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INTERNAL FRICTION IN MANGANESE-COPPER AND MANGANESE-COPPER-ALUMINIUM ALLOYS

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Abstract : Internal friction and elastic modulus of Mn-Cu alloys containing 60 and 70 wt % Mn and of Mn-Cu-Al alloys containing about 40 wt % Cu, 1.92-3.59 wt % Al were measured with acoustic frequency in the temperature range of -150 to 150°C. The martensitic transformation peak and the twin boundary relaxation peak which did not appear before ageing were observed above room temperature after a definite ageing time in the temperature range under the spinodal curve within the miscibility gap. It is shown that the transformation peak proper is originated from the stress-induced movement of the interface boundaries between the parent phase and the transformation product, and the internal friction background at the low-temperature side of the transformation peak which exhibits a very strong amplitude effect and shows a strong non-linear behaviour, is originated from the hysteretic movement of the martensite-martensite interfaces.

It has also been found that the addition of aluminium enhances the strength but reduces the internal friction of the specimen. A choice of suitable ageing time and temperature can give an optimum compromise of high strength and high internal friction.

I. Introduction

Previous experiments on the internal friction of Mn-Cu alloys were mainly done for high Mn contents [1]. Two internal friction peaks were observed : a relaxation peak at lower temperature and a transformation peak at higher temperature. In practice, the use of Mn-Cu alloys as high-damping materials requires that the Mn content should not be too high and is usually about 60 wt %. The case of cast Mn-Cu alloys has been studied in our laboratory by Wen et al. [2]. The purpose of the present research is to study the damping mechanism of Mn-Cu and Mn-Cu-Al alloys of lower manganese content subjected to different ageing treatments. Conditions for obtaining high damping and high strength around room temperature are explored. Internal friction and elastic modulus were measured with acoustic frequencies so that the system is basically in an adiabatic state and the amount of transformation product remains constant during measurements.

II. Preparation of Specimens

Ingot of the alloys were supplied by Shanghai Jiaotong University. Sheet specimens of 80 × 4 × 2 mm were prepared by hot rolling and spark cutting and were homogenized by annealing at 850°C for 100 h and then water quenched. The compositions of the specimens are shown in Table 1.

Table 1. Composition of the alloy specimens

Specimen No	Composition (wt %)			
	Mn	Cu	Al	Others
S ₀	70	30	0	<0.1
S ₁	60	40	0	<0.1
S ₂	59.35	38.73	1.92	<0.1
S ₃	58.16	39.13	2.71	<0.1
S ₄	56.16	40.25	3.59	<0.1

III. Experiments with Mn-Cu Alloys

1. Measurements of internal friction and elastic modulus

Acoustic measurements in flexure vibration were taken with a frequency of about 340 Hz in the temperature range of from -150 to $+150^\circ\text{C}$. The strain amplitude is from 1×10^{-6} to 1×10^{-4} . For the specimens in homogenized condition, no transformation peak was observed in the temperature range where the measurements were taken and the variation of elastic modulus with temperature is normal. However, as will be reported in §IV of this paper, an ageing in the temperature range under the spinodal curve within the miscibility gap will shift the phase transformation temperature M_s to higher temperatures. For specimen S1 (Mn 60/Cu 40), 450°C is in the middle of this temperature range. Therefore ageing at 450°C is selected for the following experiments. After S1 was aged at 450°C for 30 min, an internal friction peak appeared around -18°C and an abnormal drop of the elastic modulus curve appeared around -10°C as shown in Fig. 1. (a) and (b) for the strain amplitude ranging from 1.4 to 14×10^{-5} . This internal friction peak is evidently the martensitic transformation peak. When amplitude effect is small, we may consider the temperature at which the elastic modulus becomes minimum as the transformation temperature M_s . Experiments showed that the internal friction peak does not change with the frequency of vibration and the rate of change of temperature of measurements, so that it is a stable peak. No amplitude effect was observed when the strain amplitude is smaller than 1×10^{-5} . For larger amplitudes, the internal friction in the temperature range $T \leq M_s$ (-10°C) increases approximately linearly with the strain amplitude and can be expressed as $Q^{-1}(T) = b_{Q-1} \cdot A_\varepsilon$ where A_ε is the strain amplitude. The amplitude dependent coefficient b_{Q-1} increases with a decrease of temperature and approaches a saturation value at -100°C as shown in Fig. 2 (a). This saturation temperature coincides with the temperature at which the transformation peak drops to its background value, i.e. when the transformation has been completed. Consequently, we conclude that the amplitude effect begins with the appearance of martensite (fct phase) and reaches a maximum value when the parent phase (fcc phase) has been transformed completely to martensite. As such, the amplitude effect evidently originates from a process taking place between the martensite plates.

As is shown in Fig. 1 (b), the elastic modulus in the temperature range $T \leq M_s$ also decreases approximately linearly with the strain amplitude and can be expressed as $E(T) = b_\varepsilon \cdot A_\varepsilon$. The amplitude dependent coefficient b_ε increases with a decrease of temperature and approaches a saturation value at -100°C [Fig. 2 (b)], which is similar to that for b_{Q-1} .

In order to confirm the results shown in Fig. 2 (a) and (b), similar acoustic measurements were taken with S1 (Mn 60/Cu 40) aged at 430°C for 45 min. The transformation point shifts now to $M_s = 25^\circ\text{C}$ and the transformation peak appears at $T_p = -6^\circ\text{C}$. The b_{Q-1} and b_ε curves behave similarly to those shown in Fig. 2 (a) and (b), only the saturation temperature is somewhat higher but is still coincident with the temperature at which the transformation peak drops to its background value. This strengthens the belief that the amplitude effect of the internal friction and elastic modulus is closely connected with the product of martensitic transformation.

When specimen S1 was aged at 430°C for 1 h, M_s shifts to 59°C [Fig. 3 (b)] and the transformation peak appears around 34°C [Fig. 3 (a)]. In addition to the transformation peak a new internal friction peak appears at a lower temperature -16°C . Evidently the new peak is the relaxation peak associated with the twin boundaries existing in the transformation product (martensite). The optimum temperature T_{p1} for the relaxation peak is seen to be -16°C , this is the peak temperature corresponding to a frequency of 340 Hz used for internal friction measurements.

It can be seen from Fig. 3 (a) and (b) that irrespective of the appearance of the relaxation peak P_1 which is usually amplitude independent, the amplitude dependent behavior of the transformation peak P_2 and the corresponding elastic modulus curve is similar to those shown in Fig. 1 (a,b).

Similar experiments have also been done for specimen S_0 (Mn 70/Cu 30). The M_s and T_{p2} after the specimen was aged at 450°C for various times are respectively -108°C , -120°C (P_2) for 15 min ageing, -12°C , -20°C (P_2) for 30 min ageing, and 59°C , -16°C (P_1), 34°C (P_2) for 45 min ageing. The amplitude dependent behavior of P_2 and the corresponding elastic modulus curve is similar to the case of S1 (Mn 60/Cu 40) specimen.

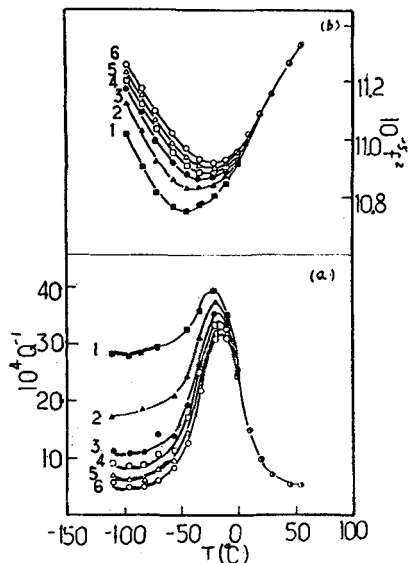


Fig. 1

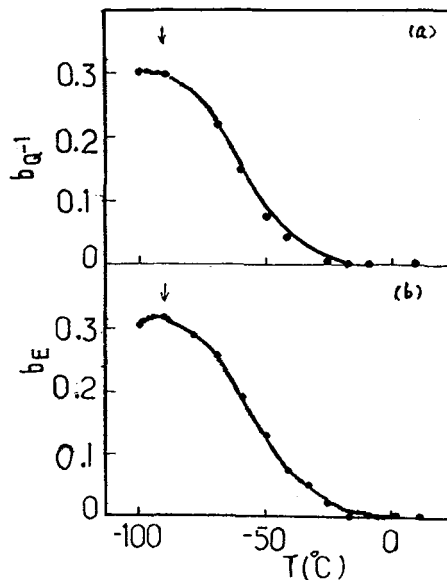


Fig. 2

Fig. 1. Variation of internal friction (a) and elastic modulus (b) with temperature of Si (Mn 60/Cu 40) aged at 450°C for 30 min and the amplitude effect. Curves 1-6 correspond to strain amplitude 14, 8.4, 5.6, 4.2, 2.8, and 1.4×10^{-5} . Frequency = 340 Hz measurements taken in ascending temperatures stepwise ($\dot{T} = 0$).

Fig. 2. Variation of the amplitude dependent coefficient b_Q^{-1} for internal friction (a) and b_E for elastic modulus (b) with temperature. The arrows in the figures indicate the temperature at which the intensity of amplitude effect reaches its saturation value.

2. Non-linear distortion of the resonance curve in flexure vibration

Simultaneously with the occurrence of amplitude dependent effect in internal friction and elastic modulus, the frequency response curve (the resonance curve) in flexure vibration exhibits an unsymmetrical distortion as shown in Fig. 4. For Si (Mn 60/Cu 40) aged at 450°C for 30 min, $M_s = -10^\circ\text{C}$, the unsymmetrical distortion of the resonance curve (with frequency of vibration about 1 kHz) starts at temperatures $T \leq M_s$. The top of the peak leans toward the lower frequency side and this behavior is enhanced with the lowering of the temperature of measurement. The vibration becomes unstable at -50, -70 and -89°C as shown in Fig. 4.

3. On the mechanism of the transformation peak proper and the low temperature internal friction background

A glance on the internal friction curves shown in Fig. 1 (a) reveals that the transformation peak can be resolved into two components: the transformation peak proper and the low-temperature background. The latter exhibits a strong amplitude effect and gives rise to an apparent shift of the top of the peak toward lower temperatures with an increase of strain amplitude. In the early stage of the martensitic transformation, the amount of the interface between the parent phase P(fcc) and the martensite M(fct) increases when the temperature is lowered, so that the internal friction increases with a lowering of temperature. However, as the transformation proceeds further, the increase of the amount of martensite and the mutual contact between the martensite plates will reduce the amount and the mobility of the P-M interface. Consequently the internal friction will decrease

with a further lowering of temperature, giving rise to an internal friction peak (the transformation peak). At the same time, the mutual contact of the martensite plates increases the amount of the martensite-martensite (M-M) interface. The hysteretic movement of the M-M interfaces gives rise to the low temperature internal friction background which is strongly amplitude dependent. The amplitude effect becomes stronger with an increase of the quantity of M-M interfaces.

The softening of the elastic modulus and non-linear behavior of resonance curve in flexure vibration corresponding to the low temperature internal friction background may be attributed to the non-linear elastic strain caused by the stress-assisted hysteretic movement.

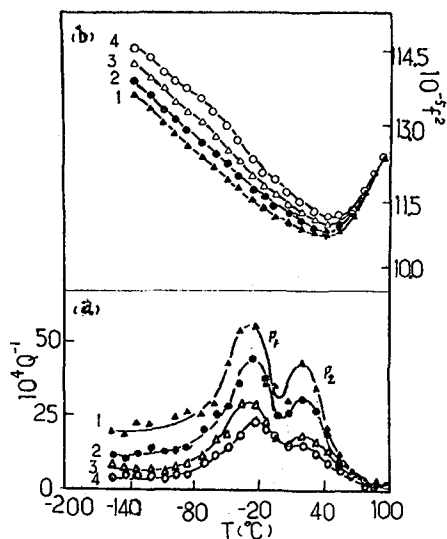


Fig. 3

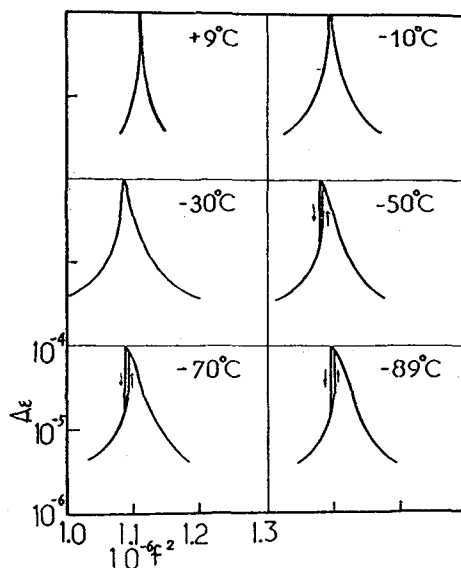


Fig. 4

Fig. 3. Variation of internal friction (a) and elastic modulus (b) with temperature of S1 (Mn 60/Cu 40) aged at 450°C for 1 h and the amplitude effect. Curves 1-4 correspond to strain amplitude 8.4, 5.6, 2.8, and 1.4×10^{-5} . Frequency = 340 Hz, $T = 0$.

Fig. 4. The unsymmetrical distortion of the resonance curve at various temperatures for specimen S1 (Mn 60/Cu 40) aged at 450°C for 30 min. Frequency : 1 kHz. $(A_e)_{\max} = 14 \times 10^{-5}$.

IV. Experiments with Mn-Cu-Al Alloys

1. Variation of internal friction and elastic modulus by ageing at various temperatures

(1) Ageing at 450°C.

According to the phase-diagram of Mn-Cu alloys shown in Fig. 5 [3], the metastable γ -phase formed by quenching the high temperature γ -phase to room temperature has the tendency of transforming to the stable $\alpha + \gamma$ at room temperature, and this process can be sped up by ageing in the temperature range under the spinodal curve within the miscibility gap. For Mn 70/Cu 30 alloy, Butler et al. [4] showed that this temperature range is around 400-500°C. Vitek et al. found that the hardness increases by ageing at 450°C. The purpose of the following research is to study the changes in internal friction and some mechanical properties of homogenized low manganese content Mn-Cu-Al alloys aged at different temperatures for various times to find out an optimum compromise of high strength and high internal friction and to understand the micro-mechanism underlying these changes.

Specimen S2 (Mn 59.35/Cu 38.73/Al 1.92) was aged at 450°C for 0.5, 1, 2, 4, and 9 h, and water quenched to room temperature, and the internal friction and elastic modulus were measured with $f = 1$ kHz, $A_\epsilon = 5.2 \times 10^{-6}$ with ascending temperatures ($\dot{T} = 1^\circ\text{C}/\text{min}$). Two internal friction peaks appear as shown in Fig. 6. The portion of the lower temperature peak around 15°C is independent of the ageing time and is evidently the relaxation peak connected with twin boundaries. The position of the higher temperature peak, the transformation peak, shifts to higher temperature with an increase of ageing time although the shift is not evident when the ageing time is larger than 4 h. It can be seen from the elastic modulus curves 1-5 that the Ms point (characterized by the lowest point on the modulus curve) shifts to high temperatures with an increase of ageing time. The height of the transformation peak reaches its maximum value for an ageing of 1 h but drops rapidly after an ageing of 4 h.

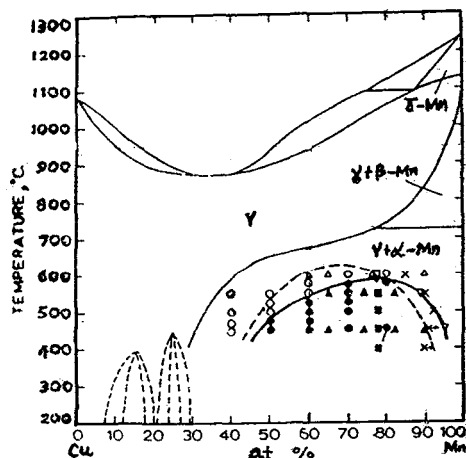


Fig. 5

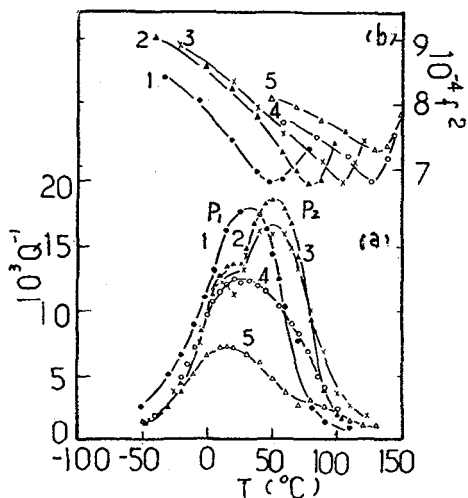


Fig. 6

Fig. 5. Phase diagram of Mn-Cu alloy and the associated miscibility gap[3].

Fig. 6. Internal friction and elastic modulus of specimen S2 (Mn 59.35/Cu 38.73/Al 1.92) aged at 450°C for various times. Curves 1-5 correspond to ageing time of 0.5, 1, 2, 4, and 9 h. $f = 1$ kHz, $A_\epsilon = 5.2 \times 10^{-6}$, $\dot{T} = 1^\circ\text{C}/\text{min}$ with ascending temperatures.

Experiments with specimen S3 (Mn 58.16/Cu 39.13/Al 2.71) and S4 (Mn 56.16/Cu 40.25/Al 3.59) give similar results as these of S2, only the height of the corresponding transformation peaks is much lower than those of S2, indicating that a higher aluminium content has the effect of reducing the internal friction. The results for specimen S4 are shown in Fig. 7. Comparing the results for S2 and S4, it is seen that doubling the aluminium content reduced the height of the internal friction peak almost to one half.

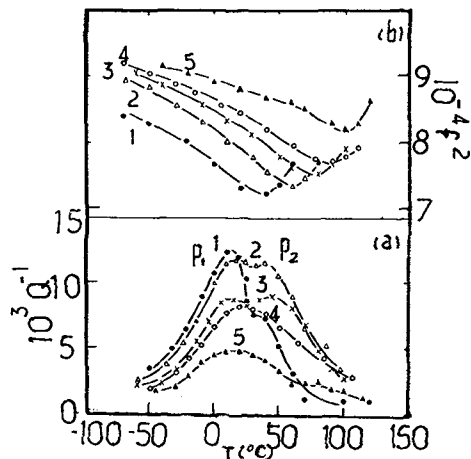


Fig. 7. Internal friction and elastic modulus of specimen S4 (Mn 56.16/Cu 40.25/Al 3.59) aged at 450°C for various times. Curves 1-5 correspond to ageing time of 0.5, 1, 2, 4, and 9 h. $f = 1$ kHz, $A_\varepsilon = 5.2 \times 10^{-6}$, $\dot{T} = 1^\circ\text{C}/\text{min}$ with ascending temperatures.

(2) Ageing at 400° and 500°C.

Ageing experiments at 400° and 500°C (respectively at the lower bound and the upper bound of the miscibility gap) show a similar tendency of the change in internal friction and elastic modulus. However, the rate of the shift of M_s with ageing time is quite different when aged at different temperatures. And the ageing time at which the transformation peak reaches its maximum value is different for different ageing temperatures. The ageing times required are 4, 1 and 0.5 h respectively for ageing at 400°, 450° and 500°C.

It can be concluded thus that a similar change has taken place in the specimens aged in 400°-500°C. This change is the spinodal decomposition, only that the rate of decomposition is different for different ageing temperatures.

(3) Ageing at 300° and 600°C.

The temperatures 300° and 600°C lie both outside the miscibility gap for the Mn content of specimens S1, S2, S3 and S4. Ageing experiments have been done for specimen S4 aged at 300° and 600°C for 0.5 and 2 h, the internal friction was found to be very low and no internal friction peak appears in the temperature range of -150° to 150°C. The elastic modulus curve is normal and no phase transformation occurs at all. This shows definitely that the phase transformation and the high internal friction observed in ageing experiments for 400°-500°C are all originated from spinodal decomposition.

2. Results of mechanical testing

In Fig. 8 are shown the Rockwell hardness (H_{RB}) (a), $\sigma_{0.2}$ (b), σ_b (c), and δ (d) for specimen S1 (Mn 60/Cu 40), S2 (Mn 59.35/Cu 38.73/Al 1.92), S3 (Mn 58.16/Cu 39.13/Al 2.71), S4 (Mn 56.16/Cu 40.25/Al 3.59) aged at 450°C for different times. It can be seen that the H_{RB} , $\sigma_{0.2}$ and σ_b all increase with ageing time and the rate of increase becomes lower after an ageing for 4 h. It can also be seen that S4, which has the largest aluminium content, exhibits a larger increase in hardness and strength.

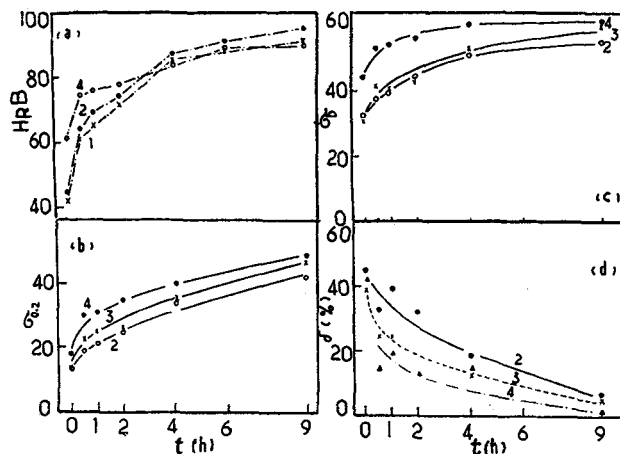


Fig. 8. Variation of H_{RB} (a), $\sigma_{0.2}$ (b), σ_b (c) and δ (d) of various specimens aged at 450°C for various times. Curves 1,2,3,4, correspond to S1,S2,S3 and S4.

The elongation δ of the specimen drops with an increase of ageing time. The rate of drop is also slowed down after an ageing of 4 h. Furthermore, the presence of aluminium has the effect of reducing the elongation δ of the specimen.

V. Concluding Remarks

Although the Mn content in the homogenized specimens used in the present experiment is only about 60 wt %, but because of micro-inhomogeneity produced by spinodal decomposition during ageing the localized content of Mn can be much higher than 60 wt %, so that martensitic transformation fcc \rightarrow fct can take place similar to the case of specimens with high Mn content.

Figs. 6 and 7 show that for the specimens aged in the spinodal curve within the miscibility gap (see Fig. 5), the internal friction first increases and reaches its maximum value for a certain ageing time and then decreases when aged for a longer time. The increase is due to the increase of the amount of martensite phase due to spinodal decomposition, and we believe that the decrease is due to the occurrence of the stable α -Mn phase. At higher ageing temperatures, the formation of Mn-rich regions is faster so that the internal friction reaches its maximum value at a shorter ageing time. However, the occurrence of α -Mn is also faster, so that the internal friction starts to decrease at a shorter ageing time. The magnitude of the internal friction is thus determined by the competition between the amount of the transformation product (fct martensite) and the amount of the stable α -Mn.

The increase of the hardness and strength of the specimen is evidently due to the lattice distortion produced by the fct transformation product and the cause of brittleness is due to the occurrence of the α -Mn.

An optimum compromise of high internal friction and high strength can be obtained by ageing the specimens at 450°C for 2-3 h.

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