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Non-linear response of internal friction to tensile strain rate and frequency during plastic deformation of high-purity aluminium

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The internal friction of high-purity aluminium during the process of plastic deformation was measured by a middle torsion pendulum on a modified tensile testing machine. The effects of tensile strain rate, $\dot{\varepsilon}$, in the range of 0.73×10^{-6} to $50\times10^{-6}\,s^{-1}$, and frequency of internal friction measurement, f, in the range of 0.38 to 2.6 Hz were studied. The results showed a non-linear dependence of internal friction, Q^{-1}, on $\dot{\varepsilon}$ and f^{-1}, or on $\dot{\varepsilon}/\omega$ ($\omega = 2\pi f$). The interrelationship between internal friction during the process of plastic deformation and dislocation motion, and the effect of non-linearity on the dynamic behaviour of dislocations are discussed.

1. Introduction

Low-frequency internal friction during the process of plastic deformation, Q^{-1}, and the technique of measurement using a middle torsion pendulum, were first reported by Maringer [1]. Subsequently, the Q^{-1} versus ε (tensile strain) curves for Al, Cu and Armco-Fe samples were determined by Kê *et al.* [2]. The fairly high values of Q^{-1} obtained by these investigators were attributed to the process of plastic deformation because they were observed only when $\dot{\varepsilon} \neq 0$. If $\dot{\varepsilon}$ was changed from $\dot{\varepsilon} \neq 0$ to $\dot{\varepsilon} = 0$ suddenly (i.e. keeping ε constant), the Q^{-1} value dropped almost at once to a low background value [2]. Postnikov *et al.* [3] and Felthan and Newhan [4] investigated the effects of tensile strain rate $\dot{\varepsilon}$ and angular frequency of internal friction measurement ω on Q^{-1}, and reported linear dependence of Q^{-1} on $\dot{\varepsilon}$ and on ω^{-1}. More recently, the internal friction (IF) during the process of plastic deformation for Armco-Fe at values of strain within the yield plateau (i.e. Q^{-1} did not change with ε) was studied by Zhang *et al.* [5], and a similar linear dependence was also observed.

Various theories have been presented in order to interpret these results. Postnikov *et al.* [3] and Felthan and Newhan [4] associated Q^{-1} with a thermal activation process and obtained a linear dependence of Q^{-1} on $\dot{\varepsilon}$ and ω^{-1} as $Q^{-1} = \beta(\dot{\varepsilon}/\omega)$, where β is a constant. Kê and Zhang [6] and Zhang [7] attributed Q^{-1} to the movement of dislocations. They obtained a similar expression but the parameter β was a function of stress σ instead of being a constant. They also obtained a dislocation dynamics expression relating the velocity V of moving dislocations to the effective stress.

The above theories were, however, based on the linear dependence of Q^{-1} on $\dot{\varepsilon}$ and ω^{-1} within a limited range of $\dot{\varepsilon}$ and ω. It is therefore important to extend this investigation by broadening the range of $\dot{\varepsilon}$ and ω studied. The areas of particular interest are the effects on Q^{-1} by varying $\dot{\varepsilon}$ at low, but constant ω, and by varying ω at high, but constant $\dot{\varepsilon}$.

The present investigation aims to extend the range of previous studies for high-purity aluminium. The significance of the results obtained on the dynamic behaviour of dislocations is discussed.

2. Experimental procedure

The experimental technique used has been described previously [1, 2, 5]. The internal friction of high-purity aluminium during the process of plastic deformation was measured by a middle torsion pendulum on a modified tensile testing machine. The tensile strain rate $\dot{\varepsilon}$ and frequency of measurement f used in the present investigation were $\dot{\varepsilon}_1 = 0.73\times10^{-6}\,s^{-1}$, $\dot{\varepsilon}_2 = 1.53\times10^{-6}\,s^{-1}$, $\dot{\varepsilon}_3 = 2.94\times10^{-6}\,s^{-1}$, $\dot{\varepsilon}_4 = 6.35\times10^{-6}\,s^{-1}$, $\dot{\varepsilon}_5 = 12.1\times10^{-6}\,s^{-1}$, $\dot{\varepsilon}_6 = 25.3\times10^{-6}\,s^{-1}$, $\dot{\varepsilon}_7 = 50\times10^{-6}\,s^{-1}$ and $f_1 = 0.382$ Hz, $f_2 = 0.5$ Hz, $f_3 = 0.836$ Hz, $f_4 = 1.0$ Hz, $f_5 = 2.03$ Hz, $f_6 = 2.63$ Hz, respectively. All measurements were made at room temperature.

The wire-shaped specimen was prepared from a 99.9991% pure aluminium rod, about 8 mm in diameter and 50 mm in length, manufactured by the Light Co. (UK).

In order to avoid contamination by oil or other metals during specimen preparation, the bar was carefully hot-forged to about 4.5 mm diameter by hand hammering at 200 to 250 °C, with repeated cleansing by dilute KOH solution before cold-drawing to 1.0 mm diameter. The last treatment was annealing at 400 °C for 0.5 h followed by furnace-cooling.

3. Theory

A common measure of the internal friction in the free decay mode, such as that in the middle pendulum used, is the logarithmic decrement δ. When δ/π or Q^{-1} is small, e.g. much less than 0.05, we have

$$Q^{-1} = \frac{1}{2\pi}\frac{\Delta W}{W} = \frac{\delta}{\pi} = \frac{1}{\pi n}\ln\left(\frac{A_0}{A_n}\right) \quad (1)$$

where W is the total energy of vibration, $\Delta W/W$ the fractional energy loss per cycle, and A_0 and A_n are the zeroth and nth amplitude of the vibration, respectively. When Q^{-1} or δ/π is large, for example more than 0.05, Equation 1 is not accurate. The precise relationship between $Q^{-1} = (1/2\pi)(\Delta W/W)$ and δ/π depends on the mechanism of internal friction, but we can obtain a simple approximate relationship by the following calculations.

Using the expansion form of $\delta = \ln(A_0/A_1) = \ln X$, we have

$$\delta = \ln X = \frac{X-1}{X} + \frac{1}{2}\left(\frac{X-1}{X}\right)^2 + \cdots \quad (2)$$

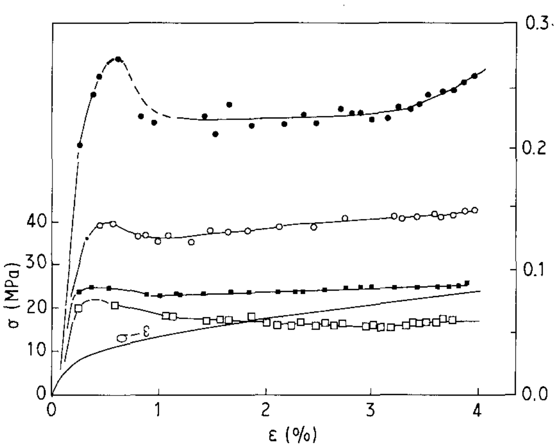

Figure 1 Effect of frequency on the δ/π versus ε curves at $\dot{\varepsilon} = 50\times10^{-6}\,\mathrm{s}^{-1}$: (●) $f_1 = 0.382$ Hz, (○) $f_3 = 0.836$ Hz, (■) $f_5 = 2.03$ Hz, (□) $f_6 = 2.63$ Hz. The corresponding σ versus ε curve is also shown.

for any value of δ, and

$$Q^{-1} = \frac{1}{2\pi}\frac{\Delta W}{W} = \left(\frac{1}{2\pi}\right)\frac{A_0^2 - A_1^2}{A_0^2}$$
$$= \left(\frac{1}{2\pi}\right)\frac{X^2-1}{X^2} = \eta(X)\left(\frac{\delta}{\pi}\right) \quad (3)$$

Thus we can relate δ to Q^{-1}. The function $\eta(X)$ depends on the number of terms incorporated in the expression for δ in Equation 2. For example, if two terms are included, when $\delta/\pi = 0.22$, $X = 2$, $\eta(X) = 0.6$ and $Q^{-1} = 0.133$; when $\delta/\pi = 0.03$, $X = 1.1$, $\eta(X) = 0.91$ and $Q^{-1} = 0.028$.

In this paper we define δ/π as the apparent internal friction and use the true value of Q^{-1} calculated by Equation 3 for comparison with theoretical analysis.

4. Results

The influence of the frequency of measurement on δ/π during the process of plastic deformation for high-purity Al at high strain rate ($= 50\times10^{-6}\,\mathrm{s}^{-1}$) is shown in Fig. 1. The stress–strain (σ versus ε) curve is also shown in the figure. The frequencies of δ/π measurement are 0.382 Hz (f_1), 0.836 Hz (f_3), 2.03 Hz (f_5) and 2.63 Hz (f_6), respectively. It is clear that δ/π decreases with increasing frequency of measurement. The δ/π versus ε curve exhibits a maximum value after macro-yielding of the samples. For $\varepsilon > 1\%$, δ/π shows a slightly increasing trend with increasing ε at low frequencies. At the highest frequency f_6, δ/π exhibits a decreasing trend with increasing ε.

The influence of frequency of measurement on δ/π at low strain rate ($\dot{\varepsilon}_3 = 2.94\times10^{-6}\,\mathrm{s}^{-1}$) is shown in Fig. 2. Also shown in the same figure is the corresponding σ versus ε curve. It is clear that δ/π decreases with increasing frequency of measurement. In Fig. 2, one sample was tested at a constant frequency, f_4 (= 1.0 Hz), throughout. The other sample was tested at three frequencies: f_1 (0.382 Hz, when $\varepsilon < 3.6\%$), f_2 (0.5 Hz, from $\varepsilon = 3.7\%$ to 4.1%) and f_4 (1.0 Hz, when $\varepsilon > 4.1\%$). The maximum after yielding observed in Fig. 1 at high strain rate disappears in Fig. 2 at low strain rate. The δ/π versus ε curves are almost parallel to the abscissa after macro-yielding of the sample. The coincidence of the δ/π versus ε curves of two samples when $\varepsilon > 4.1\%$ suggests that different

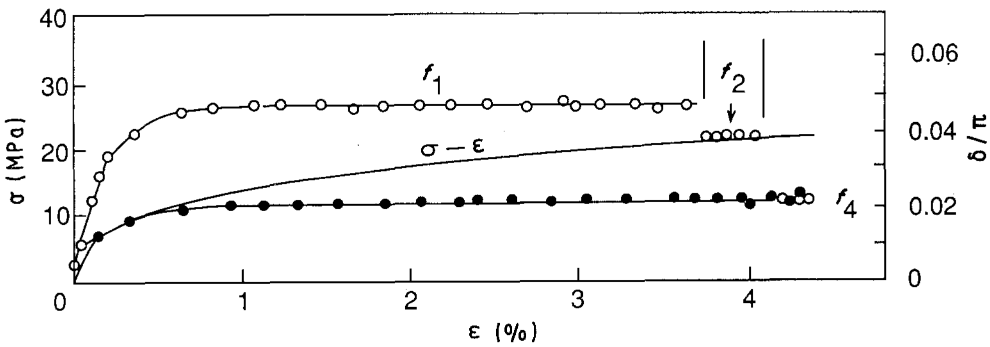

Figure 2 Effect of frequency on the δ/π versus ε curves at $\dot{\varepsilon} = 2.94\times10^{-6}\,\mathrm{s}^{-1}$ for $f_1 = 0.386$ Hz, $f_2 = 0.5$ Hz, $f_4 = 1.0$ Hz. One sample (○) was tested at three frequencies, f_1, f_2 and f_4. The other sample (●) was tested at f_4 only. The corresponding σ versus ε curve is also shown.

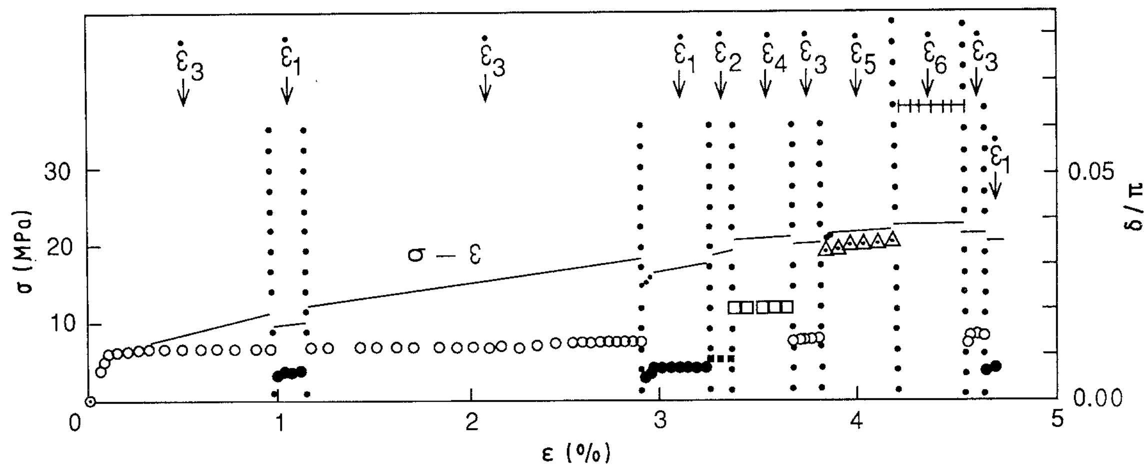

Figure 3 Effect of tensile strain rate, $\dot{\varepsilon}$, on the δ/π versus ε data at constant $f = 2.03$ Hz; $\dot{\varepsilon}_1 = 0.73 \times 10^{-6}\,\mathrm{s}^{-1}$, $\dot{\varepsilon}_2 = 1.53 \times 10^{-6}\,\mathrm{s}^{-1}$, $\dot{\varepsilon}_3 = 2.94 \times 10^{-6}\,\mathrm{s}^{-1}$, $\dot{\varepsilon}_4 = 6.35 \times 10^{-6}\,\mathrm{s}^{-1}$, $\dot{\varepsilon}_5 = 12.1 \times 10^{-6}\,\mathrm{s}^{-1}$, $\dot{\varepsilon}_6 = 25.3 \times 10^{-6}\,\mathrm{s}^{-1}$. The corresponding σ versus ε curves are also shown.

samples possess the same δ/π value provided $\dot{\varepsilon}$, f and ε are the same. It also implies that the reproducibility of internal friction measurement during plastic deformation is rather good and is unaffected by a change in the sample or in the frequency of vibration.

The effect of strain rate $\dot{\varepsilon}$ on the δ/π versus ε curve at constant frequency of measurement f_5 ($=2.03$ Hz) is shown in Fig. 3. The sample is stretched to $\varepsilon \sim 1\%$ with $\dot{\varepsilon}_3 = 2.94 \times 10^{-6}\,\mathrm{s}^{-1}$, then to $\varepsilon \sim 1.2\%$ with $\dot{\varepsilon}_1 = 0.73\% \times 10^{-6}\,\mathrm{s}^{-1}$, to $\varepsilon \sim 2.85\%$ with $\dot{\varepsilon}_3$, to $\varepsilon \sim 3.3\%$ with $\dot{\varepsilon}_1$, and then to $\varepsilon \sim 4.7\%$ with $\dot{\varepsilon}_2$ ($=1.53 \times 10^{-6}\,\mathrm{s}^{-1}$), $\dot{\varepsilon}_4$ ($=6.35 \times 10^{-6}\,\mathrm{s}^{-1}$), $\dot{\varepsilon}_3$, $\dot{\varepsilon}_5$ ($=12.1 \times 10^{-6}\,\mathrm{s}^{-1}$), $\dot{\varepsilon}_6$ ($=25.3 \times 10^{-6}\,\mathrm{s}^{-1}$), $\dot{\varepsilon}_3$ and $\dot{\varepsilon}_1$. As shown in Fig. 3, δ/π increases with increasing $\dot{\varepsilon}$ and is almost parallel to the abscissa, especially at low strain rates.

In order to show the effect of $\dot{\varepsilon}$ and f more clearly, we transform the δ/π values into Q^{-1} using Equation 3, and plot curves of Q^{-1} against $\dot{\varepsilon}$ at constant f (Fig. 4), and Q^{-1} against ω^{-1} at constant $\dot{\varepsilon}$ (Fig. 5). Fig. 4 shows the non-linear effect of strain rate, $\dot{\varepsilon}$, on Q^{-1} during plastic deformation at constant frequency of measurement. Fig. 5 shows the non-linear effect of frequency of measurement on Q^{-1} at constant strain rate. These figures show that, unlike the previously reported results [3–5], Q^{-1} exhibits a non-linear dependence on $\dot{\varepsilon}$ and on ω^{-1}. The effect is more apparent at low frequencies and high strain rates.

Fig. 6 shows a plot of Q^{-1} against $\dot{\varepsilon}/\omega$ (all symbols in Fig. 6 coincide with those in Figs 4 and 5). The non-linear dependence of Q^{-1} on $\dot{\varepsilon}/\omega$ is apparent. The scatter of data in this figure compared with Figs 4 and 5 suggests that the dependences of Q^{-1} on $\dot{\varepsilon}$ and on ω^{-1} are not the same. Even if δ/π is used as an ordinate, the dependence of δ/π on $\dot{\varepsilon}/\omega$ is still non-linear.

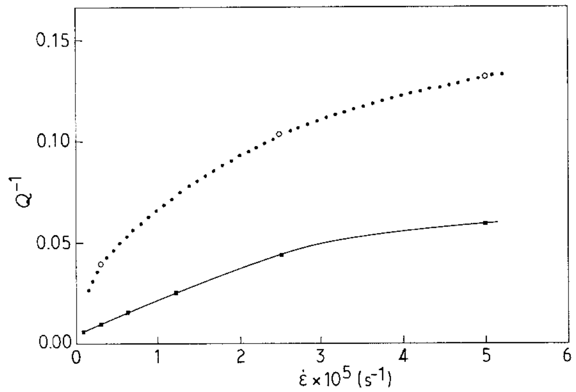

Figure 4 The non-linear dependence of Q^{-1} on $\dot{\varepsilon}$ for (○) $f_1 = 0.382$ Hz and (■) $f_5 = 2.03$ Hz; $\varepsilon = 3\%$.

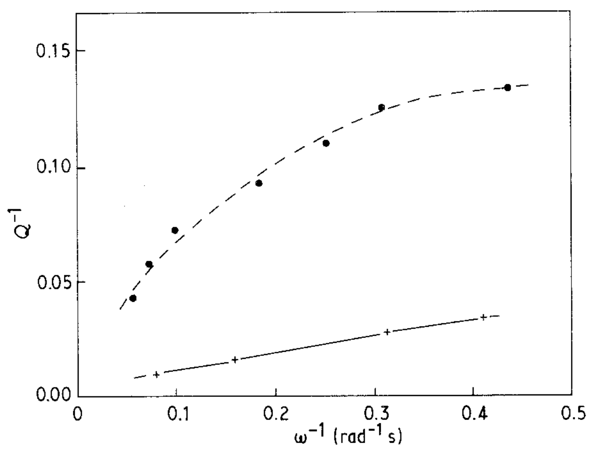

Figure 5 The non-linear dependence of Q^{-1} on ω^{-1} for (●) $\dot{\varepsilon}_7 = 50 \times 10^{-6}\,\mathrm{s}^{-1}$ and (+) $\dot{\varepsilon}_3 = 2.94 \times 10^{-6}\,\mathrm{s}^{-1}$; $\varepsilon = 3\%$.

5. Discussion

5.1. Interrelationship between Q^{-1} and $\dot{\varepsilon}$

It is well established that $\dot{\varepsilon} = \alpha \rho_m \boldsymbol{b} v$, where α is an orientation factor, ρ_m is the density of mobile dislocations, $\boldsymbol{b}$ is the Burgers vector, and v is the average velocity of the dislocations. Since the strain rates considered in this paper are low, ρ_m can be treated as independent of $\dot{\varepsilon}$ at a given value of strain. The dependence of Q^{-1} on $\dot{\varepsilon}$ is essentially a dependence of Q^{-1} on v at a given value of ε. This implies that the study of internal friction during the process of plastic deformation can lead to an improved understanding of dislocation dynamics and strengthening mechanisms.

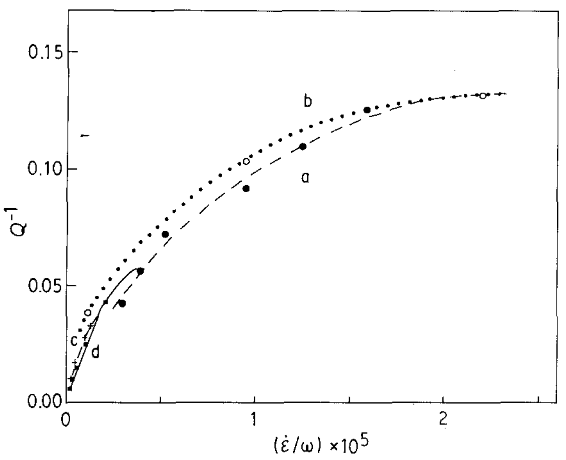

Figure 6 The non-linear dependence of Q^{-1} on $\dot{\varepsilon}/\omega$ (all symbols coincide with those in Figs 4 and 5). (a) Changing ω at constant "high" $\dot{\varepsilon}$, (b) changing $\dot{\varepsilon}$ at constant "low" ω; (c) changing ω at constant "low" $\dot{\varepsilon}$; (d) changing $\dot{\varepsilon}$ at constant "high" ω. $\varepsilon = 3\%$.

5.2. Dependence of Q^{-1} on ω

The average velocity of mobile dislocations, v, is determined by the effective stress $\sigma - \sigma_0$, where σ_0 is the back-stress dependent upon the density and distribution of various crystal defects. In this investigation, v has two components: a steady undirectional component, v_0, and an alternating component, v_a, due to the oscillation of the pendulum. The former is essentially unaffected by the frequency of IF measurement. In order to obtain the correct dependence of Q^{-1} on $\dot{\varepsilon}$, the influence of frequency will need to be separated from the effect of strain rate.

As shown in Fig. 6, the dependence of Q^{-1} on $\dot{\varepsilon}/\omega$ is different when the measurement is carried out at high frequency (curve d), and at low frequency (curve b). Thus, a complicated theoretical analysis is required to obtain the correct interrelationship between Q^{-1} and $\dot{\varepsilon}$.

5.3. Q^{-1} and dislocation dynamics

Q^{-1} versus ε and σ versus ε curves can be measured simultaneously during plastic deformation. These curves can be converted into Q^{-1} versus $\dot{\varepsilon}$ and σ versus $\dot{\varepsilon}$ curves. The functional relationship between dislocation velocity and σ can be deduced from the dependence of Q^{-1} and σ on $\dot{\varepsilon}$. This will be described in the following subsection.

5.4. Functional relationship between v and σ

Consider a cylindrical specimen subjected to a tensile stress σ parallel to the longitudinal axis. The resolved shear stress τ applied to the slip system is given by $\tau = n_p\sigma$, where n_p is an orientation factor. If the alternating resolved shear stress applied during internal friction measurement is $\tau' = \tau'_0 \sin\omega t$, where τ'_0 is a constant, ω is the angular frequency and t is the time, then the total resolved shear stress applied to the slip system is $\tau + \tau'$. Since $|\tau'| \ll \tau$, we have $v = f(\tau + \tau')$ and

$$v \simeq f(\tau) + \frac{\mathrm{d}f(\tau)}{\mathrm{d}\tau}\tau' = v_0 + \frac{\mathrm{d}f(\tau)}{\mathrm{d}\tau}\tau' \qquad (4)$$

where $v_0 = f(\tau)$ is the steady unidirectional component of v parallel to the slip direction (see section 5.2).

The vibrational energy per unit volume dissipated per cycle by the mobile dislocations is given by

$$\begin{aligned}\Delta W &= \rho_m \int_0^T b\tau' v \mathrm{d}t \\ &= \rho_m b \int_0^T \tau'\left(v_0 + \frac{\mathrm{d}f(\tau)}{\mathrm{d}\tau}\tau'\right)\mathrm{d}t \\ &\simeq \rho_m b \frac{\mathrm{d}f(\tau)}{\mathrm{d}\tau}\int_0^T (\tau'_0)^2 \sin^2\omega t \ \mathrm{d}t \\ &= \left(\frac{\mathrm{d}f(\tau)}{\mathrm{d}\tau}\Big/ f(\tau)\right)\frac{\pi\dot{\gamma}}{\omega}(\tau'_0)^2 \\ &= \frac{\mathrm{d}\ln f(\tau)}{\mathrm{d}\tau}\left(\frac{\pi\dot{\gamma}}{\omega}\right)(\tau'_0)^2\end{aligned}$$

where $\dot{\gamma} = b\rho_m v_0$ is the plastic shear strain rate. Let the stress amplitude used in internal friction measurement be τ''_0. For longitudinal vibration, the resolved shear stress amplitude τ'_0 equals $n_p\tau''_0$. The total vibration energy per unit volume may be written as $W = (\tau''_0)^2/2E = (\tau'_0)^2/2\bar{n}_p^2 E$, where $\bar{n}_p$ is an average orientation factor and E is the Young's modulus.

For torsional vibration, the resolved shear stress is $\tau'_0 = n_t\tau''_0$, where n_t is the orientation factor for torsional stress. The total vibration energy per unit volume is $W = (\tau'_0)^2/2\bar{n}_t^2 G$, where $\bar{n}_t$ is the average orientation factor and G is the shear modulus.

Thus, for longitudinal vibrations the internal friction during the process of plastic deformation is

$$Q^{-1} = \frac{\mathrm{d}\ln f(\tau)}{\mathrm{d}\tau}\bar{n}_p\frac{E\dot{\varepsilon}}{\omega} \qquad (5)$$

For torsional vibrations, the internal friction during plastic deformation is

$$\begin{aligned}Q^{-1} &= \frac{\mathrm{d}\ln f(\tau)}{\mathrm{d}\tau}\left(\frac{\bar{n}_t^2}{\bar{n}_p}\right)\frac{G\dot{\varepsilon}}{\omega} \\ &= \frac{\mathrm{d}\ln f(\sigma)}{\mathrm{d}\sigma}\left(\frac{\bar{n}_t^2}{\bar{n}_p^2}\right)\frac{G\dot{\varepsilon}}{\omega}\end{aligned} \qquad (6)$$

For b.c.c. metals, $\bar{n}_t^2/\bar{n}_p \simeq 0.223$ and $\bar{n}_t^2/\bar{n}_p^2 \simeq 0.5$; for f.c.c. metals, $\bar{n}_t^2/\bar{n}_p \simeq 0.274$ and $\bar{n}_t^2/\bar{n}_p^2 \simeq 0.85$ [5]. Thus

$$Q^{-1} = 0.85\frac{\mathrm{d}\ln f(\tau)}{\mathrm{d}\tau}G\frac{\dot{\varepsilon}}{\omega} \qquad (7)$$

If the Johnston–Gilman equation [8], $v = f(\sigma) = B'(\tau - \tau_0)^m = B(\sigma - \sigma_0)^m$, is applied, we have

$$Q^{-1} = \frac{0.85mG}{\sigma - \sigma_0}\left(\frac{\dot{\varepsilon}}{\omega}\right) \qquad (8)$$

If the other equation, $v = v^* \exp[-\sigma^*/(\sigma - \sigma_0)]$, suggested by Gilman [9] and Zhang [7] is applied, then

$$Q^{-1} = \frac{0.85\,\sigma^* G}{(\sigma - \sigma_0)^2}\left(\frac{\dot{\varepsilon}}{\omega}\right) \qquad (9)$$

where v^* is a characteristic velocity ($\lesssim$ velocity of transverse sound wave) and σ^* is a characteristic dragging force when $v = v^*/e$.

The dependence of Q^{-1} on $\dot{\varepsilon}/\omega$ in Equations 7 to 9 is non-linear because the effective stress $(\sigma - \sigma_0)$ depends on $\dot{\varepsilon}$. Different dislocation dynamics equations give different expressions for Q^{-1}. What we have shown is that the non-linear dependence of Q^{-1} on tensile strain rate and frequency can be explained on the basis of dislocation dynamics.

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