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COMPLEX INTERACTION MECHANISMS BETWEEN DISLOCATIONS AND POINT DEFECTS INVOLVING SIMULTANEOUSLY DEPINNING-REPINNING AND DRAGGING PROCESSES

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Abstract - In the case of elastic interaction between dislocations and point defects, complex interaction mechanisms can appear, which involve simultaneously depinning-repinning processes and dragging processes.

I. INTRODUCTION - In order to explain the anelastic effects due to an elastic interaction between the dislocations and the point defects (PD), numerous models of interaction have been published [1]. These models can generally be classified in five principal categories: the models of pinning, of hardening, of breakaway, of breakaway drag and of dragging.

As shown first by Lücke and Schlipf [2], a diagram of the interaction mechanisms can be plotted in the space \( \sigma_0 - T \) (applied stress amplitude versus temperature). In this paper, more detailed \( \sigma_0 - T \) diagrams are obtained by simple calculations. These diagrams present different domains in which the dislocation motion is controlled by the "classical" interaction mechanisms (pinning, breakaway, breakaway drag, dragging). But they present also a domain in which the dislocation motion is controlled by more complex interaction mechanisms, which involve simultaneously two elementary processes (depinning-repinning and dragging). It is also shown that these complex interaction mechanisms can lead to transitory effects as a function of the time when applying an harmonic stress.

II. THE ELASTIC INTERACTION MECHANISMS - In order to describe the elastic interaction mechanisms which can occur during harmonic deformation, one has to develop a simple model in which the process of depinning-repinning of the dislocations and the process of dragging of the point defects can be considered simultaneously. It will be assumed that the dislocation network is formed by dislocation segments of length \( L \) interacting with a row of equally spaced \( (2) \) pinning PD. The motion of the dislocation segments \( L \) will be described by considering an average displacement \( \ell + \) (rigid rod model) and, in the low frequency range considered here, the phonon drag will be neglected (fig.1,a).

II.1. The interaction mechanisms in glide force diagrams - In a glide force diagram (fig. 1,b), it is possible to plot (in dotted line) the effective glide force \( f_{\text{eff}} \) acting on each small loop \( \ell \) of a dislocation segment \( L \). This effective glide force depends on the applied stress \( \sigma(t) \) and on the restoring force \( F_{\text{PD}} \) due to the line tension \( \gamma \) of the whole segment \( L \) \( (K = 12\gamma /L^2) \):

\[
f_{\text{eff}} = \ell (b\sigma - F_{\text{PD}})
\]

In the same diagram, a very simplified glide resistance force profile \( f_{\text{res}} \) around an attractive PD situated in \( \text{up} \) is plotted in full line. This resistance force is characterized by an interaction energy \( U_{\text{M}} \) and by a maximum interaction force \( F_{\text{MAX}} \). The rate of decrease of the resistance force as a function of the distance \( r \) from the PD (for example \( r^{-3} \) for modulus effects and \( r^{-2} \) for size effects) is replaced...
Fig. 1: Schematic representation of the dislocation segment motion by the rigid rod model (a) and by glide force diagrams (b to f), for: (b) the breakaway mechanism, (c) the hardening mechanism, (d) the breakaway drag mechanism, (e) the transitory stage of the complex interaction mechanism in domain IVb near $T = T_1$ and (f) the stationnary state of the complex interaction mechanism in the transition zone between domains IVb and IVa.
by a cut-off length $d$, which is defined by $d = 2UM/f_{\text{max}}$. Depending on the instantaneous values of $\sigma(t)$ and $u_{PD}(t)$, one or two stable equilibrium positions are possible for the dislocation segment $L$ : the pinned position $u_{1}$ (in $u_{\text{PPD}}$) and/or the depinned positions $u_{2}$. When the two equilibrium positions $u_{1}$ and $u_{2}$ exist simultaneously, the dislocation segment $L$ can jump from one to the other position by a thermally activated breakaway mechanism. But when the applied stress and the temperature are too small, this jump is impossible and a rigid pinning mechanism takes place. It is interesting to do three remarks:

(i) if the slope of decrease of the effective glide force ($\lambda K$) is higher than the slope of decrease of the glide resistance force ($f_{\text{max}}/d$), the breakaway mechanism is no more possible and a hardening mechanism takes place (fig. 1,c).

(ii) if the PD are randomly distributed in a field on the glide plane (fig.1,d) the motion of the dislocation segment is controlled by a breakaway drag mechanism (motion by successive jumps from one to an other equilibrium position $u_{1}$).

(iii) the force which acts on the PD is given by the value of the effective glide force at its intersection with the glide resistance force of the PD (in $u_{\text{PD}}(1)$). If the mobility of the PD becomes important, this force leads to a PD dragging mechanism which replaces the breakaway or the hardening mechanism.

11.2 The dragging process - In the case of fig. 1(b), it can be assumed that the dislocation segment $L$ is rigidly pinned at position $u_{1}$ so that the dislocation and the PD have the same velocity. The PD velocity $u_{PD}$ depends on the value of the effective glide force:

$$u_{PD} = u_{1} = Mf_{\text{eff}} = (D_{0}/kT) \exp (-E_{m}/kT) f_{\text{eff}}$$

\[(2)\]

in which $M$ is the mobility of PD, depending essentially on the migration energy $E_{m}$ of the PD and on the temperature. By applying an harmonic stress $\sigma(t) = \sigma_{0} \sin \omega t$, equations (1) and (2) lead to a relaxation internal friction (IF) peak, which is given, with its height normalized to one, by

$$IF = \left(\frac{2\omega/K\lambda M}{1+(\omega/2K\lambda M)^{2}}\right)^{-1}$$

If one defines the low temperature $T_{1}$ and the high temperature $T_{2}$ for which the IF is equal to 0.01, these two temperatures can be used to characterize the efficiency of the dragging process : for $T < T_{1}$, the PD are almost immobile and for $T > T_{2}$, the PD are very mobile and can easily follow the dislocations.

11.3 The depinning-repinning process - By a thermally activated mechanism, the dislocation segment $L$ can also breakaway from the pinned equilibrium position $u_{1}$ (on the row of PD) to the depinned equilibrium position $u_{2}$. Such a mechanism depends on the effective glide force $f_{\text{eff}}(t)$ at the position $u = u_{PD} = u_{1}$. From equations (1) and (2):

$$f_{\text{eff}}(t) = \lambda \sigma_{0} \left[1+(\lambda K/\omega)^{2}\right]^{-\frac{1}{2}} \sin(\omega t+\phi)$$

\[(4)\]

This dependance of $f_{\text{eff}}(t)$ on the PD mobility $M$ means that the depinning process will depend strongly on the dragging process. For the rigid rod model used here, a complete catastrophic breakaway of the dislocation segment $L$ takes place for each elementary depinning process of a small loop. Introducing then the number $N(t)$ of dislocation segments which are depinned at time $t$ among the total number $N_{0}$, the following equation can be written:

$$N(t) = N_{0} \Gamma_{d} - N_{0} \Gamma_{r}$$

\[(5)\]

$\Gamma_{d}$ and $\Gamma_{r}$ are the jump frequencies for the depinning and the repinning processes respectively, and are given by:

$$\Gamma_{d} = \nu_{d} \exp (-\Delta G_{d}/kT) \quad \Gamma_{r} = \nu_{r} \exp (-\Delta G_{r}/kT)$$

\[(6)\]

in which $\nu_{d}$ and $\nu_{r}$ are the respective attack frequencies. The activation energies $\Delta G_{d}$ and $\Delta G_{r}$ correspond to the shaded area in fig. 1(b). They depend on the time by $f_{\text{eff}}(t)$:

$$\Delta G_{d}(t) = UM \left[\frac{f_{\text{max}} - f_{\text{eff}}(t)}{f_{\text{max}}}\right]^{2} / \left[\frac{f_{\text{max}}(f_{\text{max}} - K\lambda d)}{f_{\text{max}}(f_{\text{max}} - K\lambda d)}\right]$$

$$\Delta G_{r}(t) = UM \left[\frac{f_{\text{eff}}(t) - K\lambda d}{K\lambda d}\right]^{2} / \left[\frac{K\lambda d}{f_{\text{max}}(f_{\text{max}} - K\lambda d)}\right]$$

\[(7)\]
Fig. 2: $\sigma_0 - T$ diagrams of the interaction mechanisms for different values of $U_m/E_m$ (from 0.15 to 1.5) and for the same values of all the other parameters.

Fig. 3: Fraction of depinned dislocation segments as a function of an harmonic applied stress: a), b), c) in domain II for $T<T_A$, $T<T_T$ and $T>T_B$, d) in domain IVb for $T>T_1$, e) in the transition zone between domains IVb and IVa.

Fig. 4: Anelastic strain versus applied stress: a) in domain II for $T<T_A$, b) in domain IVb for $T>T_1$, c) in the transition zone between domains IVb and IVa. In dotted lines, the effect of the pure dragging mechanism.
Eq. (5) must be numerically integrated in order to obtain the value \( N(t) \) of depinned dislocation segments at time \( t \). One can then define a parameter \( \beta_{\text{max}} \) as the maximum fraction of depinned dislocation segments during each half-cycle of the effective glide force \( f_{\text{eff}}(t) \):

\[
\beta_{\text{max}} = \max \left( \beta(t) \right) = \max \left( \frac{N(t)}{N_0} \right)
\]  

This parameter \( \beta_{\text{max}} \) can characterize the efficiency of the depinning process: for \( \beta_{\text{max}} = 0 \), there is no breakaway mechanism and for \( \beta_{\text{max}} = 1 \), all the dislocation segments break away during each cycle of the applied stress.

III. THE INTERACTION MECHANISMS IN \( \sigma_T-T \) DIAGRAMS – The efficiency of the dragging mechanism depends only on the temperature \( T \) and the efficiency of the breakaway mechanism is characterized by the value of the parameter \( \beta_{\text{max}} \), which depends on the temperature \( T \) and on the applied stress amplitude \( \sigma_0 \). It is then possible to plot efficiency curves for these two mechanisms in \( \sigma_T-T \) diagrams (fig. 2). The curves obtained for \( T=T_1 \) and \( \beta_{\text{max}} = 0.001 \) (called the depinning critical stress \( \sigma_d \)) divide the diagram in four principal domains (I, II, III and IV), in which the interaction mechanisms are completely different. The curves obtained for \( T=T_2 \) and \( \beta_{\text{max}}=0.999 \) (called the complete depinning critical stress \( \sigma_{\text{cd}} \)) are used to subdivide these principal domains in smaller regions (IIa, IIb, etc.).

Such diagrams present always the same domains and regions. But the curves which limit these domains and regions can present very different aspects, depending strongly on the parameters \( U_M, E_M, d, L \) and \( \ell \), and less strongly on the parameters \( \sigma_d, \nu_T, D_0 \) and \( \omega \).

III.1. The domain I – The PD are not mobile and the dislocation segments cannot break away from the PD. This is the domain of the rigid pinning.

III.2. The domain II – The PD are not mobile, but a part of the dislocation segments (in region IIa) or all the dislocation segments (in region IIb) can move by a mechanism of breakaway (or breakaway drag, if the PD are randomly distributed in a field of PD on the glide plane).

In this domain, one can also define the repinning critical stress \( \sigma_r \) and the complete repinning critical stress \( \sigma_{\text{cr}} \). For applied stress amplitudes \( \sigma_0 \) greater than \( \sigma_{\text{cd}} \), those critical stresses give the values of the stress for which, during the decrease of the stress \( \sigma(t) \) after a complete breakaway, the fraction of depinned dislocation segments goes through 0.999 and 0.001 respectively. The breakaway mechanism in domain II presents several stages as a function of the temperature, depending on the four critical temperatures \( T_a \) to \( T_d \) (fig. 2). At low temperatures (\( T<T_b \)), the repinning critical stresses \( \sigma_r \) and \( \sigma_{\text{cr}} \) are different from the depinning critical stresses \( \sigma_d \) and \( \sigma_{\text{cd}} \). As a consequence, the motion of the dislocation segments is hysteretic (fig. 3,a and b), which leads to internal friction losses represented by the shaded area in fig. 4(a). For temperatures higher than \( T_b \), the populations of pinned and depinned dislocation segments are always in a state of thermal equilibrium, which means that there is no more hysteretic motion of the dislocation segments (fig. 3,c) and, as a consequence, there is also no more internal friction losses due to the breakaway mechanism.

III.3. The domain III – The dislocation segments are rigidly pinned to the PD, but they can drag the PD. This mechanism of pure dragging is responsible for the IF relaxation peak given by eq. (3) and situated in region IIIa. In region IIIb, the PD are so mobile that they can easily follow the dislocation segments.

III.4. The domain IV – The interaction mechanisms are much more complex because dragging and depinning-repining elementary processes are involved simultaneously. In region IVa, one part of the dislocation segments moves by a pure dragging mechanism when the other moves by a complex mechanism of simultaneous breakaway and dragging (§III.4.2). In region IVb, all the dislocations move by a complex mechanism, which leads to a time dependant redistribution of the PD on the glide planes, as that is shown in the next paragraph.

III.4.1. The case of very low PD mobility – In the temperature range of \( T_1 \) in domain IVb, one can consider, for each positive half-cycle of the applied stress, an average position \( \bar{\sigma}_{PD} \) of the PD on the glide plane (fig. 1,e). During the increase of
the stress $\sigma(t)$, the dislocation segment will jump successively from "positions" 1 to 1' (for $\sigma_1<\sigma(t)<\sigma_2$) and from "positions" 2 to 2' (for $\sigma_3<\sigma(t)<\sigma_4$). During the decrease of the stress $\sigma(t)$, two jumps will also occur from "positions" 3 to 3' (for $\sigma_5<\sigma(t)<\sigma_6$) and from "positions" 4 to 4' (for $\sigma_7<\sigma(t)<\sigma_8$). The average displacement $\Delta u_{PD}$, which is very small during one cycle of the stress, is due to the forces exerted by the dislocation segment from "positions" 1' to 2 and from "positions" 3' to 4.

It is easy to understand that, for an harmonic applied stress, the time $t_2-t_1$ is a little longer than the time $t_3-t_2$. This means that $\Delta u_{PD}$ has a more or less small positive value, depending on the mobility $M$ of the PD. As a consequence, the PD will be pushed towards the extremities of the glide area swept by the dislocation segments. This transitory stage, which uses more or less time (number of cycles of the applied stress) depending on the value of $M(T)$, will tend towards a stationary state when the "position" 2 corresponds approximately to the effective glide force given for $\sigma(t) = \sigma_0$.

The schematic curves of the fraction $B(t)$ of depinned dislocation segments as a function of the harmonic applied stress $\sigma(t)$ can be plotted for the stationary state (Fig.3,d). On this plot, the area included between the increase and the decrease of $B(t)$ depends on the thermodynamic reversibility of the breakaway mechanism ($T_1<T_b$ or $T_1>T_b$) and is responsible for the IF losses represented by the shaded area in Fig. 4(b).

On the other hand, this phenomenon of PD redistribution depends in fact on the wave shape of the applied stress $\sigma(t)$. This means that the anelastic behaviour (e.g. IF) in this domain IVb depend not only on the time, but also on the way to do the measurements (free decay, forced vibrations, etc.).

III.4.2. The case of higher PD mobility - In the temperature range corresponding to the transition zone between regions IVb and IVa, the motion of the dislocation segment is the following (Fig.1,f): during the increase of $\sigma(t)$, a re-pinning process with the PD situated at position $u_{PD_{max}}$ takes place for $\sigma_1<\sigma(t)<\sigma_2$; then the PD are dragged to a maximum position $u_{PD_{max}}$ (this motion presents a phase lag between the position $u_{PD}(t)$ and the applied stress $\sigma(t)$). During the decrease of the stress, a depinning process occurs for $\sigma_1<\sigma(t)<\sigma_2$, when the PD arrive at the position $u_{PD_{min}}$. Such a mechanism presents a very short transitory stage. The stationary state is then almost immediately obtained by applying an harmonic stress. For this case, the curve of the fraction $B(t)$ of depinned dislocation segments versus $\sigma(t)$ is plotted in Fig. 3(e), and the anelastic strain versus $\sigma(t)$ in Fig. 4(c), in which the shaded area corresponds to the IF losses due to this mechanism.

CONCLUSION - In this paper, it has been theoretically shown that the dislocation motion, in a domain of given values of $\sigma_0$ and $T$, is controled by complex interaction mechanisms involving simultaneously depinning-repinning processes and dragging processes. Such complex interaction mechanisms have to be observed by internal friction experiments (essentially by their effects on the dragging IF relaxation peak as a function of the applied stress amplitude, Fig. 4,c) and by harmonic bias stress experiments (which are very sensitive to the fraction $B(t)$ of depinned dislocation segments, Fig.3). Such effects have been experimentally observed in aluminium and are reported in other papers [3,4].

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