Damping Properties of Ductile Cu-Al-Mn-Based Shape Memory Alloys*1

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1. Introduction

Recently, high damping materials are drawing much attention in engineering applications because of the increasing need for the reduction of vibration and noise in various fields. Among conventional damping alloys, shape memory alloys (SMAs) are well-known as materials showing both high strength and high damping capacity. It is believed that the damping capacity of SMAs is mainly due to the energy loss by the movement of the martensite variant interfaces and the parent/martensite habit planes.1) However, conventional SMAs such as Ti-Ni, Cu-Al-Ni and Cu-Zn-Al show poor cold-workability because of their ordered structures and high cost in the case of the Ti-Ni alloys.

The present authors have recently developed Cu-Al-Mn-based shape memory alloys with excellent cold-workability and cost performance.2–4) The β phase region exhibiting martensitic transformation in the Cu-Al binary system is significantly extended to the low Al content by the addition of Mn, and the A2/B2 and B2/L21 order-disorder transition temperatures decreases with decreasing Al content.5) Thereby, Cu-Al-Mn alloys with low Al content below 18 at% have an excellent cold-workability. In addition, excellent shape memory properties, which are comparable to those of Ti-Ni alloys, can be obtained by microstructural control in Cu-Al-Mn based alloys.6–9) Those results imply that Cu-Al-Mn alloys have a high damping capacity based on the high mobility of the martensite variant interfaces and the parent/martensite habit planes. In the present study, the damping properties of ductile Cu-Al-Mn-based alloys focusing on the effect of the grain size were investigated.

2. Experimental Procedures

Cu72Al17Mn11 and Cu72.4Al16.8Mn10.0Co0.5B0.2 alloys were prepared by induction melting in an argon atmosphere. The cast alloys were hot-rolled at 800°C followed by cold-rolling, and then the specimens were cold-drawn to a diameter of 0.5 mm and 0.35 mm, respectively, and cut into length of 40 mm. All the wire specimens were solution-treated at 900°C and quenched in water, then the specimens with various grain sizes were obtained by changing the solution-treatment time (1 min–30 min). They were then finally aged at 200°C for 15 min to stabilize the martensitic transformation temperatures.

Martensitic transformation temperatures, $M_s$: martensitic transformation starting temperature, $M_f$: martensitic transformation finishing temperature, $A_s$: reverse martensitic transformation starting temperature and $A_f$: reverse martensitic transformation finishing temperature, are determined by Differential Scanning Calorimetry (DSC) with cooling and heating rates of 10°C/min. They were defined as the temperatures at which DSC curve deviated from its baseline due to the martensitic transformation as shown in Fig. 1.

Damping property $\tan \phi$ of Cu-Al-Mn alloys was investigated using a Dynamic Mechanical Spectrometer (DMS) in the tensile mode, where $\phi$ is the loss angle. An oscillating force is applied to a sample in the DMS measurement. Based on the measured displacement and phase lag, the sample modulus $\tan \phi$ are defined. The $\tan \phi$ is indicated by following relationship:

$$\tan \phi = \delta/\pi = \Delta W/2\pi W \approx Q^{-1}$$

where $\delta$ is logarithmic decrement, $\Delta W$ is energy dissipated in a full cycle, $W$ is maximum stored energy and $Q^{-1}$ is internal friction. The ranges of strain amplitude, frequency and heating/cooling rate are $1.3 \times 10^{-4}$–$1.0 \times 10^{-3}$, 0.5–20 Hz and 2°C/min, respectively. The stress changes to hold the strain constant.

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3. Results and Discussion

3.1 Damping properties due to the martensitic transformation

Figure 1 shows the results of the DMS and the DSC measurements during (a) cooling and (b) heating of the Cu$_{72}$Al$_{17}$Mn$_{11}$ alloy. The $d/D$ indicates relative grain size, where $d$ and $D$ are the grain diameter and the diameter of the wire, respectively. During cooling, when the temperature reaches the $M_s$ determined by DSC, $\tan \phi$, which was low in the parent phase state, drastically increases and then enters a steady state with a high level of $\tan \phi$. Although $\tan \phi$ starts to gradually decrease with decreasing temperature at the $M_f$, the high level of $\tan \phi$ is still maintained in the martensite single-phase state. Similarly, during heating, one can see a high level of $\tan \phi$ in the martensite single-phase state, the maximum $\tan \phi$ in the martensite + parent two-phase state and a low $\tan \phi$ in the parent phase state. The decrease of Young’s modulus associated with forward and reverse martensitic transformations is observed. Furthermore, Young’s modulus in the martensite phase is higher than that in the austenite phase. The $\tan \phi$ drastically increases with decreasing Young’s modulus. These results suggest that while there is a large energy loss due to the movement of two kinds of interfaces associated with the martensite, namely, both the parent/martensite habit planes and the martensite variant interfaces, the habit planes have a higher ability of damping due to higher mobility than that of the martensite variant interfaces. These kinds of characteristic features of the damping capacity of SMAs have been reported by Sugimoto et al.$^{10}$

Since the $\tan \phi$ is measured under oscillation stress loading in DMS, martensitic transformation temperatures determined by DMS measurement should be different from those detected by DSC measurement without stress loading. The stress loading is estimated from the static tensile test which shows that 0.05% strain level of DMS corresponds to 20 MPa stress level. Furthermore, the dependence of critical stress for martensitic transformation on temperature, i.e. $d\sigma/dT$, is about 2.1 in the same Cu-Al-Mn polycrystalline alloy.$^{11,12}$ Therefore, the martensitic transformation temperatures determined by DMS are expected to rise by about 10°C.

In the present paper, DMS curves only during the heating process are presented, because the cooling curves show tendencies similar to those of the corresponding heating as demonstrated in Fig. 1.

3.2 Dependence of frequency and strain amplitude on $\tan \phi$

Figures 2 and 3 show the dependence of frequency and strain amplitude on $\tan \phi$ in Cu$_{72}$Al$_{17}$Mn$_{11}$ alloys, where the DMS curves are shown in Figs. 2(a) and 3(a), and three kinds of exothermic/endothermic peaks are shown in Figs. 2(b) and 3(b). Figures 2 and 3 show the dependence of frequency on $\tan \phi$ in Cu$_{72}$Al$_{17}$Mn$_{11}$ alloys, where the DMS curves are shown in Figs. 2(a) and 3(a), and three kinds of exothermic/endothermic peaks are shown in Figs. 2(b) and 3(b).
of tan$\phi$ values defined in Fig. 4 are plotted in Figs. 2(b) and 3(b), respectively. In the strain amplitude range of $1.3 \times 10^{-3}$–$1 \times 10^{-4}$ and in the frequency range of 0.5 Hz–20 Hz, the peak height of tan$\phi$ in the parent + martensite two-phase state decreases with increasing frequency, but hardly depends on the strain amplitude. On the other hand, tan$\phi$ in the martensite phase state increases with increasing strain amplitude, being almost constant on the frequency. This difference of the damping behavior between the two-phase state and the martensite state is attributed to whether it is related to the transformation. It should be noted that the specimen with a strain amplitude of $1 \times 10^{-3}$ indicates a relatively high tan$\phi$ at even the $A_t$, which is caused by the stress-induced martensite due to the high strain amplitude.

3.3 Effect of $\beta$ grain size on tan$\phi$

It has been reported that shape memory properties depend on the relative grain size $d/t$ or $d/w$ due to the constraint stress among the grains, where $d$, $t$ and $w$ are grain size, thickness and width of sheet specimen, respectively. Therefore, the mobility of martensite interfaces is expected to be affected by the relative grain size. In the present study, the tan$\phi$ was determined in specimens with various relative grain size $d/D$ about 0.09 ($d = 45$ $\mu$m), 0.42 ($d = 210$ $\mu$m) and 0.71 ($d = 355$ $\mu$m), where $D$ is the diameter of the wire specimen. Figures 5(a) and (b) show the microstructures of wire specimens with different $d/D$s. With increasing $d/D$, each grain is able to penetrate the cross section of the wire
specimen, and the microstructure changes to a bamboo structure in the large grain condition over $d/D = 1$. The values of $\tan \phi$ of wire specimens with different $d/D$s are shown in Fig. 6, where the strain amplitude, the frequency and heating rate are $5 \times 10^{-4}$, 1 Hz and $2 \degree C/min$, respectively. The relatively low $\tan \phi$ in the specimen with the small $d/D$ increases with increasing $d/D$ in both the two-phase and martensite phase states. It can be concluded that $\tan \phi$ strongly depends on the $d/D$. The obtained $\tan \phi$ values at the peak in the two-phase state and at the $T_m$ defined as Fig. 4 in the martensite phase state are plotted as a function of $d/D$ in Figs. 7(a) and (b), respectively. In damping materials based on martensitic transformations, three separate contributions, $Q_{PT}^{-1}$, $Q_{PT}^{1}$ and $Q_{int}$, to the total $\tan \phi$ should be considered.\(^{(15)}\) The $Q_{int}^{-1}$ is an intrinsic part which is composed of the internal friction contributions of each phase and is strongly dependent on microstructural properties, especially in the martensite phase. The $\tan \phi$ at the peak in the two-phase state, which corresponds to the temperature region from $M_s$ ($A_s$) to $M_f$ ($A_f$), strongly depends on the $Q_{PT}^{-1}$ and $Q_{PT}^{1}$. The $Q_{int}^{-1}$ is the transient part of total $\tan \phi$ which is related to parent/martensite transformation kinetics and increases with increasing transformation rate. The $Q_{PT}^{-1}$ is non-transient part which is related to the mobility of the parent/martensite habit planes and is independent of the transformation rate. It is seen from Figs. 7(a) and (b) that the $\tan \phi$ values are divided into two regions (I and II) depending on the $d/D$ and that the $\tan \phi$ values both at the peak and in the martensite phase state linearly increase with increasing $d/D$. The slope in region II is much steeper than that in region I in both cases. This result can be explained from the standpoint of the grain constraint; i.e., in region I below $d/D = 0.4$, the relative grain size is very small, which means that the grains are three-dimensionally constrained by the surrounding grains. On the other hand, in region II, the volume fraction of the grains possessing a free surface increases with increasing $d/D$ and the microstructure becomes close to the bamboo structure. In this case, the constraint stress may be drastically released with increasing $d/D$. Furthermore, it is noted that the dependence of $\tan \phi$ on $d/D$ at the peak in the two-phase state is much greater than that in the martensite phase state. Therefore, it can be supposed that $Q_{PT}^{-1}$ and $Q_{PT}^{1}$ which are the internal friction terms related to the martensitic transformations, are more affected by $d/D$ than $Q_{int}^{-1}$.

Fig. 6 $\tan \phi$ of specimens with $d/D = 0.09$, 0.46 and 0.71.

Fig. 7 $\tan \phi$ values (a) at peak and (b) in the martensite state in relation to $d/D$.
4. Conclusions

(1) Cu-Al-Mn-based alloys show a high damping capacity \(\tan \phi\) in the martensite state as well as in the parent + martensite two-phase state, a maximum \(\tan \phi\) being obtained in the two-phase state.

(2) In the parent + martensite two-phase state, \(\tan \phi\) increases with decreasing frequency but hardly depends on the strain amplitude. In the martensite phase state, while only slightly depending on the frequency, \(\tan \phi\) increases with increasing strain amplitude.

(3) \(\tan \phi\) strongly depends on the relative grain size \(d/D\). The value of \(\tan \phi\) drastically increases with increasing \(d/D\). The largest values of \(\tan \phi = 0.07\) and \(\tan \phi = 0.54\) are obtained in the martensite state and at the peak, respectively, in the alloy with a relative grain size \(d/D \approx 1\).

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REFERENCES