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ANALYSIS AND CRITIQUE OF THE "PEAKING EFFECT" MODELS : II

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Résumé - Dans l'article précédent, nous avons montré que le modèle de Caro et Mondino ne peut décrire correctement le Peaking Effect. Nous allons maintenant analyser plus précisément notre modèle et montrer qu'il permet de donner une bonne description du PE.

Abstract - In the preceding article, we have shown that the Caro and Mondino model cannot give a good description of the Peaking Effect. Now, we analyse more in detail our own model and show that it explains well all the characteristics of the PE.

I - INTRODUCTION

Our model presented in Manchester (12) is based on the existence of two types of immobile point defects which interact differently with dislocations. There are defects localized on dislocations which pin them and defects situated near the glide plane responsible for their retardation. The latter defects provoke an increase $\Delta\tau$ of the relaxation time of the dislocation. This increase depends on ϵ because the number of defects met is proportional to the area A swept out by the dislocation (the deformation ϵ_d due to the dislocation motion is equal to $\Lambda b/L$ where Λ is the dislocation density and L the loop length. The PE is due on the one hand to the dislocation pinning which reduces the internal friction and modulus defect and on the other hand to an increase of the dissipated energy due to a dislocation retardation by the second type of points defects. The increase $\Delta\tau$ of the relaxation time is given by (12) :

$$\Delta\tau = C A$$

where C is proportional to the concentration ρ of points defects created by irradiation ($\rho = \rho_0 t^m$). ϵ_d depends on the strain amplitude ϵ by the relation (12) :

$$\epsilon_d = \epsilon \Delta / \sqrt{1 + \omega^2 \tau^2}$$

with $\Delta = \Lambda L^2 G b^2 / 12 \gamma$ = relaxation strength, G = shear modulus, γ = dislocation energy per unit length $\approx G b^2 / 2$. Thus, we obtain :

$$\Delta\tau = \frac{C L^3 G b \epsilon}{12 \gamma \sqrt{1 + \omega^2 \tau^2}} \approx C_0 \frac{\rho_0 L^3 \epsilon}{6 b} \frac{t^m}{\sqrt{1 + \omega^2 \tau^2}} \quad (10)$$

(C_0 = constant)

The dislocation pinning can be describe by the following law :

$$L = L_0 (1 + a \phi t)^{-n} \quad \text{with } a \text{ and } n : \text{constants, } \phi : \text{irradiation flux.}$$

$$\text{So, } \frac{\Delta}{\Delta_0} = \left(\frac{L}{L_0}\right)^2 = \frac{K_0}{K} = (1 + a \phi t)^{-2n} \quad (11)$$

Δ_0 = relaxation strength at $t = 0$, K = line tension term = $12 \gamma / L^2$ (4).

The modulus defect $\Delta M/M$ and the internal friction Q^{-1} are calculated by

considering that the relaxation time τ is the sum of three contributions due to the different processes which intervene :

$$\tau = \tau_0 + \frac{B_0}{K} + \Delta\tau \quad (12)$$

τ_0 is the term associated with a thermally activated phenomenon (Bordoni peak for instance). B_0/K is an athermal term where the viscosity coefficient B_0 is related to phonon effects. These two terms (τ_0 and B_0/K) determine the internal friction before irradiation. The modulus defect and internal friction are given by the classical equations :

$$\frac{\Delta M}{M} = \frac{\Delta}{1 + \omega^2 \tau^2} \quad \text{and} \quad Q^{-1} = \Delta \frac{\omega \tau}{1 + \omega^2 \tau^2} \quad (13)$$

($\Delta\tau$ is a function of ϵ and so the equation of motion of the dislocation is non-linear ; but we can consider a linear equation with a mean value for $\Delta\tau$ for calculating Q^{-1} . Rigorously, the equation should be resolved numerically but the conclusions should be similar).

II - MODEL ANALYSIS

The total relaxation time is given by the following relation (15) :

$$\tau = \tau_0 + \frac{B_0}{K_0} (1 + a \phi t)^{-2n} + \frac{k_0 \epsilon t^m (1 + a \phi t)^{-3n}}{\sqrt{1 + \omega^2 \tau^2}} \quad (14)$$

with $k_0 = \frac{C_0 \rho_0 L_0^3}{6b}$

An approximate expression for Q^{-1} and $\Delta M/M$ can be obtained when $\omega\tau$ is $\ll 1$, which is true when τ_0 is ≈ 0 (i.e. far from a relaxation peak) and when B_0/K is low (low internal friction background).

With this hypothesis, we obtain :

$$\frac{\Delta M}{M} / \left(\frac{\Delta M}{M} \right)_0 \approx \frac{\Delta}{\Delta_0} \quad \frac{Q^{-1}}{Q^{-1}_0} \approx \frac{\Delta}{\Delta_0} \quad \frac{\tau}{B_0/K_0}$$

thus

$$M = \frac{\Delta M}{M} / \left(\frac{\Delta M}{M} \right)_0 \approx (1 + a \phi t)^{-2n} \quad (15)$$

$$F = Q^{-1}/Q^{-1}_0 \approx (1 + a \phi t)^{-4n} \left[1 + x t^m (1 + a \phi t)^{-n} \right]$$

where $x = \frac{k_0 \epsilon K_0}{B_0} = \frac{k_0 \epsilon \omega \Delta_0}{Q^{-1}_0} \quad (16)$

The subscript 0 indicates $t = 0$.

(However, even when $\omega\tau$ is not $\ll 1$, the same conclusions as the following can be obtained).

The principal features of our model are as follows :

i) The PE existence and height depend on the term x : when x is too low there is no PE and only a decrease of Q^{-1} . So, we can specify the effect of :

- strain amplitude ϵ : the higher the amplitude, the higher is the PE as shown by fig. 5 where the PE is calculated from equation (12).

- The initial background : x is proportional to Q_0 , thus the effect of ϵ and Q_0 are similar. Fig. 6a shows the variation of the PE height with ϵ for different values of the initial background and Fig. 6b presents the same variation with Q_0^{-1} for different amplitudes ϵ . We can note that the variation of the PE height is almost linear as a function of ϵ or Q_0 (except for low values).

- The plastic deformation : the PE depends on the plastic deformation ϵ_p on account of the dependence of the term k_0 with L_0 ($k_0 \propto L_0^3$). If the loop length L_0 varies as $1/\epsilon_p$ (4), we have $x \propto k_0 \propto \epsilon_p^{-3}$; so, an initial plastic deformation decreases the PE compared with an undeformed state.

ii) The evolutions of modulus defect and internal friction depend on the existence of the PE. Indeed, let's consider the expressions of M and F given by relations (15) for two cases :

. $x = 0$ or very low (there is no PE) : we have $M^2 = F$; so, the slope of the straight line $\log M$ versus $\log F$ is $1/2$. (Fig. 7a and a').

. x higher and for significant t (there is a PE) : F and M are given approximately by :

$$F \approx x t^m (\alpha \phi t)^{-5n} \quad M \approx (\alpha \phi t)^{-2n}$$

Thus, $F \propto M^{(5-m/n)/2}$

The slope of the line $\log M = f(\log F)$ is equal to $p = \frac{2}{5-m/n}$ and thus varies from specimen to specimen. In Fig. 7 (b, c), we have $n = 0.3$ and $m = 1/3$ or $2/3$ and $p \approx 0.51$ or 0.72 respectively.

iii) The position of the PE maximum ϕt_M is linked to the value of $x = k_0 \epsilon K_0/B_0$ (fig. 8) : it varies as $\log x$ (excepted for high or very low x values). This slope of the curves is almost independent on the initial background Q_0^{-1} as predicted by relation (15) but depends strongly on m and n exponents.

4i) The effect of principal parameters on the PE is elucidated by the derivative dQ^{-1}/dT .

a) The PE height depends on the temperature. In the range $T < T_p$, T_p : temperature of a relaxation peak (due to the term τ_0), there is no PE (the derivative is negative). In the range $T > T_p$, appears but becomes decreasingly as T nears T_p . Indeed, the initial background increases and so the PE decreases as indicated in i).

b) The PE variation with the strain amplitude (or Q_0) shows a saturation because the derivative dQ^{-1}/dT decreases when τ (or ϵ) increases. The maximum value of the PE height is obtained when $\omega\tau = 1$.

5i) When the term B_0 is independent of frequency, the PE is also independent on frequency as shown by the x parameter (relation (16)) :

$$x = k_0 \frac{\epsilon K_0}{B_0} = k_0 \epsilon \omega \frac{\Delta_0}{Q_0^{-1}}$$

This hypothesis requires that the background Q_0^{-1} is proportional to ω , Δ_0 being constant. This variation has been observed often in the kHz and MHz range but is not observed at low frequency.

III - COMPARISON WITH EXPERIMENTAL RESULTS

-i) a) The general form of the curves $Q^{-1}(t) / Q_0^{-1}$ and their evolution with ϵ (fig. 5) are very similar to the experimental results. The coefficients a , n and m must be fitted to obtain the best agreement. a and n are obtained by measuring simultaneously internal friction and modulus defect ; indeed, we have :

Fig. 5 - PE calculated from equation (15) for different values of X
 $a = 0.7 \times 10^{-15} \text{ cm}^2$, $n = 0.3$, $m = 1/3$ (a), $m = 2/3$ (b).

Fig. 6 - Variation of the PE height (a) with ϵ : (1) $Q_0^{-1} = 2.10^{-3}$ (2) 10^{-3} (3) 6.10^{-4} (4) 4.10^{-4} ; (b) with Q_0^{-1} : (1) $x = 0.83$ (2) $x = 1.67$ (3) $x = 4.17$ ($a = 0.7 \times 10^{-15}$, $m = 1/2$, $n = 0.3$).

Fig. 7 - Variation of $\log \Delta M/M$ as a function of $\log a'/a_0$
 Q^{-1} : $a = 0.7 \times 10^{-15}$
 $n = 0.3$, (a) $m = 1/3$,
 $x = 0.167$ (a') $m = 2/3$
 $x = 0.167$ (b) $m = 1/3$
 $x = 3.17$ (c) $m = 2/3$
 $x = 3.17$.

$$\frac{\Delta M/M}{(\Delta M/M)^2 + (Q^{-1})^2} = \frac{K}{\Delta G b^2} \propto L^2 = L_0^2 (1 + a\phi t)^{-n}$$

The variation of this ratio during irradiation gives a and n (4). For example, we have $a = 0.7 \times 10^{-15} \text{ cm}^2$, $n = 0.3$ for Ag (3,4) and $a = 1.41 \times 10^{-15} \text{ cm}^2$, $n = 0.5$ in Cu (4). The maximum position ϕ_{tM} gives m but a more precise value can be obtained by using the variation of ϕ_{tM} with ϵ .

b) The linear dependence of the PE height with Q_0 observed by Caro (5) is well described by our model (fig. 6b), except for the high values of Q^{-1} (or low PE). The slopes of the lines $Q^{-1}_{\text{max}}/Q^{-1}_0 = f(Q_0)$ are approximately $10^{-3} \Delta_0$ (4.5×10^{-3} for $\omega k_0 \epsilon = 10^{-2}$, fig. 6 b) i.e. near 10^{-4} with $\Delta_0 \approx 0.1$. This value is near the value obtained by Caro (5) in the case of Cu (5×10^{-4}).

c) The Grenoble Group has shown that the PE decreases when the amount of plastic deformation increases in agreement with our model.

ii) The slope p of the experimental line $\log M$ versus $\log F$ is always one half when there is no PE and ϵ is low (4). When the PE appears, this slope is about 1. According to our model, p is equal to $1/2$ without PE and $p = 2/(5 - m/n)$ for long time when the PE is present. This value of p depends on the experimental conditions, microstructural state of the specimen and its temperature (4).

iii) The linear dependence of the PE maximum position ϕ_{tM} with $\log \epsilon$ is well verified by experimental results in Ag (3) and Cu (4). From the slope of the curve ϕ_{tM} versus $\log \epsilon$ we can obtain a precise value of exponent m ($m = 0.45$ in Ag). One can note that a reduction of loop length by plastic deformation (4) produces a similar effect to a decrease of ϵ .

4i) a) Often, the PE has been studied at temperature higher than the temperature T_p of Bordoni peaks. When the temperature is near T_p , the PE becomes low and disappears for $T = T_p$ (4, 11). This result agrees well with our model. However, some authors have observed a PE below the Bordoni peak (4K), which can be due to the second kind of Peierls valleys (11).

b) The experimentally observed saturation of the PE height with the strain amplitude ϵ (fig. 3) is due to the fact that the internal friction cannot exceed the relaxation strength. Thus the PE dependence on ϵ varies with temperature: the saturation is observed earlier when the temperature is nearer the Bordoni peak as seen on Fig. 3.

5i) The PE independence of the applied frequency shows that the ratio K_0/B_0 must stay constant (relation (16)). But, the initial background $Q^{-1}_0 \approx \Delta_0 \omega B_0 / K_0$ must vary linearly with ω . Caro (5) has observed an inverted variation. But it would be necessary to study the ratio Q^{-1}_0/Δ_0 . Indeed, the relaxation strength decreases when the applied frequency increases, as observed by several authors (1). Therefore, it would be desirable to measure Q^{-1}_0 and Δ_0 versus frequency to specify the frequency effect.

IV - CONCLUSION

The comparison of experimental results with the preceding theoretical analysis shows that our model describes the principal features of the PE. Our model can be improved by taking into account some secondary effects such as the depinning of loop lengths with ϵ , responsible for the variation of Q^{-1}_0 with ϵ . Thus, a better agreement with experimental results can be obtained. But, such an effect is not necessary to obtain a PE as in the Caro and Mondino model. A better agreement with experiments can be also obtained by choosing a better law for the variation of loop lengths: the law $L = L_0 (1 + a\phi t)^{-n}$ can be replaced by the law $1/[1 + a(\phi t)^{-n}]$ as proposed by Lauzier (4).

Lastly, we have shown that the existence and the non-linear effects of the PE are not linked to the initial background dependence on the strain amplitude this dependence is only responsible for some secondary effects only.

REFERENCES

- (1) SIMPSON H.M., SOSIN A. and JOHNSON D.F., Phys. Rev. B, 5, 4, (1972) 1393
- (2) SEIFFERT S.L., SIMPSON H.M. and SOSIN A., J. Appl. Phys. 44, 8, (1973) 3404
- (3) GIRARD P. and MINIER C., J. Phys. 39, (1978) 981
- (4) LAUZIER J., Thèse, Université de Grenoble, 1981
- (5) CARO J., Thèse, E.P.F. Lausanne, 1981
- (6) CARO J., MONDINO M., J. Appl. Phys. 52, (1981) 7147
- (7) LAUZIER J., MINIER C. and SEIFFERT S.L., Phil. Mag. 31, (1975) 893
- (8) SIMPSON H.M., SOSIN A. and SEIFFERT S.L., J. Appl. Phys. 42, (1971) 3977
- (9) BONJOUR C., Thèse, E.P.F. Lausanne, 1978
- (10) MINIER C., LAUZIER J., ESHOUF C., FANTOZZI G., Phys. Stat. Sol.(a)71 (1982)381
- (11) MINIER C., LAUZIER J., ESHOUF C., FANTOZZI G., this conference
- (12) ESHOUF C. and FANTOZZI G., 3 ECIFUAS, Manchester, ed. C.C. SMITH, Pergamon Press, (1980) p. 109
- (13) CARO J., GLASS N.E. and MONDINO M., J. Appl. Phys. 53, 7, (1982) 4854
- (14) GRANATO A.V. and LUCKE K., J. Appl. Phys. 27, (1956) 583
- (15) RITCHIE I.G., ATRENS A., SO C.B. and SPRUNGMAN K.W., J. Phys. C5, 10,42(1981)319
- (16) FANTOZZI G., ESHOUF C., BENOIT W., RITCHIE I., Prog. Mat. Sci. 27, 3-4(1982) 311

Fig. 8 - Variation of the integrated flux ϕt_M at the PE maximum with X
: (a) $m = 1/3$ (b) $m = 2/3$ (c) $m = 1$
($a = 0.7 \times 10^{-15}$, $n = 0.3$, $Q_0^{-1} = 10^{-3} \text{ \AA L}_0^2$).

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