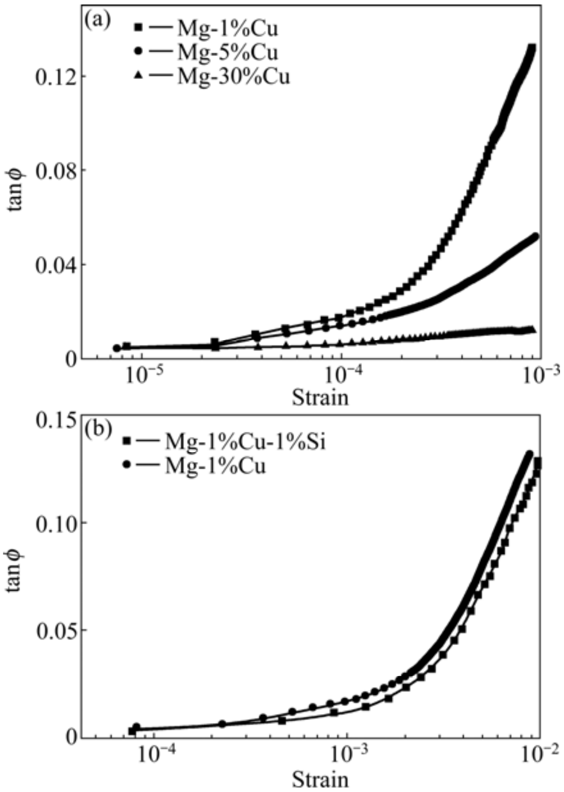

Fig.2 Damping capacities of Mg-Cu based alloys: (a) Mg-Cu binary alloy; (b) Mg-1%Cu-1%Si

4 Discussion

4.1 Effect of microstructure on damping of Mg-Cu based alloys

According to other information of Mg-Cu binary phase diagram[11], Cu has little solubility in α-Mg solid solution; hence, it can barely play a role as a serious obstacle to pin the dislocation and guarantees the high damping capacity of the matrix. However, as shown in Fig.2(a), Cu content has a significant effect on damping capacities of Mg-Cu binary alloys because of its influence on the α-Mg dendrite size and the volume fraction of eutectic phase (α-Mg+Mg_2Cu), which has different intrinsic damping capacity from the matrix. The well-accepted theory on the dislocation damping is G-L theory[12−13], which describes pinned or unpinned dislocations to explain the anelastic energy loss. According to G-L dislocation damping theory, the length of the dislocation line has a significant influence on unpinning of the dislocations from weak pinners. The longer the dislocation line is, the easier the dislocation will break away from weak pinners, and finally results in the strain amplitude dependent on damping characteristics. Hence, α-Mg dendrite size is an important factor impacting on the movement of dislocations by providing the movement space and total mobile dislocation density. The greater the size of dendrites, the more easily the dislocations move, and the better the damping properties of the alloys are. In addition, the presence of the eutectic phases changes the microstructure of interfaces and dislocations and hence leads to a change in the overall damping behavior of alloys. The eutectic phase may possess different intrinsic damping capacities from those of the matrix material and thereby may lead to a mixture effect on the overall damping behaviors. As shown in Fig.2(a), it is found that Mg-Cu alloy with the composition close to the eutectic point has poor damping capacity; thus, the eutectic phase should have smaller damping capacity than α-Mg dendrites. Generally, dislocations in the lamellar eutectic phase which are anchored by the interface are difficult to move. WELLER et al[14] found that the movement of dislocation lines with both ends anchored by the interface in laminar γ-TiAl are only activated at high temperature. The poor movability of dislocation in the eutectic phase makes it contribute little to the overall damping properties. The authors of this article have previously applied the mixing rule to describe the effect of the eutectic phase on damping capacity of hypoeutectic Mg-Ni binary alloys, and details were described in Ref.[15].

4.2 Temperature dependent damping of Mg-Cu based alloys

At a heating rate of 5 ˚C/min, strain amplitude of 4×10^{-5} and cyclically changing the frequency, the high temperature damping measurement of Mg-Cu based alloys was carried out. The temperature dependence of damping properties is shown in Fig.3.

As shown in Fig.3, there are mainly two broad damping peaks in the scope of the tested temperature. One appears around 100 ˚C, and the other appears around 220 ˚C. The damping peak shifts to higher temperatures with increasing frequencies, which indicates that the damping performance of Mg-Cu based alloys at the high temperature is actually a thermally activated relaxation process. It is necessary to point out that the characteristics of low-frequency damping spectrum are distinguishing. On one hand, the damping value of the alloy in low-frequency condition is much higher than that in high-frequency condition. On the other hand, some sub damping peaks (such as P_1 shown in Fig3.(a)) appear from the very broad P1 on the low-frequency spectrum; however, it does not appear on the high frequency damping spectrum. It may be due to the fact that more internal defects could be activated under the low-frequency condition. As shown in Fig.3, P_1 and P_2 damping peaks are general; hence, it is necessary to carry out the detailed study of its physical mechanism. The very broad P_1 relaxation peak is usually obtained in high damping magnesium alloys around the room

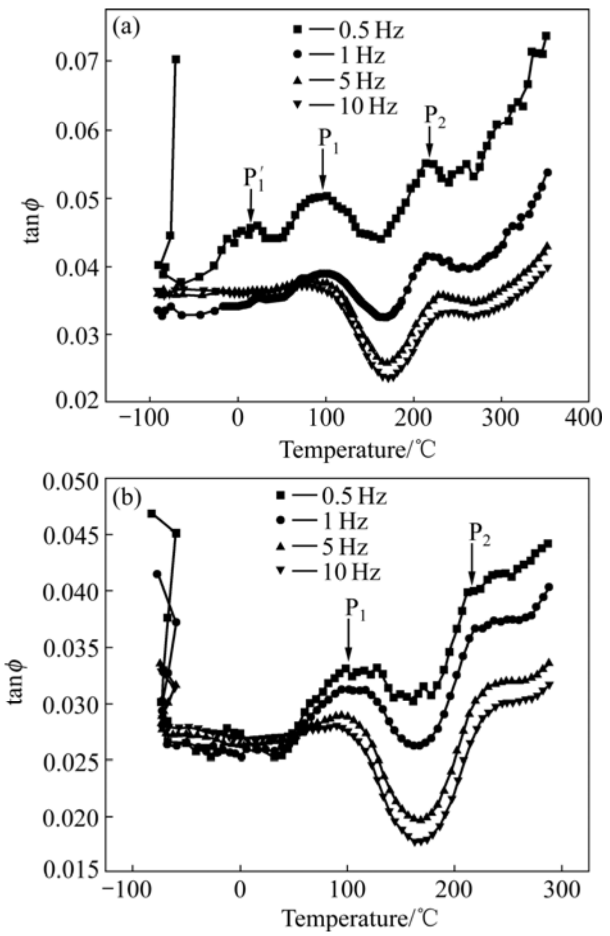

Fig.3 Temperature dependent damping of Mg-Cu base alloys: (a) Mg-1%Cu-0.5%Si; (b) Mg-1%Cu-1%Si

temperature. The relaxation peak is dislocation-related, which is probably caused by the interaction between dislocation and point defects (vacancy and solid atoms) during the dislocation movement on the basal plane by thermal activation.

P2 damping peak is a grain-boundary damping peak, which is caused by the grain boundary sliding at high temperature. The grain boundary damping peak of pure magnesium was first reported by KE[16], which appears at around 218 ˚C. The Arrhenius formula is further applied to determine the activation energy of P_2:

$$f = f_0 \exp(-H / kT_P) \quad (2)$$

where f is the frequency; f_0 is a constant; H is the activation energy; k is Boltzmann constant; T_P is the peak temperature. The following equation could be achieved after logarithmic transformation of Eq.(2):

$$\ln f = \ln f_0 - \frac{H}{kT_p} \quad (3)$$

Hence, it is clear that the activation energy could be determined by different frequency peak temperature values. A peak-searching software (Peak Fit V4.12 professional) was used to analyse the exact value of peak temperature and the results are shown in Table 1.

Table 1 Peak temperature of P2 at different frequencies

Testing frequency/Hz	P2 temperature of Mg-1%Cu-1%Si/K	P2 temperature of Mg-1%Cu-0.5%Si/K
0.5	488	492
1	500	505
5	506	513
10	513	524

Fig.4 shows the Arrhenius curves of the damping peak of P2 for both Mg-1%Cu-1%Si and Mg-1%Cu-0.5%Si alloys. The activation energy of P2 for Mg-1%Cu-1%Si alloy is 1.41 eV, which is very close to the activation energy of grain boundary damping of pure Mg, 1.38 eV [16], while the activation energy of P2 for Mg-1%Cu-1%Si is 1.43 eV, which is higher than that of Mg-1%Cu-1%Si alloy. It is possible that the trace dissolved Si segregation on the grain boundary pins its high temperature sliding and increases the activation energy.

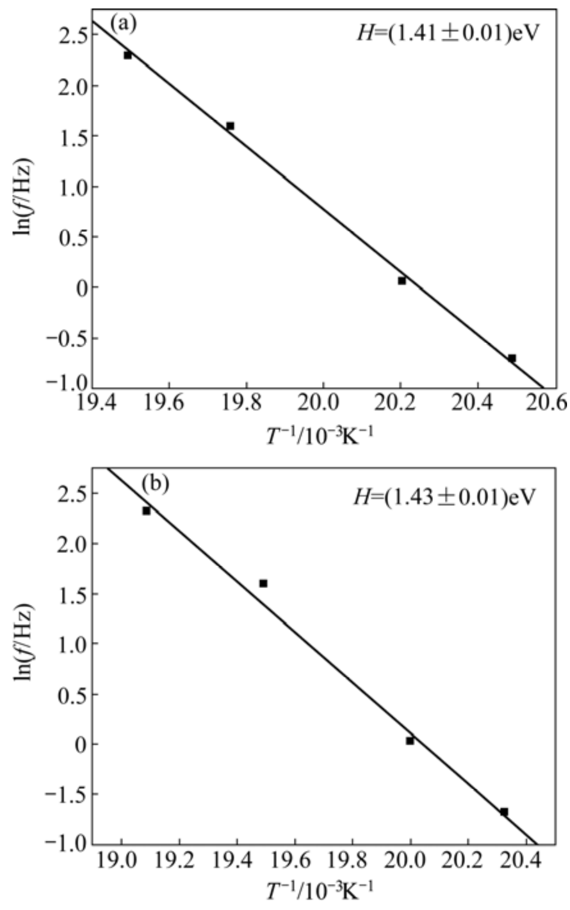

Fig.4 Arrhenius plots for Mg-1%Cu-1%Si (a) and Mg-1%Cu-1%Si-0.5%Si (b)

5 Conclusions

1) Mg-Cu hypoeutectic alloys exhibit good damping capacities, which could be a good candidate for damping magnesium alloy. The amplitude dependent damping capacity can be divided into two parts: strain independent damping and strain dependent damping, which can be explained by the G-L theory.

2) Cu has a significant effect on the damping capacities of Mg-Cu binary alloys. The more the content of Cu, the lower the damping capacities, which is due to the decrease of the α-Mg dendrite size and increase of volume fraction of eutectic phase.

3) The eutectic alloy has a poor damping capacity. This is mainly because the microstructure of eutectic alloy is laminar, in which the dislocation movement is very difficult. In terms of Mg-Cu hypoeutectic alloys, only α-Mg dendrite can guarantee the high damping capacity of alloys and the strain amplitude dependent damping properties.

4) Two damping peaks are observed on the temperature dependent spectra of Mg-Cu based alloys. One is located at the room temperature, which is dislocation related, and the other is located at the moderate temperature, which is caused by the grain boundary sliding.

References

[1] KONDRATEV S Y, YAROSLAVSKII G Y, CHAIKOVSKII B S. Classification of high-damping metallic materials [J]. Strength of Materials, 1986, 10: 1325−1329.

[2] SUGIMOTO K, NIIYA K, OKAMOTO T, KISHITAKE K. A study of damping capacity in magnesium alloys [J]. Transactions of Japan Institute Metals, 1977, 18: 277−288.

[3] DE BATIST R. High damping materials: Mechanisms and applications [J]. Journal de Physique, 1983, C9(12): 39−50.

[4] LIU Chu-ming, JI Ren-feng, ZHOU Hai-tao, CHEN Min-gan. Research and development progress of damping capacity of magnesium and magnesium alloys [J]. The Chinese Journal of Nonferrous Metals, 2005, 15(9): 1319−1325. (in Chinese)

[5] WAN Di-qing, WANG Jin-cheng, WANG Gai-fang, YANG Gen-cang. High damping properties of Mg-Si binary hypoeutectic alloys [J]. Materials Letters, 2009, 63(3/4): 391−393.

[6] HU X S, WU K, ZHENG M Y. Low frequency damping capacities and mechanical properties of Mg-Si alloys [J]. Scripta Materialia, 2006, 54(9): 1639−1643.

[7] LIAO Li-hua, ZHANG Xiu-qing, WANG Hao-wei, LI Xian-feng, MA Nai-heng. Influence of Sb on damping capacity and mechanical properties of Mg_2Si/Mg-9Al composite materials [J]. Journal of Alloys and Compounds, 2007, 430(1/2): 292−296.

[8] NISHIYAMA K, MATSUI R, IKED Y A, NIWA S, SAKAGUCHI T. Damping properties of a sintered Mg-Cu-Mn alloy [J]. Journal of Alloys and Compounds, 2003, 355(1): 22−25.

[9] ZHENG Ming-yi, FAN Guo-dong, TONG Li-bo, HU Xiao-shi, WU Kun. Damping behavior and mechanical properties of Mg-Cu-Mn alloy processed by equal channel angular pressing [J]. Transactions of Nonferrous Metals Society of China, 2008, 18: s33−s38.

[10] ZHANG J, PEREZ R J, WONG C R. Effects of secondary phases on the damping behavior of metals, alloys and metal matrix composites [J]. Materials Science and Engineering R, 1994, 13(8): 325−390.

[11] ASM international's binary alloy phase diagrams (electronic version) [M]. 2nd Edition. Ohio: ASM International Materials Part, 1990.

[12] GRANATO A, LÜCKE K. Theory of mechanical damping due to dislocations [J]. Journal of Applied Physics, 1956, 27(6): 583−593.

[13] GRANATO A, LÜCKE K. Application of dislocation theory to damping phenomena at high frequencies [J]. Journal of Applied Physics, 1956, 27(7): 789−805.

[14] WELLER M, CHATTERJEE A, HANECZOK G, CLEMENS H. Internal friction of γ-TiAl alloys at high temperature [J]. Journal of Alloys and Compounds, 2000, 310(1/2): 134−138.

[15] WAN Di-qing, WANG Jin-cheng, WANG Gai-fang, LIN lin, FENG Zhi-gang, YANG Gen-cang. Effect of eutectic phase on damping and mechanical properties of as-cast Mg-Ni hypoeutectic alloys [J]. Transactions of Nonferrous Metals Society of China, 2009, 19(1): 45−49.

[16] KE Ting-sui. Experimental evidence of the viscous behavior of grain boundaries in metals [J]. Phys Rev, 1947, 71: 533−546.

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