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Studies on Internal Friction Associated with the Motion of Interfaces in Cu-Al-Zn-Ni Alloy

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Abstract. An internal friction peak associated with the viscous motion of interfaces was measured in the 50-150kHz range for the Cu-Al-Zn-Ni sample. The internal friction formula based on the viscous motion of interfaces has been derived. Also, corresponding parameters, which play an important role in shape memory effect such as viscosity coefficient, pinned force constant were obtained.

I. INTRODUCTION

The internal friction (Q^{-1}) associated with first order phase transition in the low frequency range has been known to consist of a transient component, Q_t^{-1} and a stationary component, Q_s^{-1} . The experimental results for the Q_t^{-1} on cooling or heating at finite rate ($\dot{T}$) showed that the Q_t^{-1} is proportional to $\dot{T}/f$ [1-4]. For the Q_s^{-1} , the mechanism of the stress induced movement of coherent interfaces including phase interfaces, variant and twin boundaries has been widely accepted [1-11]. Most experimental results showed that the Q_s^{-1} is independent of frequency in the low frequency range (below KHz). Huang et al. [12] found the Q_s^{-1} peak to be related to the viscous motion of domain walls in KH_2PO_4 (KDP) and $(\text{NH}_2\text{CH}_2\text{COOH})_3\text{H}_2\text{SO}_4$ (TGS) crystals in the higher frequency range. It is not known if there appears the viscous motion of interfaces in martensitic alloys in some higher frequency range. As we know that the mobility of interfaces is important in shape memory effect (SME) because it affects the life and the responding speed of SME. So, in this study, the dynamics of interfaces was studied by using internal friction measurements at higher frequencies and the corresponding parameters such as the spontaneous shear strain, pinned force constant and viscous coefficient, which are closely related to the mobility of interfaces, were obtained for Cu-Al-Zn-Ni alloys.

II. EXPERIMENTS

A shape memory material with the composition Cu-28.76at%Al-4.76at%Zn-2.33at%Ni was prepared by vacuum induction melting and homogenized at 970°C for 5 hours. Then, it was cut into sheets of 3mm thickness. Samples for internal friction measurements were prepared from above treated sheets by the spark cutting and were kept at 830°C for 10 minutes, followed by air quenching to room temperature. The starting and finishing temperature of austenitic transformation, measured by the four ends electric resistance method are $A_s=60^\circ\text{C}$ and $A_f=95^\circ\text{C}$, respectively. Internal friction was measured by using the resonant bar apparatus with the static electric drive and detection in the kilohertz range and the piezoelectric composite oscillator in the 50-150 kHz range. X-ray diffraction was conducted to study the structure and spontaneous strains in the Cu-Al-Zn-Ni sample.

III. RESULTS AND DISCUSSION

Fig. 1 shows the results of internal friction (Q^{-1}) as a function of temperature on heating with $\dot{T}=0.4^\circ\text{C}/\text{min}$ in the kHz range for the Cu-28.76at%Al-4.76at%Zn-2.33at%Ni sample. An internal friction peak appears at 78°C and is independent of the measuring frequency, which reveals that the internal friction is of the static hysteresis type. Moreover, the results measured by using the Marx three component resonator, on heating, in the 50-150 kHz range show that an asymmetrical internal friction peak appears below A_f (95°C) as shown in fig. 2. The peak temperature (T_p) increases with the measuring frequency and the relationship between $\ln f$ and T_p does not obey the Arrhenius relationship, which indicates that the internal friction peak is neither a static hysteresis loss peak nor a thermally activated Debye relaxation peak. The behavior of the internal friction is very similar to that of the internal friction associated with the viscous motion of domain walls in KDP and TGS crystals[12].

Fig. 1. Internal friction as a function of temperature on heating with $\dot{T} = 0.4^\circ\text{C}/\text{min}$ at different frequencies $\circ$ 710 Hz $\bullet$ 1982 Hz.

Fig. 2. Internal friction as a function of temperature on heating at different frequencies $\circ$ 49 kHz $\square$ 93 kHz $\triangle$ 148 kHz. — results of the computer simulation.

During interfaces motion, there are four forces acting on the unit area of interfaces:

- (a) the configuration force F_C ;
- (b) the interaction force between nearest-neighbour interfaces F_I ;
- (c) the viscous force $-\Gamma\dot{x}$, where Γ is the viscous coefficient;
- (d) the recovering force $-k_0x$ due to defects pinning, where k_0 is the force constant.

Let m be the effective mass per unit area of the interface and x be the displacement of the interface under the applied stress, the equation of the movement of an interface is

$$m\ddot{x} + \Gamma\dot{x} + k_0x - F_I = F_C \quad (1)$$

It is easily deduced from the energy change due to the change of the interfaces configuration under the applied force that

$$F_I = -2C_{ijj}N[\epsilon_{ij}^{(s)}]^2 x \quad (2)$$

$$F_C = 2\epsilon_{ij}^{(s)}\sigma_{ij} \quad (3)$$

$$\epsilon_{ij}^{(d)} = \epsilon_{ij}^{(s)} x / d \quad (4)$$

where $\epsilon_{ij}^{(s)}$ is the spontaneous shear strain, C_{ijj} is the corresponding shear modulus, N is the average number of parallel interfaces per unit perpendicular distance. So, $N=d^{-1}$ where d is the distance between nearest-neighbour interfaces, σ_{ij} is the effective shear stress which can drive interfaces to move, $\epsilon_{ij}^{(d)}$ is the shear strain caused by interfaces moving under applied stress.

Let $\sigma_{ij} = \sigma_0 e^{i\omega t}$ and when $\omega^2 < k/m$ where $k=k_0+2C_{ijj}N[\epsilon_{ij}^{(s)}]^2$, the internal friction (Q^{-1}) can be obtained from formulas (1)-(4)

$$Q^{-1} = \frac{2N[\epsilon_{ij}^{(s)}]^2}{Jk} \frac{\omega\tau}{1+\omega^2\tau^2} \quad (5)$$

where $\tau = \Gamma/k$ is the relaxation time.

According to the expression obtained by Combs and Yip[13] for the viscous coefficient

$$\Gamma = Ae^{-B/(T_c-T)} \quad (6)$$

where A and B are constants, T_c is the corresponding A_r on heating in martensitic alloys. We can obtain $A/k=7 \times 10^{-4}$ second and $B=130$ K by using the computer simulation based on the internal friction experimental results as shown in fig. 2. In order to obtain the effective force constant k from the formula (5), we calculated the spontaneous shear strain, $\epsilon_{ij}^{(s)}$, density of interfaces N and modulus J^{-1} based on the results of X-ray diffraction, metallographic observation and internal friction measurements.

The results of X-ray diffraction in the Cu-Al-Zn-Ni sample show that the structure of the orthorhombic r_1' martensitic is Cu_3Ti type with lattice parameters, $a=0.4382$ nm, $b=0.5356$ nm, $c=0.4222$ nm and the principal axes in r_1' martensitic phase are parallel to the directions of $[10\bar{1}]$, $[010]$, $[101]$ of β_1 cubic parent phase with $a_0=0.5836$ nm, which is similar to the results obtained by K. Otsuka et al.[14]. In the principal axes coordinate system of the r_1' orthorhombic phase, we can obtain the strains due to martensitic phase transformation based on the results of X-ray diffraction experiments and the Neumann principle.

$$\begin{aligned} \epsilon_{11} &= (a - \frac{\sqrt{2}}{2}a_0) / \frac{\sqrt{2}}{2}a_0 = 0.061, & \epsilon_{22} &= (b - a_0) / a_0 = -0.082 \\ \epsilon_{33} &= (c - \frac{\sqrt{2}}{2}a_0) / \frac{\sqrt{2}}{2}a_0 = 0.022, & \epsilon_{ij} (i \neq j) &= 0 \end{aligned}$$

So, the spontaneous shear strain in β_1 cubic phase coordinate system

$$S_{ij}^{(s)} = 2 \sum_{i,j=1}^3 a_{ii}a_{jj}\epsilon_{ij} = 0.0389.$$

where $a_{11} = a_{31} = a_{33} = \sqrt{2}/2$, $a_{13} = -\sqrt{2}/2$, $a_{12} = a_{32} = 0$

The average density of interfaces N is $1.2 \times 10^5/\text{m}$ based on the results of metallographic observation. The elastic modulus is 1.5×10^5 MPa based on the formula $J^{-1}=4\rho l^2P^2$ where $\rho=7.59\text{g/cm}^3$, $l=2.42\text{cm}$ and $f=93$ kHz.

The pinned force constant k_0 , k and the viscous coefficient Γ can be obtained based on the results mentioned above and the formulas (5) and (6). They are

$k=1.6 \times 10^{15}\text{N/m}^3$, $k_0=1.54 \times 10^{15}\text{N/m}^3$ and $\Gamma=11.2 \times 10^{11}\exp[-130/(363-T)]\text{Kg/m}^2\text{s}$.

IV. CONCLUSION

The internal friction peak in the 50–150 kHz range is neither a static hysteresis loss nor a thermally activated Debye relaxation peak. It relates to the viscous motion of interfaces. The viscous coefficient and the pinned force constant have been obtained in the Cu-Al-Zn-Ni by using internal friction measurements, metallographic observation, X-ray diffraction analysis and the model of the interfaces viscous movement.

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