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Low-frequency damping behavior of CuAlMn shape memory alloy

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In the present study, the damping behavior of bulk Cu–11.9Al–2.5Mn (wt%) was investigated using a multifunction internal friction apparatus through the method of forced vibration over the temperature range from room temperature to 400 °C. Two internal friction peaks are found at around 150 °C and 325 °C during heating. It is suggested that the high-temperature peak originates from the phase transition from martensite to austenite while the low-temperature peak from the pseudo-first-order phase transition associated with the thinning process of the twins. The related mechanisms are also discussed in terms of the interaction between the microstructure defects.

1 Introduction

There are increasing needs to passively dissipate undesirable vibration and noise in many industrial fields. The use of high-damping materials has been proved to be one of the most effective measures to meet this requirement. Alloys that undergo thermoelastic martensitic transformation can be promising candidates for this purpose due to their high damping capacity, in which CuAlMn shape memory alloys (SMA) have recently attracted more attention because of their good shape memory effect comparable to that obtained from Ni-Ti alloys, relatively low cost and good machining properties in addition to their outstanding damping capacity. The other favorable property of such an alloy arises from its excellent thermal stabilization such that it can be safely used without losing high damping capacity. A number of investigations have been conducted into the shape memory and pseudoelasticiy effect as well as the mechanical properties of CuAlMn shape memory alloy in recent years [1–4]. However, there has been very little work systemically studying the damping behavior of the alloy and we have very limited knowledge of its intrinsic damping property and its dependency on the surroundings. The present study is therefore aimed at giving a clear physical image of the damping behavior and correlated mechanisms of the alloy with the objective of finding reasonable processing technology and applications.

2 Experimental procedure

A Cu-based SMA with a nominal composition of Cu–11.9 Al–2.5 Mn (wt%) was prepared in a vacuum induction furnace. The obtained ingots were homogenized at 1173 K for 3 h. To avoid heterogeneity in the chemical composition and solidified structure, all the specimens used in the damping measurements were cut from the same ingot and had dimensions of 70 × 30 × 0.8 mm. The damping behavior of the alloy was characterized by internal friction (IF), Q^{-1}, and the measurements were performed using a

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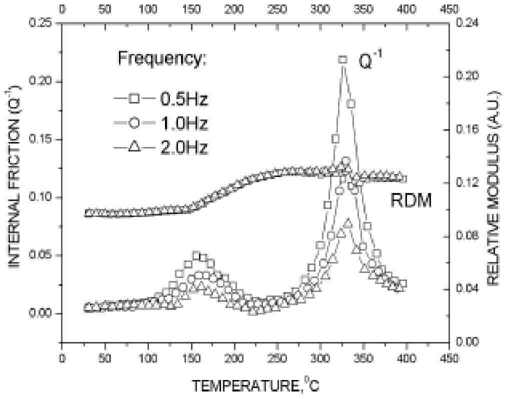

Fig. 1 Dependence of internal friction (Q^{-1}) and relative dynamic modulus (RDM) on the measuring frequency (heating rate 6 °C min^{-1}).

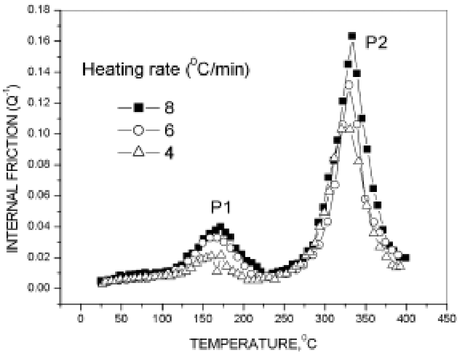

Fig. 2 Dependence of internal friction on heating rate (frequency 1.0 Hz).

computer-controlled automatic inverted torsion pendulum by forced vibration over the temperature range from room temperature to 400 °C. The apparatus basically consists of an inverted torsion pendulum, a temperature programmer and a photoelectron transformer. The whole measurement is controlled by an IBM*PC586 computer and an 8087 processor and the data can be processed in real time. The range of the maximum excitation strain amplitude is $10^{-6}-10^{-4}$. The resolution in the internal friction measurement is 1×10^{-4}. The details of the experimental apparatus can be found in [5].

3 Results and discussion

3.1 Essential internal friction feature

Figure 1 shows the typical IF and relative dynamic modulus (RDM) against temperature upon heating for the present CuAlMn alloy. The most outstanding feature should be that two IF peaks arise at about 150 °C (termed P1) and 325 °C (termed P2), respectively. The RDM shows different changes corresponding to these two IF peaks. It begins to rise rapidly after the appearance of P1 peak, while it has a discontinuity corresponding to P2 peak.

Figures 1 and 2 show the dependence of IF and RDM on measuring frequency and heating rate. It is seen that the two peaks exhibit similar tendencies. Their heights decrease, whereas their positions remain almost unchanged with increasing frequency, showing a nonrelaxational feature. However, the two peaks rise as the heating rate increases. The above characteristics of the two IF peaks are in good agreement with those of the first-order phase transition.

To identify the origins of the peaks, a differential scanning calorimetry (DSC) measurement was conducted upon heating. It can be seen from Fig. 3 that only a endothermal peak appears at about 335 °C at a

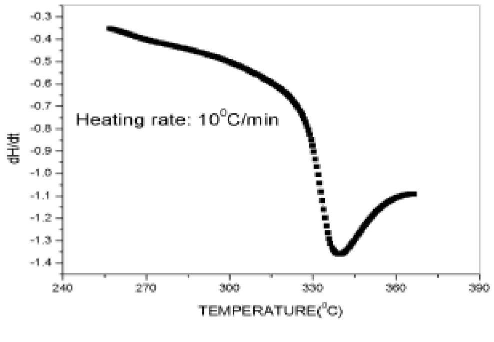

Fig. 3 Differential scanning calorimetry (DSC) curve for the CuAlMn alloy (heating rate 10 °C min^{-1}).

heating rate of 10 °C min^{-1} that accords well with the P2 temperature, showing that a first-order phase transition takes place at this temperature. It is therefore suggested that the appearance of peak P2 should be related to the reverse martensitic phase transition during heating. It should be noted that a discrepancy of around 10 °C exists in the peak temperatures in DSC and IF measurements. This can be attributed to the high sensitivity of IF to any changes in microstructure in addition to the difference of heating rate in the measurements.

Although the height of peak P2 increases with increasing heating rate $\dot{T}$ or decreasing frequency f, it does not bear a linear relation to $\dot{T}/f$ shown by Delorme's model [6]. This discrepancy has been also found by a number of researchers in a thermal elastic martensitic transformation (MT) and they attributed this nonlinear phenomenon to the higher sensitivity of nucleation to stress in the elastic softening temperature range [7, 8]. According to the model of phase interface [9], the IF of phase transition in the present CuAlMn SMA can be defined as:

$$Q^{-1} = Q_{\text{new}}^{-1} x(t,T) + Q_{\text{old}}^{-1}[1 - x(t,T)] + Q_{\text{int}}^{-1} s(t,T,\dot{T}) \frac{\mathrm{d}x}{\mathrm{d}T} \frac{\dot{T}}{f} \tag{1}$$

where Q_{new}^{-1} and Q_{old}^{-1} denote the IF of the new and old phase per unit volume, respectively; Q_{int}^{-1} is the IF of the phase interface per unit area; $x(t, T)$ is the volume fraction of the new phase; t is time; T is absolute temperature; $\dot{T}$ is the heating/cooling rate; f is vibration frequency; s is the total area of the two phases during transformation and is a function of t, T and $\dot{T}$. It is obvious that the third term of Eq. (1) relates to the motion of phase interfaces and is a nonlinear function of $\dot{T}/f$. The present results accord well with this relationship.

Wang et al. [10] observed an IF peak at a temperature below the second-order phase transition peak in $La_{1-x}Nd_xP_5O_{14}$ (LNPP), and associated it with the thinning or coarsening process of the twins. Through examination of the microstructure they found that the density of twin boundaries increased with increasing temperature. This increase of the twin domains is similar to the shearing motion of martensite variants, belonging to the type of abrupt change. Taking into account the abnormality of the specific heat [11], the thinning or coarsening of twin domains can be regarded as a kind of pseudo-first-order phase transition without changing the structural symmetry. These findings have also been confirmed by other researchers in the $\alpha \to \beta$ phase transition of $PbLa(Zr, Ti)O_3$ (PLZT) [12].

From Fig. 4 it can be seen that the typical microstructure of the alloy in the martensite state is characterized by a substructure composed of twin plates. Such a high density of twins will, of course, play an important role in the internal friction properties of CuAlMn alloy. In view of the aforementioned observation and the typical characteristic of the first-order phase transition, the appearance of the P1 peak should relate to the thinning process of twins during heating.

It is known that the predominant lattice defects present in the substructures of the martensite of Cu based SMA are twins or fault ribbons as seen in Fig. 4. As the martensitic phase transition proceeds, elastic strains are accumulated within the austenite that can be partially relieved through the formation of twins. These twins will give rise to energy dissipation during cooling, leading to a pronounced asymmetry of the martensitic phase-transition peak. However, the number of twins will increase with increasing

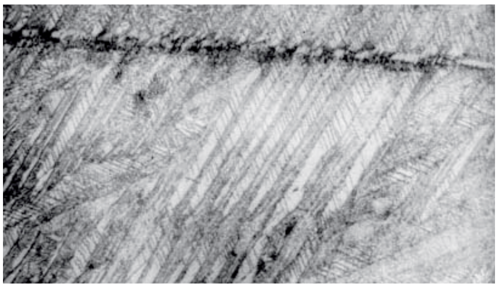

Fig. 4 Microstructure of the CuAlMn alloy in the martensite state.

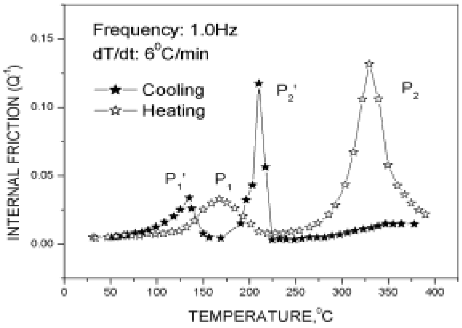

Fig. 5 Internal friction as a function of temperature during heating and cooling (heating/cooling rate 6 °C min^{-1}).

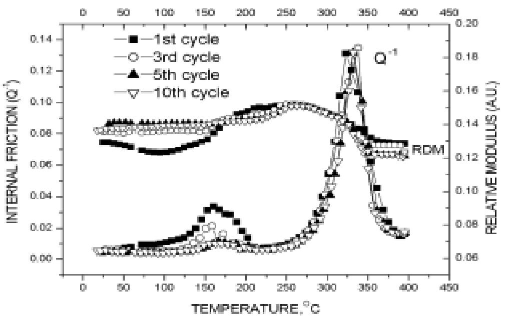

Fig. 6 Effect of thermal cycling on the internal friction Q^{-1} and RDM (frequency 1.0 Hz, heating rate 6 °C min^{-1}).

temperature during heating and as an index of energy dissipation, the internal friction increases until a maximum arises where the twins reach a metastable state of so-called pseudo-martensite [11]. The appearance of numerous twins imposes a compressive stress on their neighboring structures, making the motion of the neighboring twins difficult and as a result, the energy dissipation decreases, i.e. an internal friction peak appears corresponding to this pseudo-martensite state.

Now that the P1 peak arises from the pseudo-first-order phase transition, a thermal hysteresis phenomenon should take place during cooling like that corresponding to the P2 peak. The results shown in Fig. 5 further demonstrate the origin of the P1 peak, i.e. the P1 peak during heating relates to the thinning process of the twins while the hysteresis P1′ peak during cooling corresponds to the coarsening process.

It can be noted from Fig. 1 that both the P1 and P2 peaks decline as the measuring frequency increases. This is understandable because the lower the vibration frequency, the longer the period of oscillation. Thus, more transformed product is produced in one cycle, leading to a relatively high IF peak.

3.2 Effect of thermal cycling on the internal friction peaks

As mentioned above, thermal stability of a SMA is extremely important for its performance in practical damping applications. As is seen in Fig. 6, the P1 peak drops with increasing the thermal cycling whereas its location remains unchanged. For the P2 peak, however, no discernible variation is found with increasing thermal cycling. The decline of the P1 peak can be attributed to an increased density of dislocations during the thermal cycling and the new dislocations will, subsequently, obstruct the interface movement, leading to decreased internal friction [13].

3.3 Stationary internal friction

Stationary damping is another important characteristic of SMA. The damping capacity of SMA usually tends to decrease to a stable value when it is held at a given temperature for 15–20 min [14]. To study the stationary damping behavior of the present alloy, a step heating was adopted during internal friction measurements with a step of 6 °C and a holding time of 15 min, as shown in Fig. 7. It can be seen that only the P2 peak still appears and the P1 peak is absent. Compared with the IF peaks measured during continuous heating, the stationary IF peaks are much lower, while the relative dynamic modulus is much higher, as exhibited in Fig. 8.

It has been known from the aforementioned results that the P1 peak measured during continuous heating approximately meets the relation of $Q^{-1} \propto \dot{T}/f$. Under stationary condition with $\dot{T} = 0$, however, there is no longer sufficient chemical energy on the phase boundaries to drive the phase boundaries to move a long distance [9]. The thinning process of the twins is thus restrained to a high degree and as a result, the P1 peak is almost indiscernible in the cases of step heating and isothermal measurement.

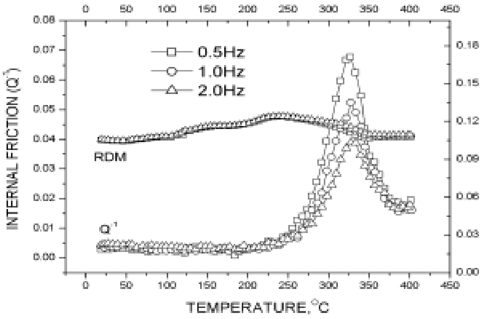

Fig. 7 Internal friction as a function of temperature during step heating (heating rate 6 °C min^{-1}, heating step 6 °C with holding time 15 min).

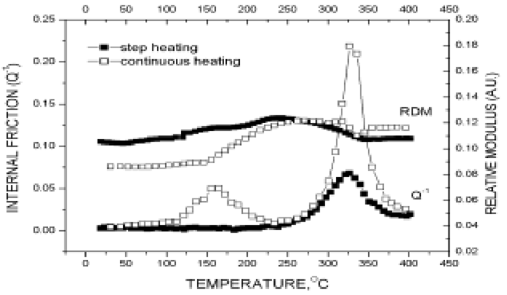

Fig. 8 Comparison of the internal friction between continuous heating and step heating.

It has been known that the total internal friction during martensitic phase transition is composed of three parts as given by the following equation [15–17]

$$Q_{\mathrm{tot}}^{-1} = Q_{\mathrm{tr}}^{-1} + Q_{\mathrm{pt}}^{-1} + Q_{\mathrm{int}}^{-1}\,, \tag{2}$$

where Q_{tr}^{-1} denotes the transient internal friction, which is operative only on continuous heating or cooling; Q_{pt}^{-1} is related to the phase transition and Q_{int}^{-1} comes from the contribution of each phase. Figure 8 shows that Q_{tr}^{-1} is much larger than any of the other components.

4 Conclusion

The low-frequency damping properties of a Cu–11.9Al–2.5Mn (wt%) shape memory alloy have been investigated in the present study. The most outstanding feature is that two internal friction peaks appear at about 150 °C and 325 °C, respectively, during continuous heating. The low-temperature peak is attributed to the thinning process of twins and approximately obeys the relation $Q^{-1} \propto \dot{T}/f$. The high-temperature peak originates from the reverse martensitic phase transition in terms of the characteristic of the peak and DSC measurement. In stationary measurements, however, only the high-temperature peak appears. This is due to the decreased driving force for the motion of the phase boundaries and restrained thinning process of the twins. It is also found that thermal cycling makes the low-temperature peak drop but has no obvious effect on the high-temperature peak.

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