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Non-linear internal friction and resonance in manganese–copper alloys

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Internal friction and modulus at different amplitudes and frequencies were measured for as-cast $Mn_{60}Cu_{40}$ alloy. Strong non-linear internal friction and resonance were observed. It was proposed that the sources of these were derived from different factors. A parameter, P, which can be used to weigh up non-linear resonance of materials, is proposed. A high damping mechanism is discussed for manganese–copper alloy.

1. Introduction

Anelastic studies have yielded a significant insight into the properties of metals and alloys. The major conceptual limitation of most anelastic studies is that interpretation of the data has ultimately been based on the model of a linear anelastic solid. The classical theory of standard or linear anelastic solids [1, 2] is not adequate for anelastic studies performed at finite deformations. This is particularly true in investigations of first-order martensitic transformation, or interface controlled deformations in general, where finite deformations are of the essence. In these cases, standard anelastic solid theory must be extended to include non-linear phenomena. The concept of non-linear anelasticity has been introduced by Wutting and coworkers [3–5]. The aim of this paper is to attempt to interpret the phenomena of non-linear internal friction and non-linear resonance in manganese–copper alloys.

2. Experimental procedure

MnCu alloys were supplied by Shanghai Jiaotong University. The composition is $Mn_{60}Cu_{40}$ (wt %). The specimens were prepared by electric-spark cutting into 80 × 4 × 2 and 60 × 4 × 1 mm sections for acoustic and low frequency measurement, respectively. Homogenized specimens were obtained from solution at 850 °C for 100 h, followed by water quenching. Due to the low content of Mn, this alloy did not undergo martensitic transformation (MT) near room temperature. After ageing at 430 °C for different times (t), the modulus (MS) increased due to spinodal decomposition, which may result in Mn-rich and Cu-rich zones in the specimens.

Internal friction, Q^{-1}, at low frequency was measured with a forced vibration torsion pendulum, developed in the laboratory; by which the phase lag, φ, between the stress and strain was determined and $Q^{-1} = \tan\varphi$. Acoustic internal friction was studied in the flexural vibration mode by the "method of half-peak width" and $Q^{-1} = (\omega_2 - \omega_1)/(3\omega_r)^{1/2}$. A parameter, $P = (\omega_r - \omega_1)/(\omega_2 - \omega_r)$, which is the weight of non-linear resonance of materials, is proposed. Here ω_1 and ω_2 are the frequencies corresponding to the 0.5 maximum of amplitude, and ω_r is the resonance frequency. For the standard anelasticity solid, $P = 1$, and the resonance curve is symmetric. $P < 1$ corresponds to the non-linear resonance of softened modulus. The smaller P is, the stronger the non-linear resonance is. When $P < 0$, a jump phenomenon appears in the resonance curve. For hardened cases, $P > 1$.

3. Results

The transformation f.c.c. $\leftrightarrows$ f.c.t. does not occur in alloys with less than 70 at % Mn, as the Néel temperature falls down to acceptable levels as shown in Fig. 1.

Fig. 2 shows the internal friction curves at low frequency for as-cast $Mn_{60}Cu_{40}$ alloy. Curves 1 and 2 correspond to the as-cast sample and homogenized sample, respectively. For the as-cast sample, two peaks, P_1 at about −34 °C and P_2 at about 110 °C, respectively, were observed in the temperature range −150–200 °C. P_1 is caused by stress relaxation across the twin boundaries. P_2 can be attributed to martensitic transformation in the sample [6]. As for the homogenized sample, no peak was found, and there is no anomalous change of the modulus curve. The value of internal friction is very small, and is about the order of 10^{-4}.

Internal friction and Young's modulus were measured at acoustic frequencies for the sample. For the homogeneous sample, no MT peak was observed and the modulus showed normal behaviour, i.e. $\mathrm{d}T/\mathrm{d}t < 0$. After ageing at 430 °C for 30 min, the internal friction manifested a peak at about −18 °C, whereas the modulus (Ms) exhibited a minimum at about −10 °C

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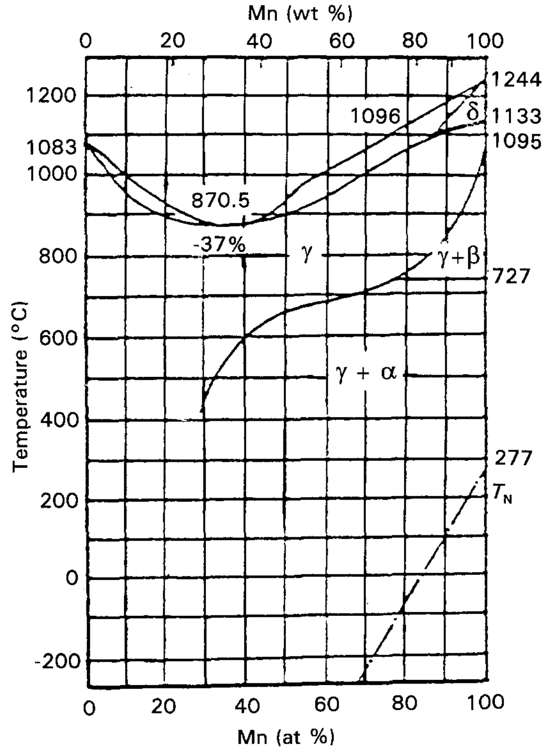

Figure 1 Equilibrium phase diagram for the binary system Mn–Cu.

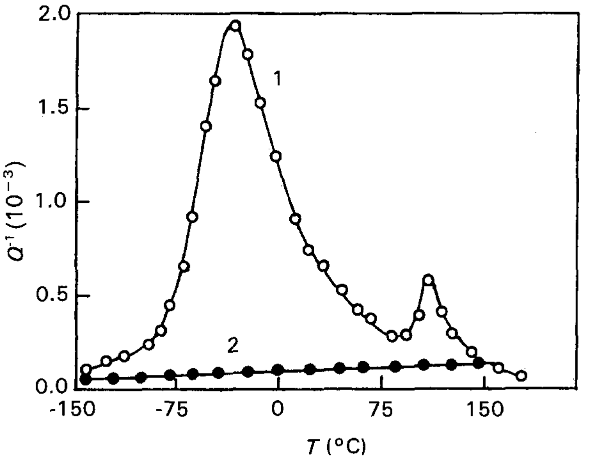

Figure 2 Internal friction curves, Q, versus temperature at 2.5 Hz and strain amplitude of 7×10^{-6} for $Mn_{60}Cu_{40}$ samples: (1) cast specimen, and (2) homogenized specimen.

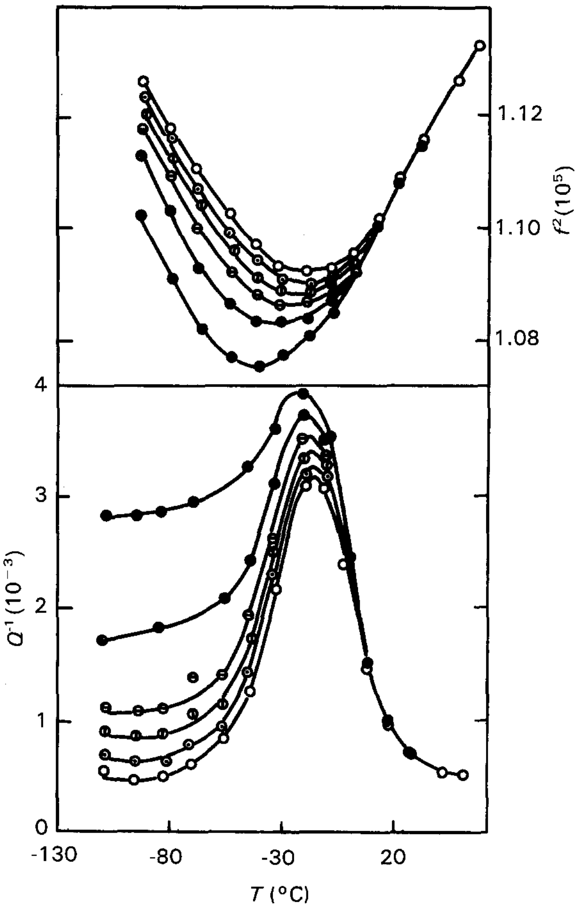

Figure 3 Variation of internal friction and modulus with descending temperatures in aged $Mn_{60}Cu_{40}$ samples at a frequency, f, of 1.01 kHz. The strain amplitudes are: (○) 1.4×10^{-5}, (⊙) 2.8×10^{-5}, (⦶) 4.2×10^{-5}, (⊖) 5.6×10^{-5}, (⊕) 8.4×10^{-5}, and (●) 1.4×10^{-4}, respectively.

as shown in Fig. 3. This peak was obviously an MT peak because of its correspondence with modulus softening. The height of the peak is independent of the ratio (dT/dt), which is a good illustration of an adiabatic characteristic. Within the strain amplitude range from 1×10^{-6} to 1×10^{-5}, the internal friction had no amplitude effect. When the amplitude became larger than 1×10^{-5}, the internal friction exhibited a strong amplitude effect in the temperature range $T <$ Ms; whereas the position of the peak shifted slightly towards lower temperatures with increasing amplitude. The Young's modulus for this sample also manifested a very strong strain amplitude effect.

Fig. 4 gives the internal friction curves for as-cast $Mn_{60}Cu_{40}$ at different amplitudes and frequencies. Fig. 4a and b corresponds to the results of low frequencies and acoustics, respectively. Whether it is at low or acoustic frequencies, the amplitude effects of internal friction for the sample is the same. The peak appearing at higher temperatures is a twin peak, and the source of an incomplete peak appearing in the lower temperature range is unknown at present. Strong non-linear internal friction was observed at the temperature range of the twin peak and a low temperature peak appeared; but for the background internal friction, the amplitude effect is not stronger than that of the former. The width of the twin peak measured at acoustic frequencies is larger than that at low frequencies; which can be attributed to the superposition of the twin peak and the MT peak, because the relaxation peak shifts to the higher temperature side when the frequency increases.

The non-linear resonance curves of as-cast sample $Mn_{60}Cu_{40}$ at various temperatures are shown in Fig. 5. Fig. 5a–d corresponds to 80, − 13, − 58 and − 104 °C, respectively. The lower the temperature, the stronger the non-linear resonance. A "jump" phenomenon appeared in the resonance curve for the as-cast $Mn_{60}Cu_{40}$ sample when the temperature decreased to about − 60 °C, i.e., the "λ" resonance curve was observed.

Fig. 6 gives the parameter, P, and internal friction curves for the as-cast $Mn_{60}Cu_{40}$ sample. It was found that the parameter P minimum appeared at about the

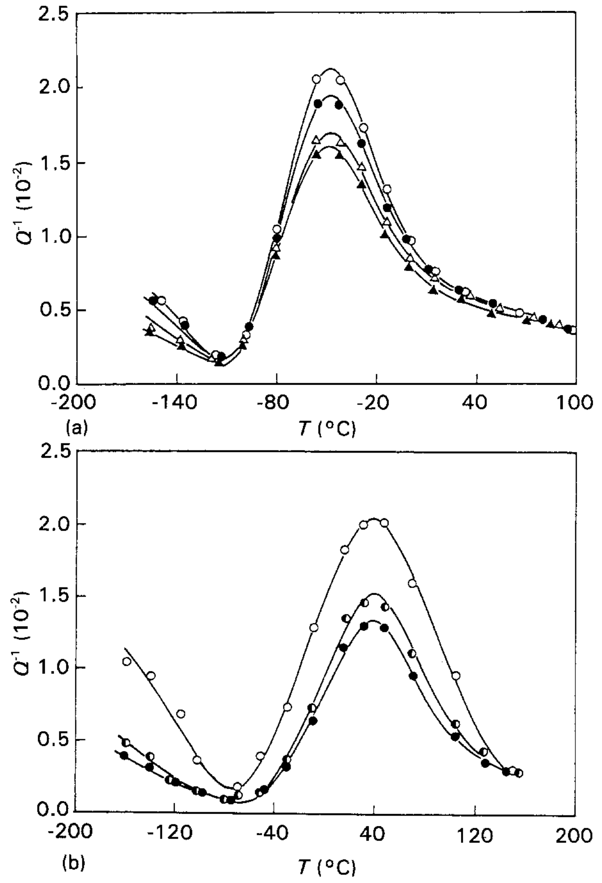

Figure 4 Internal friction curves at different amplitudes for as-cast $Mn_{60}Cu_{40}$ alloy: (a) $f = 1.0$ Hz, at (○) 9×10^{-5}, (●) 5×10^{-5}, (△) 2×10^{-5}, (▲) 1×10^{-5}, (b) $f = 900$ Hz, at (○) 1×10^{-4}, (◐) 1×10^{-5}, and (●) 1×10^{-6}.

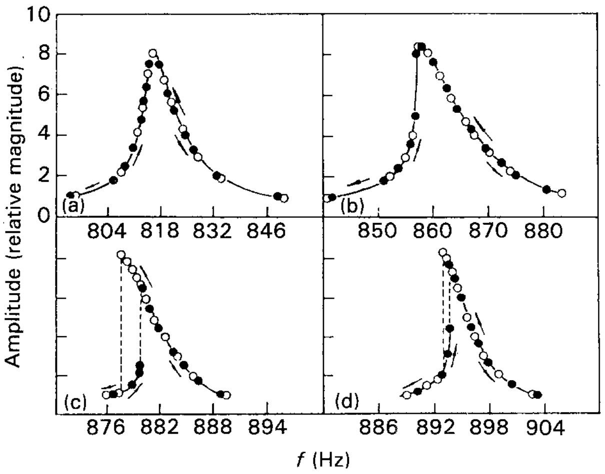

Figure 5 Resonance curves at different temperatures and at a strain amplitude of 1×10^{-4} for as-cast samples. (a) 80 °C, (b) − 13 °C, (c) − 58 °C, and (d) − 104 °C. (●) homogenized sample, (○) cast sample.

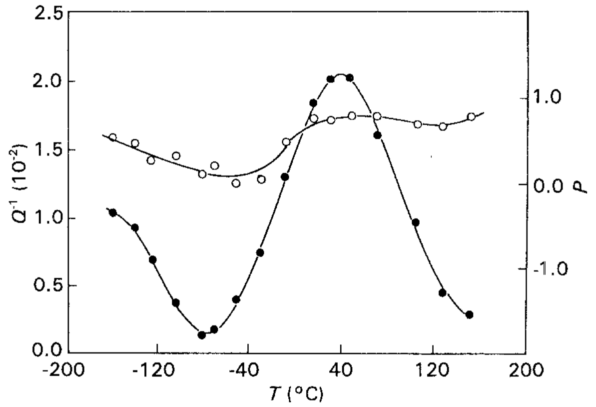

Figure 6 Parameter P (○) and internal friction curves (●) versus temperature for as-cast samples: $\dot{T} = 0\,°\mathrm{C\,min}^{-1}$, $A_\varepsilon = 1\times10^{-4}$ and $f = 850$ Hz.

temperature range of the internal friction minimum. This temperature was about − 60 °C. Although non-linear resonance existed in other temperature ranges, it is less strong.

4. Discussion

For the sample with lower Mn-content, the internal friction curves of the cast specimen are completely different from those of the homogenized specimen. This is due to the effect of compositional fluctuation. Due to the existence of some small Mn-rich areas in the cast specimen, the transformation temperature for those areas is raised to around room temperature; consequently the transformation peak and the relaxation peak can be observed in the experiments. However, for the homogenized specimen, the transformation temperature is close to absolute zero degrees, so the specimen always consists of the high temperature phase, and both the transformation peak and the twin peak cannot be observed.

For temperatures lower than the Ms point, three possible mechanisms for internal friction can be considered:

1. the interface boundaries between the parent phase and martensite, i.e. the *P*–*M* interface;
2. the interfaces between martensites, i.e. *M*–*M* interfaces;
3. the twin boundaries.

The stable internal friction peak, i.e. the MT peak was mainly caused by *P*–*M* interfaces. The hysteresis movement of *M*–*M* interfaces can bring about energy dissipation under applied stress. Owing to the amount of *M*–*M* interfaces, which increase monotonously with descending temperature, their contribution to internal friction will get larger and approaches a saturated level, corresponding to a certain quantity of the interfaces under a certain strain amplitude, just like the behaviour of amplitude-dependent internal friction in the experiments. At very low temperatures, the martensite volume fraction and the quantity of *M*–*M* interfaces reach an almost constant level under a definite strain amplitude, and may increase with increasing strain amplitude. The analysis above seems to be a possible interpretation for low temperature amplitude-dependent internal friction.

Internal friction caused by the twin boundaries in as-cast MnCu alloys is a kind of relaxation mechanism; the boundaries do not possess an amplitude effect at amplitudes $< 1\times10^{-5}$ [6]. But, when the strain amplitude is larger than 1×10^{-5}, a strong amplitude effect appeared in the internal friction peak caused by twin boundaries; especially, at the zenith of the peak. Background internal friction caused by $M-M$ interfaces possesses less of an amplitude effect. Consequently, the source of high damping for as-cast MnCu alloy can be attributed to twin boundaries, whether or not the amplitude is of lower or higher strain.

Fig. 5 shows that asymmetric resonance curves appear at temperatures lower than Ms and larger strain amplitudes, i.e. the resonance frequency, (f_r), depends strongly on the strain amplitude; therefore, the elastic modulus ($\propto f_r^2$) also decreases. The "amplitude effect" becomes stronger with descending temperature and gradually approaches saturation. This viewpoint agrees with conclusions in the literature [7]. But, internal friction only exhibits strong amplitude effects in some temperature ranges. Therefore, the sources of the two amplitude effects may be attributed to different factors for cast MnCu alloys. It is proposed that the non-linearity of elastic modulus (non-linear resonance) mainly comes from the movement of $M-M$ interfaces, and the source of non-linear internal friction is related to the non-linear movement of twin boundaries. As for enhancement of the parameter P at about the temperature of the twin peak and $-120\,^{\circ}\mathrm{C}$, this is due to an increase in internal friction and to a widening of the resonance curve; non-linear resonance was covered.

For the increase of internal friction at temperatures lower than $-120\,^{\circ}\mathrm{C}$, a new internal friction peak may appear at further lower temperature ranges. This work needs further investigation.

5. Conclusions

1. Non-linear internal friction was caused by the irreversible movement of twin boundaries and non-linear elastic modulus, i.e. modulus softening and non-linear resonance can be attributed to movement of interfaces between martensites.
2. Whether it is at lower or higher strain amplitude, the source of high damping for as-cast MnCu alloys comes mainly from the twin peak which possesses a strong amplitude effect.
3. The parameter P can be used to weigh up non-linear resonance for materials.

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