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Internal Friction Peak P_1 in Copper

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The present theoretical knowledge concerning deformation-induced relaxation peaks in metals is still in the early stage of development, despite the many models proposed. All of these models contain fundamental flaws and cannot, when compared with experimental evidence, account for the characteristics of the peaks. Experimental results are given to illustrate the weakness of the present theories regarding the Hasiguti peak P_1; and a model, based upon the occasional breakaway of dislocation loops from vacancy pinning points, is postulated on the basis of modulus defect results associated with the peak. This is shown to account for the major aspects of the peak.

1. Introduction

Relaxation peaks in plastically deformed metals have been recognised for many years [1]; but theories explaining all their characteristics are incomplete [2]. These peaks, which are referred to as Bordoni [3] and Hasiguti [4] peaks, occur in the temperature range 10 to 300° K for most metals. The Hasiguti relaxation actually consists of three peaks, referred to as P_1, P_2, and P_3 by the original investigator, which appear only after deformation and low-temperature annealing. The present paper is concerned only with P_1, which, for copper, is caused by a relaxation mechanism having activation energy 0.3 eV and frequency factor of 10^{11} sec^{-1}. Various theories have been postulated but, as will be seen in section 2, all contain flaws, and as yet no completely satisfactory model has been described. Section 3 of the paper deals with the experimental work, results, and a discussion of the results; and, in section 4, a model is suggested which accounts for the major characteristics of the peak and its relation to other deformation-induced peaks. This model differs from previous models in that: (i) the relaxation peak is produced by the unpinning of a few dislocation segments from vacancy pinning points; (ii) at temperatures above and below the peak temperature, very little unpinning occurs.

2. Previous Models

Several mechanisms have been proposed by different authors for dislocation relaxation associated with point defects, which are intended to explain peak P_1. The most recent model of Koiwa and Hasiguti [5] considers dislocation segments with pinning points as the elements of anelastic strain. At temperatures other than 0° K, unpinning of dislocations with the help of thermal energy may be expected at stresses lower than the critical stress for mechanical unpinning.

The assumptions made by Kiowa and Hasiguti are as follows.

(*a*) There are N elements per unit volume which succeed in jumping out with frequency

$$\nu \exp\left[\frac{-(U - a\sigma)}{kT}\right] \text{ sec}^{-1}$$

where: ν is a frequency factor; U, the activation energy of the process; a, the activation volume; σ, the applied stress; and T, the temperature. But with zero applied stress ($\sigma = 0$) no jumping occurs. An element is defined as a dislocation segment with a pin, jumping-out as unpinning, and jumping-back as repinning.

(*b*) Once an element has jumped out, it does not jump back until the stress is zero. All elements which have jumped out, jump back at every instant that the stress becomes zero.

Both of these assumptions contain flaws. Internal stresses are present in cold-worked metals, which affect the "jump-out" and "jump-back" frequency. A factor should be included in the Arrhenius relationship to allow for this. The presence of this internal stress changes the

unpinning frequency, which is not zero even under zero external stress. The stress factor also complicates the second assumption, since some of the elements will have been repinned with the defects before the external stress reaches zero, and complete repinning will not occur at one instant of time. The model considers that, at temperatures other than 0° K, unpinning of the dislocations with the help of thermal energy may be expected at stresses lower than the critical stress at which mechanical unpinning occurs. A maximum for the damping loss occurs at intermediate temperatures, such that at low temperatures no unpinning occurs and there is only a small decrement, while at high temperatures almost complete unpinning occurs and again the decrement is small. Experimental results [6] and theory [7] show that the damping increases with increasing temperature owing to thermal breakaway; and increasing the temperature is similar to lowering the critical strain amplitude.

Koiwa and Hasiguti evaluate N to be of the order of 10^{14} to $10^{17}/cm^3$; that is most of the vacancies located on the dislocation lines are left behind by the dislocation segments under the action of the applied stress. It will be shown in a later section that only a few vacancies are involved in the unpinning process.

Okuda and Hasiguti [8] proposed a model based on an idea of Kessler [9], in which small vibrations of dislocation line segments cause displacements in the point-defect distributions surrounding the dislocations. This results in a relaxation time, τ, the order of 10^{-15} sec and a decrement loss term $>10^{-2}$. Experimentally, $\tau = 10^{-11}$ sec, and the decrement is about 10^{-4}. The activation energy of the process, which is the activation energy for diffusion of the defect in the stress field of the dislocation, does not correspond to the energy found experimentally.

Bruner's theory [10] is based on the "flip-flopping" of partial dislocations about a point defect. Analysis of this model shows that it is only applicable to fcc materials and not to bcc materials, which also exhibit peaks [11].

Hasiguti has considered two models [12, 13] based on: (i) the diffusion of dislocation kinks trapped by point defects; and (ii) the unpinning of Mott-Friedel-type loops. He considers [12] the two processes to be similar, and obtains mathematical expressions for the decrement and relaxation time, the latter being $\tau_0 = L^2/\pi^2 \nu \Lambda$; where: L is the average loop-length between point defects; ν, an atomic frequency; Λ, the distance moved by a kink after breakaway. It would appear that the frequency factor is strain-amplitude dependent, in the early stages of growth at least, but this is not evident from the results. It has been assumed that the kinks move under the action of the applied stress, but the back stress has not been included [14]. The existence of kinks is debatable; values of the Peierls stress are so low in copper, that a dislocation line lying across the close-packed directions should retain its identity and not contain kinks. With a strain amplitude of 10^{-7}, the maximum displacement of a dislocation loop of length 10^{-4} cm would be 10 Å. So that repinning with another vacancy would not occur, and the second mechanism cannot account for the peak at low strain amplitudes.

It can thus be concluded that none of the models described in this section can account for the properties of the P_1 peak in copper.

3. Experimental Results

Measurements of internal friction and modulus have been made on polycrystalline copper from 80 to 350° K at a frequency of 10 kc/sec [15]. The results for a specimen deformed 8% in tension at 300° K, and subsequently annealed at different temperatures, are shown in figs. 1 and 2. After deformation, peaks P_1 and P_2 are present at temperatures −47 and −10° C, P_2 decaying rapidly after a low-temperature anneal.

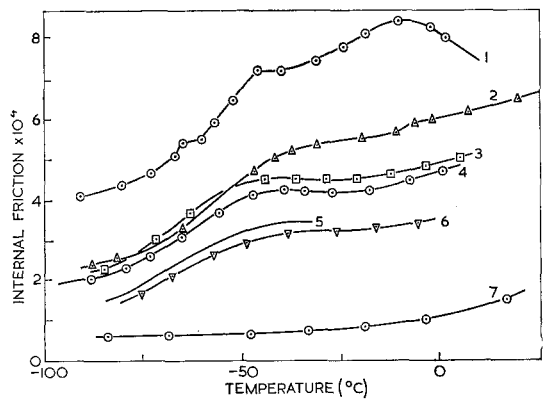

Figure 1 Internal friction versus temperature of a specimen deformed 8% in tension at 300° K, and its subsequent behaviour on annealing. Curve 1, deformed 8%; 2, annealed at 20° C for 20 min; 3, annealed at 40° C for 20 min; 4, annealed at 15° C for 12 h; 5, annealed at 60° C for 20 min; 6, annealed at 15° C for 80 h; 7, annealed at 300° C for 20 min.

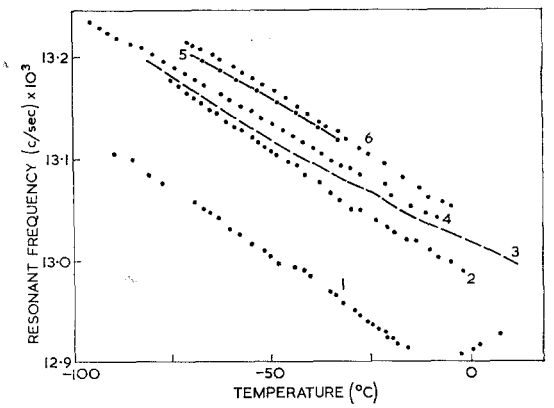

Figure 2 Resonant frequency versus temperature of the previous specimen. (Curve numbers refer to treatments described in fig. 1.)

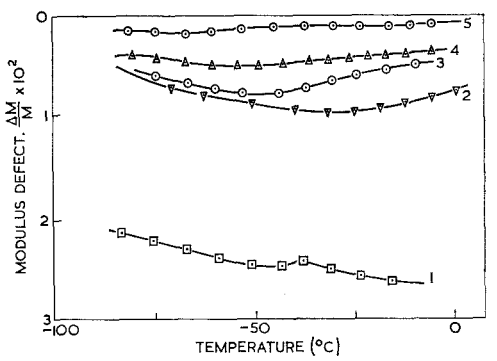

Figure 3 Modulus defect versus temperature obtained from fig. 2. (Curve numbers refer to treatments described in fig. 1.)

Fig. 2 shows the results of plotting resonant frequency versus temperature (corresponding to the curves of fig. 1), and these curves decrease with annealing (Koster effect). The modulus defect gives more information on the peaks than the resonant frequency; this can be related to the latter by

$$\frac{\Delta M}{M} = \frac{2\Delta f}{f} \tag{1}$$

where $\Delta M/M$ is the modulus defect and $\Delta f/f$ the change of resonant frequency with annealing. From fig. 2, curve 6 is taken as a reference, in that after this amount of annealing most of the recovery has occurred; so that equation 1 becomes

$$\frac{\Delta M}{M_6} = \frac{2\Delta f}{f_6} \tag{2}$$

$\Delta M/M_6$ is then calculated for the curves 1, 2, 3, 4, and 5 in fig. 2, and the results plotted against temperature (fig. 3).

Now, from the string model of a dislocation [16, 17], the modulus defect due to the vibration of dislocation loops of length l is

$$\Delta M/M = \alpha n l^3 \tag{3}$$

where n is the number of dislocation loops per cubic centimetre, and α is a dimensionless constant of order 0.1. Fig. 3 shows that the modulus defect decreases during annealing. It is unlikely that n changes at low temperature, so l must decrease, possibly by the diffusion of point defects to dislocations. If the cause of the P_1 peak is due to the complete breakaway of dislocations from the point defects, then the modulus defect should tend to the "as-deformed" value at the temperature of the peak. This does not occur and a new model based on the occasional breakaway of a dislocation loop from a point defect is postulated.

4. Discussion

In copper that has been deformed at room temperature, the dislocations will be pinned by vacancies, and a relaxation peak will be produced by the occasional detrapping of a dislocation loop from a vacancy pinning point. The relaxation strength and frequency factor are given by the expressions

$$Q^{-1} = \frac{\Delta M}{M}\left(\frac{\omega\tau}{1+\omega^2\tau^2}\right) \tag{4}$$

$$f = f_0 \exp(-U/kT) \tag{5}$$

The contribution to the overall modulus defect by the internal friction represented by the peak P_1 can be written, assuming a vibrating string model, as

$$\Delta M/M = \alpha N l^3 \tag{6}$$

where N is the number of dislocation loops pinned by vacancies and contributing to the damping associated with this maximum, and l is the length of the loop. At the peak temperature, the contribution to Q^{-1} will be proportional to the modulus defect given by equation 6, and a relatively large peak will be observed only when

$$\mathrm{d}[N(l)_x l^3]/\mathrm{d}l = 0 \tag{7}$$

This equation determines the most probable loop-length l_0. Clearly small deviations of l from l_0 could lead to a disappearance of the peak, and

a narrow spectrum of relaxation times is therefore expected in agreement with observation [12, 14].

If we assume a stress wave of amplitude $\Delta\tau$ is applied to the specimen, the resonant frequency of the loop, which is the same as the attempt frequency, will be given approximately by

$$f_{P_1} = \left[\nu \exp\left(-\frac{U}{kT}\right)\right]\left[\frac{\partial\tau_i}{\partial\tau}(\Delta\tau)\right]\left[\frac{b^2 l_0}{kT}\right] \quad (8)$$

where: ν is an atomic frequency of order 10^{13} sec^{-1}; U, the binding energy between an edge dislocation and a vacancy; τ_i, the internal stress acting on the dislocation near a given pinning point in the absence of an oscillating stress; b, the lattice spacing. Inserting typical values into equation 8 yields a frequency factor of 10^{11} sec^{-1}, which agrees with the measured values [15]. This model also accounts for the small modulus defect and height associated with the peak P_1 [18].

Unfortunately, an expression for the internal friction is more difficult to obtain, owing to the fact that the system passes from the initial state to the final state without passing through a well-defined saddle-point configuration. Other difficulties have also been described by Granato, Lucke, and Teutonico [19], who produced expressions for the damping but found them too complex to be used. It is possible that this problem will only be solved when dislocation kinetics are better known.

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