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Anomalous Behaviour of the Zener Relaxation in Cu-Au

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Abstract: Measurements of the Zener relaxation in single crystals of Cu-18at.%Au and Cu₃Au are presented. In the 18at.% alloy only one internal friction peak is observed at low frequencies (of the order of 1 Hz). This peak is only slightly wider than a Debye's peak. An additional hump appears at intermediate frequencies (of the order of 60 Hz). The Zener peak in the Cu₃Au alloy is accompanied by an additional maximum produced by the order-disorder transition.

A measurement of the derivative of the damping with respect to the frequency through the use of a pendulum with variable moment of inertia shows that non-linear effects are present in the Zener relaxation in both alloys.

1 INTRODUCTION

The Zener peak is due to stress-induced ordering which occurs in substitutional solid solutions. A survey of this relaxation process has been made recently [1]. Data on the Zener relaxation in the Cu-Au system in single and polycrystals have been reported [2, 3]. The analysis of these experimental data, however, was mainly based on linear viscoelasticity and no amplitude-dependent effects were considered. Furthermore, the Zener peaks are normally assumed to be amplitude independent.

It is the purpose of this paper to analyze the frequency dependence of the Zener relaxation in two Cu-18at.%Au and Cu₃Au single crystals, showing that they manifest non-linear effects.

2 THEORETICAL BACKGROUND

The internal friction F of any viscoelastic material can be expressed as [4]

$$F(\omega, T) = \frac{1}{2} \int_{-\infty}^{\infty} \frac{\Phi_t(\tau, T)}{\cosh[\ln(\omega\tau)]} d(\ln \tau) \quad (1)$$

where τ is the relaxation time, Φ_t the tangent distribution function, ω the angular frequency of the applied stress and T the absolute temperature. If eq. (1) is fulfilled, then [5]

$$\left| \frac{\partial \ln F}{\partial \ln \omega} \right|_T \leq 1 \quad (2)$$

This condition is necessary for a process to be linear but is not enough to establish the linearity of a damping behaviour. In other words, non-linear processes may satisfy eq. (2) but, if this condition is not obeyed, the presence of non-linear mechanisms in the relaxation can be assured.

3 EXPERIMENTAL PROCEDURE

The Zener relaxation was measured as a function of temperature in high vacuum using a modified traditional torsion pendulum [6]. This allows to keep the frequency constant in the whole temperature range of the damping peak, due to the slightly variable moment of inertia. In this way not only the traditional curves of F and ω but also that of F_c —internal friction at a constant frequency ω_c —are determined as a function of temperature. Then, the slight changes of ω with temperature justifies the following approximation

$$\left. \frac{\partial \ln F}{\partial \ln \omega} \right|_T \approx \left. \frac{\ln(F_c/F)}{\ln(\omega_c/\omega)} \right|_T \quad (3)$$

Thus, the data obtained with the pendulum with variable moment of inertia are used to determine whether non-linear processes are involved.

Two different types of single crystal wires were employed: Cu-18at.%Au and Cu₃Au. The experimental procedure to obtain the single crystal specimens is described elsewhere [2]. The internal friction measurements were made on heating at approximately 60 K/h both at low and intermediate frequencies. The orientation factors of the two crystals were of the order of $\Gamma = 1/3$.

4 RESULTS

Fig. 1 shows the data obtained in Cu-18at.%Au at low frequencies after subtracting out a small background. The frequency at the maximum is $\omega_m \approx 52.3 \text{ s}^{-1}$. $\partial \ln F / \partial \ln \omega|_T$ obtained by using eq.(3) is also indicated. Fig. 2 shows the results obtained in another part of the same single crystal at low and intermediate frequencies. ω_m is indicated in the same figure. It can be observed that a hump, which appears at intermediate frequencies, is not present in Figs. 1 and 2 at low frequencies.

Fig. 3 shows the data obtained in a Cu₃Au single crystal at intermediate frequencies, together with $\partial \ln F / \partial \ln \omega|_T$. An additional small peak, produced by the order-disorder transition, can be observed at lower temperatures. Finally, the results obtained in the same specimen at low and intermediate frequencies are compared in Fig. 4.

Fig. 1: Zener peak and its derivative for Cu-18at.%Au.

Fig. 2: Zener peaks in Cu-18at.%Au at two frequencies.

Fig. 3: Zener peak and its derivative for Cu_3Au . Fig. 4: Zener peaks in Cu_3Au at two frequencies.

5 DISCUSSION

It is clearly seen from Figs. 1 and 3 that the condition given by eq. (2) is not satisfied neither in $\text{Cu-18at.\%Au}$ nor in Cu_3Au . This condition is not fulfilled even far from the tails of the peaks where no so large errors are involved in the calculation of $\partial \ln F / \partial \ln \omega|_T$ by eq. (3). In effect, it should be taken into account that a background has been subtracted out from the peaks of Figs. 1 to 4 introducing large errors in the determination of the tails, particularly at high temperatures. From the phase diagram, it is well-known that an order-disorder transition in Cu_3Au occurs at 663 K [7]. This transition is shown clearly by the small peak at low temperatures of Fig. 3. It is also illustrated in the same figure how $|\partial \ln F / \partial \ln \omega|_T| > 1$ except in a small region near the maximum of the internal friction. This shows that non-linear phenomena are present in the Zener relaxation in Cu_3Au . Finally, Fig. 4 compares the Zener peaks measured at two frequencies. At the lower one the internal friction peak produced by the order-disorder transition is masked by the Zener relaxation. Furthermore, the Zener peak is higher as the temperature of the maximum approaches the order-disorder transition, as it is shown on comparing the peaks measured at low and intermediate frequencies. As shown in Fig. 1, non-linear effects are also present in $\text{Cu-18at.\%Au}$ alloys, since $|\partial \ln F / \partial \ln \omega|_T| > 1$, except in a region near the maximum of the internal friction peak. As shown in Fig. 2 there is a perturbation in the low temperature tail of the peak measured at 51.6 s^{-1} , which is not present in the same specimen measured at 15.8 s^{-1} , since the small hump is masked by the Zener peak. As for Cu_3Au , the Zener peak increases when the maximum approaches the temperature corresponding to the small hump, that is, when the peak is measured at the lower frequency. In fact, it is generally observed that the temperature dependence of the relaxation strength, Δ_M , obeys a Curie-Weiss-type law [1]

$$\Delta_M^{-1} \propto [T - T_M^{(an)}]$$

where $T_M^{(an)}$ is the anelastic critical temperature at which ordering would occur spontaneously if

atomic movements were possible. This means that the Zener peak should increase as the peak temperature approaches $T_M^{(an)}$. If $T_M^{(an)}$ is of the order of the critical temperature for ordering, as suggested in [3], then the hump in the Cu-18at.%Au alloy should occur at temperatures lower than for Cu₃Au, because according to the most accepted phase diagram [7] the order-disorder transition in the former occurs at lower temperatures than in the later. In any case, the exact temperature dependence of the relaxation strength can be evaluated only numerically and eq. (4) is only an approximation valid in the high temperature limit [1].

The linear characteristics of the Zener peaks in Cu-18at.%Au and Cu₃Au have been discussed in detail elsewhere [2, 3]. It should be pointed out that the width at half maximum of the Zener peaks shown in Figs. 1 to 4 are close to those predicted for Debye peaks, on using the activation enthalpies measured by the shifts of the maxima with frequency. However, $\partial \ln F / \partial \ln \omega|_T$ shows clearly that non-linear phenomena are involved. In any case, more work is needed to establish the mechanisms which produce the non-linear effects and the hump observed in the peak measured at intermediate frequency in Cu-18at.%Au.

Finally, it is noticed that non-linear phenomena were determined [5] on calculating the logarithmic derivative of the Zener peak measured as a function of frequency in Ni-25.5at.%Al at 831, 864 and 883 K [8].

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