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

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Résumé : De nombreux modèles théoriques ont été proposés pour interpréter le Peaking effect observé généralement lors d'une irradiation électronique ou γ dans les métaux c.f.c. ou h.c. En particulier, Caro et Mondino ont proposé récemment un modèle qui semble décrire correctement les récents résultats expérimentaux. Après une présentation de ces résultats une critique du modèle de Caro et Mondino montre que ce modèle ne peut décrire correctement le Peaking Effect.

Abstract : Several theoretical models have been proposed for interpreting the Peaking Effect observed generally during electron or γ irradiation in f.c.c. or h.c.p. metals. In particular, Caro and Mondino have recently proposed a model which seems to explain all the characteristics of the PE. After a review of these characteristics, a critique of the model of Caro and Mondino shows that this model cannot give a correct description of the PE.

I - INTRODUCTION

The peaking effect (PE) was first observed in Cu by Simpson et al (1) in 1972. During electron irradiation, the internal friction (IF) first increases, reaches a maximum then decreases giving a peak of IF. At the same time, the modulus increases continuously. Almost since the initial observations, the existence of the PE has been the subject of controversy. Since then it has been observed in a number of f.c.c. metals and in h.c.p. Mg either during electron or γ irradiation or with increasing solute concentration in dilute substitutional alloys (1-11). The PE is only observed when the applied amplitude of oscillation is high enough, as shown clearly by Lauzier et al (7), Girard et al (3) and Caro (5). Several models of the PE have been proposed and are reviewed by Minier et al (11). Minier et al show that the models proposed up to now do not give a correct description of the PE. Consequently, we proposed a model (12) where the IF is due to dislocation retardation by point defects encountered by the dislocation during its oscillating motion. Two types of immobile point defects are considered: pinning points in the core of the dislocation and defects close enough to the glide plane to create a drag effect on the dislocation thereby retarding its motion. These latter defects increase in number as the strain amplitude increases because of the increased area of the slip plane swept by the dislocation. Thus the PE is amplitude dependent. This model has been criticized by Caro (5), mainly because of the frequency dependence. Caro and Mondino (5, 6, 13) have proposed a similar model based on the existence of two types of defects. However, the development is different. In particular, the amplitude dependence of the PE is attributed only to the amplitude dependence of the background IF. In this article, we present an analysis and critique of the last two models which take into account the recent experimental results reported by Minier et al (11).

II - RECENT EXPERIMENTAL RESULTS

Recent experimental results are reviewed by Minier et al (11). We just

detail some important points.

Simultaneous measurements of modulus and IF during the PE show that the generation of point defects provokes a decrease in vibrating length of the dislocation motion which increases the friction coefficient. The relative height of the PE depends on the initial preirradiation value of the IF background Q^{-1}_0 . Caro (5) has proposed the following empirical relationship to describe this effect :

$$\left(\frac{Q^{-1}_{\max}}{Q^{-1}_0} \right)_{\epsilon_n} = 1 + \frac{A}{(Q^{-1}_0)_{\epsilon_n}} \quad (1)$$

$Q^{-1}_{\max}$ and Q^{-1}_0 are measured at the same strain amplitude ϵ_n and A is a constant of the order of 5×10^{-4} . Numerous experimental results reported in the literature are described rather well by this expression (13) with the precise value of A depending on the microstructural state of the sample. In Cu, Lauzier (4) has shown for example that $Q^{-1}_{\max} - Q^{-1}_0$ is not constant and that A decreases as the amount of plastic deformation increases. Verification of equation (1) for polycrystalline Cu (5) is shown in Fig. 1. In addition, Caro et al (5, 6, 13) have shown that the dependence of the PE on amplitude ϵ is linked to the amplitude dependence of the IF background. The following empirical relation is proposed :

$$\left(\frac{Q^{-1}_{\max}}{Q^{-1}_0} \right)_{\epsilon} = 1 - B + \frac{A + B (Q^{-1}_0)_{\epsilon}}{(Q^{-1}_0)_{\epsilon_n}} \quad (2)$$

This describes the strain amplitude dependence very approximately and asserts that the height of the PE is amplitude dependent only when the background itself is amplitude dependent. A number of experimental results are at variance with this assertion. An example of PE dependence of ϵ in Cu is shown by Fig. 2, where the background is almost ϵ -independent (actually it decreases slightly with ϵ). According to equ. (2) the PE should not change with ϵ , which is clearly not the case as seen in Fig. 2. A similar result has been observed for Mg (10). Therefore the ϵ -dependence of the PE cannot be attributed to an ϵ dependence of the background IF alone. The ϵ -dependence of the background IF can only induce some secondary effects.

Caro (5) states that in Cu single crystals, the PE only exists in the range of strong ϵ dependence of the background. In fact, more careful analysis of the results reported by Caro himself indicates that for ϵ -values corresponding to strong amplitude dependence of the background, the PE is not always observed (fig. IV.23 and 24, ref. 5).

In conclusion, the experimental results show clearly that ϵ dependence is involved in the PE and is not directly related to the ϵ dependence of the background.

The height of the PE generally saturates with increasing ϵ as shown in fig. 3. The existence of saturation depends on the metallurgical state of the specimen but does not depend upon the ϵ dependence of the background as asserted by Caro. Indeed, a saturation of the PE with ϵ can be observed in the absence of a saturation of the background.

Temperature is also an important parameter for the observation of the PE. Usually, the PE is only observed above the temperature of the Bordoni relaxation as shown by Minier et al (11). Nevertheless, in some cases, the PE has been observed at very low temperature.

The PE depends upon the amount of preirradiation plastic deformation. Lauzier (4) has shown that in Cu the PE height decreases with the amount of cold-work and its ϵ -dependence is stronger in well annealed samples.

Fig. 1 - Variation of the PE height with the initial value of the background Q_0^{-1} for copper (after Caro (5)).

Fig. 2 - Variation of background (a) and of PE (b) with strain amplitude of vibration ϵ in Cu (after Lauzier et al. (7)).

Finally, the existence and properties of the PE are independent of the applied frequency throughout the range 0.3 to 30 KHz (5).

All of the observed characteristics of the PE given above must be accounted for in an acceptable model of the PE.

III - ANALYSIS AND CRITIQUE OF THE CARO AND MONDINO MODEL

Caro and Mondino (5, 13) assume that the energy dissipated per cycle is given by :

$$W = 2 \sigma_c b A \quad (3)$$

where b is the Burgers vector of the dislocation, A , the area it sweeps out and σ_c the sliding friction stress. They further assume that A is the total area swept out by the dislocation during its motion, whereas it seems more logical to us to consider the area swept out up to the stress σ_c ; then, W becomes proportional to σ_c^2 . The stress σ_c is taken to be proportionnal to the energy a_0 radiated from a broken bond, but the physical meaning of a_0 is not specified in any more detail. This radiated energy is assumed to be proportional to the concentration of points defects in the bulk n_L :

$$a'_0 = a_0 + a_1 n_L$$

With the preceding relations and taking into account the ϵ dependence of the background and the ϵ dependence of the dislocation length during irradiation (some unpinning occurs), Caro and Mondino obtain the following expression of the IF :

$$Q^{-1}(t, \epsilon) = Q^{-1}_{oo} \left(\frac{\epsilon}{\epsilon_n} \right)^{2N-1} \frac{1 + A' t}{\left[1 + B' \left(\frac{\epsilon}{\epsilon_n} \right)^{N-M} t \right]^2} \quad (4)$$

with $Q^{-1}_{oo} = \text{IF at } t = 0 \text{ and } \epsilon = \epsilon_n$

$A' = A_L a_1 / a_0$ $n_L(t) = A_L(t)$: number of defects in the bulk during irradiation

$B' = \frac{dL_{oo}}{A}$ d : constant A : dislocation density

$L_o(\epsilon) = L_{oo} \left(\frac{\epsilon}{\epsilon_n} \right)^N$: amplitude dependence of the loop length at $t = 0$

$L_o(t, \epsilon) = \frac{L_o(\epsilon)}{1 + n_D(t) \left(\frac{\epsilon}{\epsilon_m} \right)^{-M}}$: this expression indicates that the amplitude dependen-

ce is not the same in the irradiated state. $n_D(t)$: number of defects on dislocation at time t ; Exponents N and M are obtained from ϵ -dependence of IF in the initial state $Q^{-1}(t=0, \epsilon)$ and in the irradiated state $Q^{-1}(t=\infty, \epsilon)$, respectively. Thus equ. (4) shows clearly that in this model, the PE and IF background $Q^{-1}(t=0, \epsilon)$ correspond to the same phenomenon.

The internal friction background is given by :

$$Q^{-1}_o = Q^{-1}(t=0, \epsilon) = Q^{-1}_{oo} \left(\frac{\epsilon}{\epsilon_n} \right)^{2N-1} \quad (5)$$

$$Q^{-1}_{oo} = \frac{4}{3} \frac{a_0 A L_{oo}}{b^3 G} \frac{1}{\epsilon_n} \quad (6)$$

G = shear modulus

From eqs. (4), (5) and (6), several remarks are pertinent : -(1)- if the loop length is ϵ -independent (i.e. $N = 0$), the IF background varies as $1/\epsilon$, which has never been reported -(2)- the background is ϵ -independent when $N = 1/2$; thus, simultaneously the loop length must depend on ϵ . This result is surprising. Indeed, experimentally both the background and the modulus defect show a similar ϵ -dependence. However, the modulus defect is proportional to the square of the

loop length ; thus the dislocation length cannot vary with ϵ in the range of ϵ - independent IF or modulus defect. Consequently, equ. (5) does not account for the experimental results. -(3)- IF is always proportional to ΔL^2 regardless of the value of ϵ . Experimentally, numerous authors have shown that the IF tends to be proportional to L^2 for the high ϵ - values which give a PE and to L^4 for low ϵ - values when there is no PE. Fig. 4 shows an example of the variation of normalized modulus defect and IF for different values of ϵ during irradiation. The slope is near 1/2 for low ϵ - values and near 1 for $\epsilon > 10^{-6}$. The value of 1/2 means that the IF is proportional to L^4 . Thus, when the PE is absent at low ϵ - values, the IF is proportional to L^4 as predicted by the Granato - Lücke theory (14). Only for high ϵ - values, where the PE occurs, the IF is proportional to L^2 . Similar observations were reported by Simpson et al (1). Once again, the Caro - Mondino model does not adequately describe the observed behaviour.

-(4)- The Caro - Mondino model gives a qualitative variation of the PE with the background as described by equs (1) and (2). From equs (4) and (6), one finds that :

$$\left(\frac{Q^{-1}_{\max}}{Q^{-1}_o}\right)_{\epsilon_n} \propto \frac{1}{(\epsilon_n)^{1/2}} \quad (7)$$

$$\left(\frac{Q^{-1}_{\max}}{Q^{-1}_o}\right)_{\epsilon} \approx \frac{A'}{4B'} \left(\frac{Q^{-1}_o}{Q^{-1}_{oo}}\right)^{\frac{M-N}{2N-1}} = \frac{A'}{4B'} \left(\frac{\epsilon}{\epsilon_n}\right)^{M-N} \quad (8)$$

The exponents are not the same as those in equs (1) and (2) but qualitatively there is agreement between the model and experimental results

-(5)- The relative PE height depends on loop length ; we have (5) :

$$\left(\frac{Q^{-1}_{\max}}{Q^{-1}_o}\right)_{\epsilon_n} \propto \frac{A'}{L_{oo}} \quad (9)$$

The height increases when the dislocation length decreases. After plastic deformation the PE amplitude decreases, which does not correspond to the relation (9).

-(6)- The occurrence of a PE depends only on the ϵ - dependence of the background.

To observe the PE, two conditions must be fulfilled : both the position and height of the PE must increase with ϵ . This implies that $M > N$ and $M + N > 1$. Moreover, experimentally, IF generally increases with ϵ regardless of the time ; thus in addition to the preceding conditions we must add $M > 1/2$ and $N > 1/2$.

Therefore, in the Caro and Mondino model, the conditions for the occurrence of the PE are very restrictive. In particular, if the loop lengths do not depend on ϵ ($N = M = 0$), only an abnormal PE can occur (it is ϵ - independent or decreases with ϵ). Moreover, the condition $M > N$ means that the amplitude dependence of the IF is higher after irradiation than before. This is not in agreement with observed results. In the study by Caro (5), M is fixed to obtain agreement between the model and experimental results. M is not obtained from the ϵ -dependence of Q^{-1} ($t \rightarrow \infty$). Furthermore, the results show that neither M nor N are constant but vary with ϵ and t and that the ϵ -dependence is lower after irradiation than before. This leads to a more difficult analysis.

Finally, if, in equ. (3) A is taken to be proportional to σ_c instead of σ , the IF becomes proportional to ϵ^{2N-2} so that the N value is equal to the Caro - Mondino value plus 1/2 and the $N < M$ condition is no longer fulfilled.

-(7)- For $M + N > 1$, the height of the PE always increases with ϵ ; i.e. equ.(4) does not predict a saturation with ϵ . Experimentally a saturation is observed (fig. 3) regardless of the ϵ -dependence of the background.

-(8)- The Caro Mondino model does not explain the occurrence of the PE above the temperature range of the Bordoni relaxation. It only explains the evolution of the PE by point defect diffusion and dislocation pinning.

-(9)- There is no frequency dependence in the Caro - Mondino model ; this is because of the frequency independence of the dissipated energy. This frequency independence is in agreement with reported experimental observations.

In conclusion, the model proposed by Caro and Mondino, based on our idea of two levels of interaction between the point defects and the dislocations, does not give an acceptable description of the experimental results. In particular the model incorrectly predicts the ϵ -dependence of the PE linked to an ϵ -dependent background. In part II, we show that our model gives a good description of all the experimental results.

REFERENCES : In part II

Fig. 3 : Effect of strain amplitude ϵ on PE height : (1) copper at 160 K (4) (2) : copper at 115 K (4) ; (3) copper at 350 K (5)

Fig. 4 : Variation of normalized modulus defect and internal friction for different values of ϵ during 35 K irradiation of Cu (after Lauzier et al (7)).