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Internal Friction in Copper and α-Brasses During Plastic Deformation

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The internal friction Q^{-1} of annealed copper and α-brass wires containing 10, 20, 30 and 35 at. % of zinc was studied by a torsional oscillation method during plastic deformation. The results are interpreted in terms of two theoretical models ascribing the amplitude-dependent internal friction, observed in the pre-yield stage, to coupling of the cyclic stress with the creep component of the deformation, and the amplitude-independent internal friction at larger, plastic, strains to losses arising from contributions of the torsional stress to the plastic deformation. Up to the maximum tensile strain of 1% used in the experiments, the influence of zinc content on Q^{-1} is not pronounced.

1. Introduction

Although the measurement of internal friction by the superposition of low-amplitude torsional oscillations on wire specimens undergoing tensile deformation is a technique of considerable scope in the study of the mechanisms of metal plasticity, it has not been explored extensively. On the basis of data published up to 1965 Feltham [1] proposed a theoretical interpretation of the unusually high internal friction observed in such experiments. This was based on the assumption that, due to the occurrence of slip on many slip planes in any given grain, the torsional oscillations coupled into the time-dependent, creep, component of the plastic strain, $\partial\epsilon/\partial t$, defined by the work-hardening relation for an isothermal tensile test:

$$\frac{\mathrm{d}\epsilon}{\mathrm{d}\sigma} = \frac{\partial\epsilon}{\partial\sigma} + \frac{\partial\epsilon}{\partial t}\frac{\mathrm{d}t}{\mathrm{d}\sigma}. \tag{1}$$

The energy per unit volume dissipated per cycle was then proportional to $\Delta\tau_0\, \partial\epsilon/\partial t$, where $\Delta\tau_0$ is the shear stress amplitude at the wire surface. As the "elastic" energy stored is proportional to $\Delta\tau_0{}^2$, the internal friction should be amplitude-dependent, with $Q^{-1} \propto (1/\Delta\tau_0)$.

At about the same time Postnikov [2] also examined the problem, but considered that the torsional stresses contributed to the "plastic" work of deformation; the resulting internal friction is amplitude-independent. Although Ke *et al* [3] had remarked that the internal friction observed in armco-iron under conditions similar to those employed in the present experiments was amplitude-independent, no conclusive evidence concerning the effect of amplitude on Q^{-1} had been reported in any other work.

The principal object of the research described in this paper was to study the internal friction of copper and α-brasses during plastic deformation at room temperature, employing the tensile strain rate $\dot{\epsilon}$, the angular frequency of oscillation ω and the maximum shear stress at the wire surface $\Delta\tau_0$ as variables. The use of α-brasses was intended to contribute, in the form of alloy content, a new variable of potential value in the analysis and interpretation of the results.

2. Experimental

In a given test a specimen was fixed in the grips of an Instron machine, and a small inertia bar with a plane mirror was attached to its centre. A small load was applied to the wire to hold it taut so as to facilitate focussing a narrow light beam, reflected from the mirror, onto the sensor of a cybernetic "spot-follower" (Sefram, Paris) placed about 150 cm from the mirror. A deflection of 1 cm then corresponded to a shear strain at the wire surface of about 10^{-5}. The inertia bar was set into motion by blowing gently onto one of its arms, and the recorder was synchronised with the oscillations. The spot-follower chart and the cross-head movement of the Instron machine were then switched on simultaneously. After the oscillations had decayed they were again induced as described. The internal friction of the taut wire, not subjected to plastic deformation, was in general about 10^{-3}, and hence negligible compared with the values of Q^{-1} observed during tensile deformation.

Wire specimens were 65 cm long and of 1 mm diameter. The copper was of 99.999% purity; the brasses contained nominally 10, 20, 30 and 35 at. % of zinc, the principal impurities being iron (< 10 ppm) and smaller amounts of tin, lead and bismuth. The straightened, hard-drawn, wires were annealed in argon at 500° C for various periods, obtained from grain-growth data of Feltham and Copley [4], to yield equiaxed grains with 80 ± 20 μm diameter in all cases. Dezincification was found to be negligible.

The effect of amplitude and composition on Q^{-1} is shown in fig. 1, the tensile strain rate being 6.8×10^{-5} per sec. In the upper set of diagrams the stress/strain curves, denoted by σ,

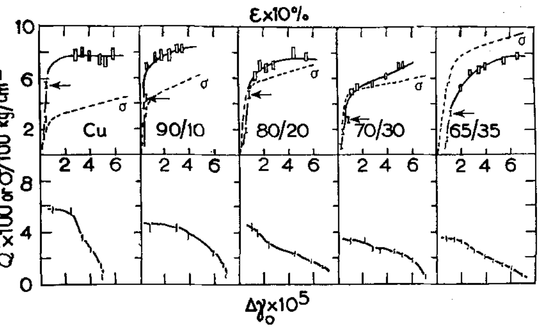

Figure 1 Composition-dependence of the internal friction of copper and α-brass wires subjected to deformation at room temperature at a tensile strain rate of 6.8×10^{-5} per sec. The dependence of Q^{-1} on the torsional strain amplitude at the wire surface, measured at points indicated by arrows, is shown in the lower set of curves.

are drawn, together with the internal friction curves. At the points denoted by rectangles Q^{-1} was found to be amplitude-independent over the range of amplitudes employed, i.e.

$$1 \times 10^{-5} \leqslant \Delta\gamma_0 \equiv (\Delta\tau_0/G) \leqslant 7 \times 10^{-5}. \quad (2)$$

In the "pre-yield" region, extending up to about 0.1% of tensile strain, Q^{-1} was found to be amplitude-dependent, increasing with decreasing amplitude. The effect is shown in the lower set of curves; measurements were made at points indicated by arrows on the corresponding Q^{-1}/ϵ curves. Values indicated by the arrows are the highest levels of internal friction observed at that tensile strain, i.e. at a shear strain amplitude of about 10^{-5}.

Fig. 2 shows the frequency-dependence of Q^{-1} in 80/20 brass wires deformed at a strain rate of 6.8×10^{-5} per sec, as well as the strain rate-dependence of Q^{-1} for the same type of brass at a frequency of 3.3 cps. On plotting the maxima of the Q^{-1} values of these curves as functions of the corresponding variable one finds that Q^{-1} is approximately linearly dependent on the tensile strain rate and on the period of oscillations (fig. 3), as required by theories of both Feltham [1] and Postnikov [2]. The straight lines do not

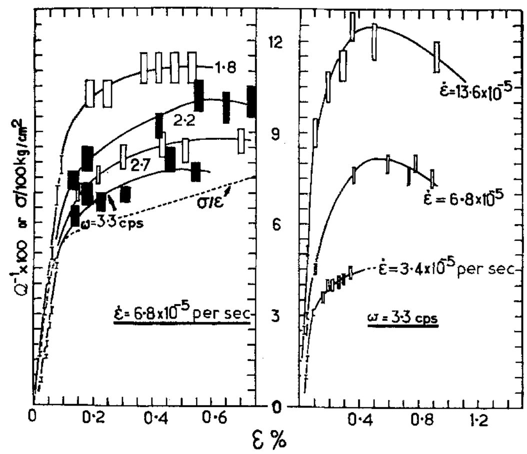

Figure 2 The internal friction of 80/20 brass wires as function of the tensile strain rate at a series of frequencies of torsional oscillations with an invariant tensile strain rate of 6.8×10^{-5} per sec, and at a series of tensile strain rates, the frequency being invariant at 3.3 cps.

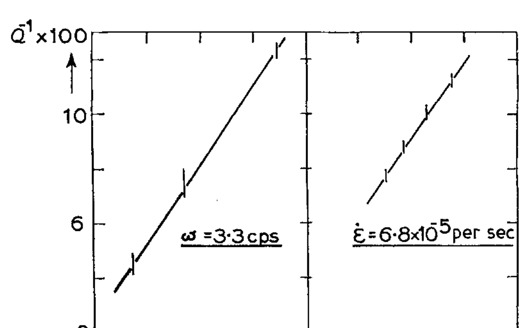

Figure 3 Peak values of the internal friction obtained from figure 2 plotted respectively as functions of the tensile strain rate and the period of torsional oscillations.

however pass through the origin on extrapolation; the intercept on the Q^{-1} axis is too large to be ascribed to miscellaneous losses.

3. Theory and Discussion

A given Q^{-1} versus ϵ curve may be considered to consist of the pre-yield and plastic regions. In the former the plastic and elastic components of the total strain rate are commensurate; the plastic component is small initially, but begins to predominate at higher strains. The steep increase of the internal friction with strain, observed in this stage, which originates from the plastic component, is thus readily explained. A detailed analysis of the amplitude-dependence of Q^{-1} in the pre-yield stage cannot be made on hand of the available data, but the decrease of the internal friction with increasing torsional strain amplitude is consistent with creep effects, as previously suggested [1].

An inverse amplitude-dependence of Q^{-1} can in general arise if the strain increment associated with an elementary activated event is not determined by the effective local stress, but by some structural obstacle, e.g. impurity pinning points or Peierls valleys. The energy dissipated per cycle is then proportional to the first, not the second, power of the stress amplitude, as would be the case if the elementary strain depended on $\Delta\tau_0$.

In the latter instance, when the torsional strain contributes to the plastic work on the wire, the internal friction can be evaluated as follows. Considering a process in which the stress reduces the activation energy of the rate determining mechanism, one can write formally

$$\dot{\epsilon} = \dot{\epsilon}_0(T) \exp(V\tau/kT) \qquad (3)$$

where $\dot{\epsilon}_0$ and V are constants in an isothermal test over a small range of stress, and $\tau \approx \frac{1}{3}\sigma$. The macroscopic torsional strain of amplitude $\Delta\tau_0$ will induce perturbations of the stress tensor at any point in a given grain. They may either increase or decrease the shear rates in some of the operative slip systems. In the first case energy is lost, in the second gained, by the torsional oscillations. If half of the active slip systems are dissipative in this manner, then the energy lost in a half period, π/ω, per unit volume of material is

$$\tfrac{1}{2}\overline{\Delta\tau}\ [(\pi/\omega)\,\dot{\epsilon} \exp(V\overline{\Delta\tau}/kT)]\,, \qquad (4)$$

where $\overline{\Delta\tau}$ is the rms of the local shear stress perturbations. The same expression is obtained for the energy gained, with $\overline{\Delta\tau}$ replaced by $-\overline{\Delta\tau}$ in the exponential term. The net loss per half cycle is then equal to the difference between both amounts. The same loss is incurred in the second half cycle of the oscillation under consideration; it is clearly invariant with respect to the sense of the torsional oscillations. The loss per cycle is therefore given by

$$\overline{\Delta\tau}\,(2\pi/\omega)\,\dot{\epsilon}\sinh(V\overline{\Delta\tau}/kT)\,, \qquad (5)$$

and for $V\overline{\Delta\tau} \leqslant kT$ one obtains

$$\Delta W = (\overline{\Delta\tau})^2\,(2\pi/\omega)\,(V/kT)\,\dot{\epsilon}\,. \qquad (6)$$

Hence with the energy stored per cycle equal to $W = (\overline{\Delta\tau})^2/G$, one obtains the relation

$$Q^{-1} \equiv \frac{\Delta W}{2\pi W} = \dot{\epsilon}\,\frac{GV}{\omega kT} = \dot{\epsilon}\,\frac{\partial \ln \dot{\epsilon}}{\partial\tau}\,\frac{G}{\omega}\,, \qquad (7)$$

as derived, in a somewhat different manner by Postnikov [2].

We shall now examine some implications of this result, considering first a rather simple model of slip in a single crystal, the dislocation mean velocity being v and the density of moving dislocations ρ. With the usual relation

$$\dot{\ } = \alpha\rho b v\,, \qquad (8)$$

where α is a "geometrical" constant, assuming a linear dependence of the activation energy on the effective shear stress τ^*, one obtains

$$\dot{\gamma} = \alpha\rho A\nu \exp\left[-\frac{H}{kT}\left(1-\frac{\tau^*}{\tau_{00}{}^*}\right)\right]\cdot \qquad (9)$$

Where A is the area swept out by a dislocation in one activated jump, and ν is an atomic frequency of order 10^{12} per sec. It is clear that $\tau^* \rightarrow \tau_{00}{}^*$ as $T \rightarrow 0°$ K. We shall assume it permissible to replace the ratio of the "effective" stresses by applied stresses, i.e. writing $\tau^*/\tau_{00}{}^* = \tau/\tau_{00}$. Further, if the strain rate $\dot{\ }$ were maintained at zero. i.e. in a stress relaxation experiment, the stress τ would fall to the "static" flow stress τ_0, related to τ_{00} through the Cottrell-Stokes ratio R, i.e.

$$R = \frac{\tau_0}{\tau_{00}} \leqslant 1\cdot \qquad (10)$$

Now on relating the mean shear rate in a single crystal, e.g. grain, to the observed tensile strain rate of the polycrystal by $\dot{\gamma} = 3\dot{\epsilon}$, [5] one obtains

$$\dot{\epsilon} = \left[\tfrac{1}{3}\,\alpha\rho A\nu \exp\left(-\frac{H}{kT}\right)\right] \exp\frac{RH\tau}{kT\tau_0}\cdot \qquad (11)$$

In the case of copper R is constant, strain-independent, at room temperature [6]; with the brasses the Cottrell-Stokes ratio may depend somewhat on the strain [7], a point we shall not however take into further consideration here. From equations 7 and 11 one finds that for the simple model considered

$$Q^{-1} = \frac{\dot{\epsilon} G}{\omega}\left[\frac{\partial \ln(\rho A)}{\partial \tau} + \frac{H\mathrm{R}}{\mathrm{k}T\tau_0}\right]. \qquad (12)$$

As, for copper, R is equal to about 0.85 at room temperature, we shall make the approximation $\mathrm{R}/\tau_0 \equiv {\tau_{00}}^{-1} = \tau^{-1}$, so that

$$Q^{-1} = \frac{\dot{\epsilon} G}{\omega\tau}\left[\frac{\partial \ln(\rho A)}{\partial \ln \tau} + \frac{H}{\mathrm{k}T}\right]. \qquad (13)$$

The logarithmic ratio will in general be negligible compared with $H/\mathrm{k}T$, as $H \gg \mathrm{k}T$, except possibly in the very early stages of deformation of crystals of high perfection, so that

$$Q^{-1} = \frac{\dot{\epsilon} G}{\omega\tau}\frac{H}{\mathrm{k}T}. \qquad (14)$$

On taking $\tau = \sigma/3 = 100$ kg/cm^2, $\dot{\epsilon} = 10^{-5}$ per sec, $G = 4.5\ 10^5$ kg/cm^2, $\omega = 20$ radians/sec, $Q^{-1} = 0.1$ and $\mathrm{k}T = 0.025$ eV, one obtains $H = 1.1$ eV. This value is equal to that generally assumed for vacancy formation in copper; however uncertainties, particularly those relating to the value of τ used above, and also the simplifications introduced in the derivation of equation 14 preclude putting undue reliance on this result at the present stage of development of the theory.

Although the dependences of Q^{-1} on the tensile strain rate and on the frequency are in approximate agreement with the experimental results, and the amplitude-independence of the internal friction required by equation 14 is also observed, the effect of the applied stress does not seem to be as pronounced as is suggested by equation 14. This discrepancy, as well as deviations from equation 14 referred to in connection with the results in fig. 3, appear to be consequences of shortcomings of the model. The principal of these is probably the assumption of a single activation energy in equation 9. If a spectrum of activation energies is considered, one finds that the stress perturbations in the metal due to the oscillatory shear will "trip" preferentially, dislocations which have the lowest barriers to surmount. Such "low-energy" units will also, on the whole, be associated with the largest activation volumes in the distribution, i.e. on writing $\mathrm{V} = H/\tau$ in equation 12, a value of the stress smaller and less variable with strain than τ should probably be used.

4. Conclusions

The present considerations, in conjunction with the experimental results, suggest that the internal friction during plastic deformation in the plastic range is basically in accord with the model of Postnikov, which leads to equation 7. The discussion leading to equation 14, shows however that some discrepancies between theory and experiment remain; these appear to be due to the simplifications which it was found necessary to use in the present stage of development of the model. The fact that the level and general character of the internal friction are similar in brasses and in copper also suggests that at least at room temperature similar mechanisms, not greatly sensitive to alloying, are operative in the pure metal and in the solid solutions.

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