Research Letter

Internal Vibrations of Edge Dislocation Dipoles

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The resonance frequency of vibrations of dislocation dipoles in fatigued f.c.c. metals is found rather high, in the range of 100 GHz. Because of high attenuation of ultrasound in the GHz range, the contributions of these self-vibrations to degradation of the dipole structures could be expected only in thin layers.

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1. INTRODUCTION

A high density of edge dislocation dipolar loops is formed during plastic deformation of crystalline materials, especially under cycling loading [1–3]. During deformation, the loops are clustered becoming main building blocks of the dipolar deformation microstructure (tangles, veins, dipolar walls). The size of the prismatic dipolar loops is typically of the order of 10 nm (in Ni crystals deformed cyclically at room temperatures, the averaged loop height is 4 nm, the averaged length is 60 nm [2, 3]). The leading factor, which influences the rate of clustering and hence the degradation process, is the loop mobility expressed through the drift coefficient. In principle, this coefficient can be decreased by internal vibration of the loops, in analogy to the effect of temperature increase. There is experimental evidence that higher temperature accelerates the clustering process [4].

In this note, small internal vibrations in the slip planes of two long elastically interacting dislocation arms forming a dipole will be studied as forced vibrations due to an oscillating external shear stress. The effect of damping will also be briefly discussed. This approach is similar to the study of vibrations of two partials forming a split dislocation in f.c.c. metals [5] and of internal vibrations of the core of screw dislocations in b.c.c. metals modeled by four partials in [6].

2. FORCED VIBRATIONS

An edge dislocation dipole with the dislocation lines in the z -direction (Figure 1) is formed by dislocation 1 in the

slip plane $y = h/2$ with the Burgers vector of length b in the x direction and by dislocation 2 in the slip plane $y' = -h/2$ with Burgers vector $b' = -b$. Length l of the dipole in the z direction will be assumed much larger than the dipole height h . In the equilibrium configuration of the dipole, $x = h/2$ and $x' = -h/2$, the force components in the slip planes are zero [6]. The force components in the direction perpendicular to the slip planes, which may induce the climbing of dislocations, will not be considered.

For changed positions x and x' , the interaction force F_{int} from dislocation 2 on 1 is equal to $F_{\text{int}} = b\tau_{xy}^{(2,1)}$ and that from 1 on 2 $F'_{\text{int}} = -b\tau_{xy}^{(1,2)} = -F_{\text{int}}$. The stress component τ_{xy} for an edge dislocation lying in the z -axis is well known [6], $\tau_{xy} = [Gb/2\pi(1-\nu)]x(x^2 - y^2)/(x^2 + y^2)^2$, where G is the shear modulus and ν the Poisson's ratio, so that for the displaced dislocations (forces will be given on unit lengths of dislocations),

$$F_{\text{int}} = -D \frac{(x - x')[(x - x')^2 - h^2]}{[(x - x')^2 + h^2]^2},$$

$$F'_{\text{int}} = -D \frac{(x' - x)[(x' - x)^2 - h^2]}{[(x' - x)^2 + h^2]^2} = -F_{\text{int}}, \quad (1)$$

where $D = Gb^2/[2\pi(1-\nu)]$.

Only the vibrations symmetrical to the central y - z plane will be considered (which may be called optical mode), so that $x' = -x$. The deviation of dislocation 1 from the

FIGURE 1: Dislocation dipole.

equilibrium position $x = h/2$ will be denoted as u , $x = u + h/2$, so that the width of the dipole L is $L = h + 2u$ (Figure 1). For small deviations, $u \ll h/2$, the equation for force vibrations is reduced to the equation of a standard linear undamped oscillator. For oscillating external shear stress $\tau_{xy}^{\text{ext}} = \tau_0 \cos \omega t$, the equation of motion reads as follows:

$$m \frac{d^2 u}{dt^2} = -D \frac{u}{h^2} + b \tau_0 \cos \omega t. \quad (2)$$

The amplitude A of harmonic solution $u = A \cos \omega t$ is

$$A = \frac{b \tau_0}{D/h^2 - m \omega^2} = \frac{b \tau_0}{m(\omega_S^2 - \omega^2)}. \quad (3)$$

The assumption of small deviations is violated when the frequency of external oscillations ω approaches the frequency of self-vibrations ω_S :

$$\omega_S = \frac{1}{h} \sqrt{\frac{D}{m}} = \frac{1}{h} \sqrt{\frac{G}{2\pi(1-\nu)\rho}}. \quad (4)$$

In the last equation the effective mass m of a dislocation per unit length can be estimated [7] as $m = \rho b^2$, where ρ is the mass density. For example, for copper, $G = 45.5$ GPa, $\nu = 0.35$, $b = 0.256$ nm, $\rho = 8930$ kg/m³ [3], it is $\omega_S [\text{s}^{-1}] = 1.12 \times 10^3 (1/h [\text{m}]) = 1.12 \times 10^9 (1/h [\mu\text{m}])$. Therefore, for the expected values of the typical dipolar loop height, $h \sim 10$ nm, the circular self-frequencies are very high, $\omega_S \sim 10^{11} \text{ s}^{-1}$, that is, ω_S is in the range of 100 GHz, that is, the frequencies f in the range of 10 GHz.

3. FORCED VIBRATIONS WITH DAMPING

The damping decreases the amplitude accompanied by a phase shift. The main part of the damping force can be taken proportional to the dislocation velocity, $F_{\text{dam}} = -R du/dt$ [5],

where R is the damping constant. The equation of motion modifies to

$$m \frac{d^2 u}{dt^2} = -D \frac{u}{h^2} + b \tau_0 \cos \omega t - R \frac{du}{dt} \quad (5)$$

with the solution $u = B \cos(\omega t - \alpha)$, where B is the amplitude of damped vibrations and α is the phase shift,

$$B = \frac{b \tau_0}{\sqrt{m^2(\omega_S^2 - \omega^2)^2 + R^2 \omega^2}}, \quad \text{tg} \alpha = \frac{R \omega}{m(\omega_S^2 - \omega^2)}. \quad (6)$$

The value of the damping constant R for metals like Al and Pb was estimated in [5] to be of the order $R \cong 10^{-6} \text{ Nm}^{-2} \text{ s}$ (the estimate corresponds to the temperature independent electronic damping, for higher temperature R increases due to the phonon damping). Amplitude B reaches maximum for $\omega_M = (\omega_S^2 - R^2/2m^2)^{1/2}$, however, as $R/m \approx 10^9 \text{ s}^{-1}$, we have $\omega_M \approx \omega_S$ and $B_{\text{max}} \approx b \tau_0 / R \omega_S$. For the validity of the linearized model, the vibrations have to be small, that is, $B_{\text{max}} \ll h/2$, hence $\tau_0 \ll h R \omega_S / 2b \approx 2 \text{ MPa}$.

4. DISCUSSION

According to the presented estimate, the mobility of a typical dipolar loop approximated as the edge dipole of the height ~ 10 nm can be facilitated by ultrasound waves in the 100 GHz range of frequencies. The commercial apparatus works with the frequencies up to 10 GHz, using special equipment, the ultrasound frequency 600 GHz was reached in thin foils [7]. The main problem is a strong attenuation increase at higher frequencies, especially in metals. Therefore, the effect of ultrasound in the GHz range on dislocation dipole vibrations can be reached in principle, however, only in thin specimens; for example, in fatigued specimens exposed to GHz ultrasound waves, the degradation process could be accelerated. To our knowledge, no experiments of that kind have been done, as a verification of this effect seems to be rather difficult. The contribution of dislocations dipoles to distortion of ultrasound waves was analyzed and measured in [8] at frequency 5 MHz, that is, far below the resonance frequency estimated in the present note.

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REFERENCES

- [1] H. Mori, M. Tokuwamk, and T. Miyazaki, "Cyclic deformation of silicon-iron single crystals oriented for single glide," *Philosophical Magazine A*, vol. 40, no. 3, pp. 409–433, 1979.
- [2] B. Tippelt, J. Bretschneider, and C. Holste, "Influence of temperature on microstructural parameters of cyclically deformed nickel single crystals," *Philosophical Magazine Letters*, vol. 74, no. 3, pp. 161–166, 1996.
- [3] B. Tippelt, J. Bretschneider, and P. Hähner, "The dislocation microstructure of cyclically deformed nickel single crystals at different temperatures," *Physica Status Solidi A*, vol. 163, no. 1, pp. 11–26, 1997.

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- [4] J. Bretschneider, C. Holste, and B. Tippelt, "Cyclic plasticity of nickel single crystals at elevated temperatures," *Acta Materialia*, vol. 45, no. 9, pp. 3775–3783, 1997.
 - [5] H. Kronmüller, "The eigen-frequency of extended dislocations," *Physica Status Solidi B*, vol. 52, no. 1, pp. 231–240, 1972.
 - [6] F. Kroupa, "Vibration modes of split screw dislocations in b.c.c. metals," *Physica Status Solidi B*, vol. 84, no. 2, pp. 725–730, 1977.
 - [7] J. Vollmann, D. M. Profunser, and J. Dual, "Sensitivity improvement of a pump—probe set-up for thin film and microstructure metrology," *Ultrasonics*, vol. 40, no. 1–8, pp. 757–763, 2002.
 - [8] J. H. Cantrell and W. T. Yost, "Nonlinear ultrasonic characterization of fatigue microstructures," *International Journal of Fatigue*, vol. 23, supplement 1, pp. 487–490, 2001.