Plastic Relaxation at Crack Tip: Micromechanical Analysis

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The influence of a plastic zone developed at a crack tip is analyzed under a micromechanical point of view. Mechanical interaction is described in terms of crack shielding caused by the stress intensity factor induced by a dislocation loop in the three opening modes. Numerical calculations and experimentally studied configurations quantify the total relaxation rate induced by this dislocation loop.

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1. Introduction

The stress intensity factor, K , is a measure of the singularity in the stress field around a stress concentration defect, such as a crack under loading. In brittle materials, the crack propagation criterion is established as a function of a critical stress intensity factor, K_{IC} , usually called toughness. When the applied stress intensity factor, K_a , reaches the critical value, K_{IC} , the crack propagates. In ductile materials, such as in FCC metals, a stress relaxation occurs when yielding is reached and, as a consequence, the singularity in the stress field around the crack smooths out. In fact, although there still exists an applied stress intensity factor, K_a , its effective value K_{eff} , may reach a zero value under plasticity.

In general, the stress concentration created by the crack tip leads to a plastic zone in its neighborhood during loading. This plastically deformed region changes the conditions under which crack propagate. Hence, in ductile materials the crack propagation criteria based simply on the value of K_{IC} is not enough and one should prefer the COD (crack opening displacement) method.¹⁾

To explain the plastic relaxation effects around a crack tip there are basically two mechanisms: the *blunting mechanism* and the *shielding mechanism*.

Blunting is the plastic deformation that develops at the crack tip, altering its shape or its radius and, thus, reducing the stress concentration factor. It may occur due to:

- (i) the surfacing of the dislocations close to the crack tip, although limited by the geometry of the plastic zone, since the plane where dislocations slide must fully contain the crack tip to allow its surfacing (see Fig. 1);
- (ii) the atomic diffusion at the free surface may show up itself stronger at the crack tip, leading to a change in its shape and, consequently, the stress concentration factor, as shown in²⁾ (see Fig. 2).

Shielding is actually the interaction of the stress field induced by the crack tip and the one induced by the set of dislocations, which are emitted during loading (plastic zone).

For semi-brittle materials, as those with a BCC or covalent crystal lattices, due to a strong temperature influence on the generation and on the mobility of dislocations, a full plastic relaxation is incompatible with the low kinetic energy of the

Fig. 1 Blunting by emergence of the dislocation in the crack tip. Plastic zone around a crack with the crack edge fully contained in the slopping plane.

Fig. 2 Blunting by atomic diffusion at crack tip.

dislocations. The effective stress intensity factor is strongly dependent on the loading application rate and on the temperature and, in general, it does not vanish. Hence, these materials show a brittle-ductile transition behavior that depends on the dislocation activity and, consequently, on the size and shape of the resulting plastic zone, on the stress field induced by the interaction of that plastic zone and the applied stress field.

2. The Shielding Concept

The shielding concept was introduced in order to account for a partial relaxation of the stress concentration at crack tip. Since full relaxation results from any model assuming physical continuity between the crack and the plastic zone,³⁾ a continuity solution has been introduced. Two reasons can be put forward to sustain the existence of such an elastic crack tip enclave.^{4,5)} Firstly, all close to the crack tip in the

plastic zone, the displacement is certainly elastic at distances smaller than the mean separation distance between dislocation or than the size of the dislocation cells. Secondly, the image force attraction overcomes the crack repulsion for smaller radial distances from the crack tip. The introduction of an elastic enclave decreases the applied stress intensity factor, K_A . This so-called shielding effect results from the introduction of a dislocation free zone at the crack tip⁶⁾ in the BCS model.⁷⁾ The same observation is derived from the equilibrium of a continuous distribution of dislocations pushed away by a $r^{-1/2}$ stress field and slowed down by a constant yield stress (or a constant lattice friction stress). Since the shielding amplitude is strongly affected by the size of the dislocation free zone,⁸⁾ other physical considerations are needed to determine its extension: it could be, for instance, the halt of dislocation source activity below a minimum shear stress (or SIF, K_{min}). This is a microscopic parameter usually ignored in continuum mechanics. The shielding concept was, in fact, first introduced in a microscopic level before its applications were extended to continuum mechanics.^{9,10)} The isolated dislocation is considered as an internal loading with an associated SIF, K_d (Fig. 3). The effective SIF K_H is the algebraic addition of the applied K_A and of the shielding contribution K_D . The formalism was detailed for mode III and then extended to the general case and to crack opening.

3. Amount of Relaxation at Crack Tip

3.1 A first bi-dimensional approach

To calculate the stress intensity factor induced by the presence of a single dislocation, K_D , a first bi-dimensional model was used for an infinite dislocation parallel to the crack plane, as shown in Fig. 4, where the dislocations position parameters used in the mechanical analysis in the next paragraphs are defined.

3.1.1 The principle of superposition

With the aid of the superposition theorem and a weighting function one may assume (Fig. 5) that the dislocation in a continuum is equivalent to a cracked material loaded with a closing force $dF = -\sigma \cdot nd\alpha$ for $K_A = K_B = 0$ with σ being the stress imposed by the dislocation and n is a vector in x_2 -direction. Since $K(a) = K(b) = 0 = K(c) + K(d)$, the stress intensity factor is given by

$$K_d^A = \frac{1}{\sqrt{\pi\xi}} \int_{-\xi}^{+\xi} \sqrt{\frac{\xi+x}{\xi-x}} \sigma \cdot ndx. \quad (1)$$

For a semi-infinite crack, the stress intensity factor is given by^{11,12)}

Fig. 3 Bi-dimensional model used to calculate K_D —Mode III.

Fig. 4 Bi-dimensional case: straight and infinite dislocations parallel to the crack edge—Modes I and II.

Fig. 5 Evaluation of the shielding amplitude, using the superposition principle (2D situation).

$$K_J = \frac{k_{Jj} b_j}{2(1-\nu)} \frac{\mu}{\sqrt{2\pi r}}, \quad (2)$$

with

$$k_{I1} = k_{II2} = -\sin\theta \cos(3\theta/2), \quad (3a)$$

$$k_{I2} = -[2\cos(\theta/2) + \sin\theta \sin(3\theta/2)], \quad (3b)$$

$$k_{II1} = -[2\cos(\theta/2) - \sin\theta \sin(3\theta/2)], \quad \text{and} \quad (3c)$$

$$k_{III3} = -2(1-\nu) \cos(\theta/2), \quad (3d)$$

where the first index denotes the opening mode and the second one the Burgers vector component.

3.1.2 Forces acting on the dislocations

The above analysis assumes the dislocation is placed at a fixed distance. However, one cannot ignore the dislocation source problem and its kinetics, which is caused by temperature and by external work. What is needed is an analysis of the forces acting on the dislocation and its interaction with the crack, since the shielding effect diminishes as the dislocation increases its distance from the crack edge.

The force component following x_1 -direction acting on the dislocation is given by¹³⁾

$$F_1 = -\frac{\partial E_p}{\partial x_1} = -\frac{\partial E_d^s}{\partial x_1} + \frac{\partial W_{ad}}{\partial x_1}. \quad (4)$$

For an unloaded crack, if one assumes $\partial/\partial\xi = -\partial/\partial x_1$, the first term in the above equation may be expressed as

$$F_{11} = -\frac{\partial E_d}{\partial x_1} = \frac{\partial E_d}{\partial \xi} = -\frac{K_d^2}{H} = -G_d. \quad (5)$$

F_{11} is the image force component. Newton's third law being satisfied, the image force component along the x_1 -direction (attraction) is equal and opposite to the crack extension force (also attraction).

The F_{12} component is not as evident to be calculated. One proceeds from the dislocation image distribution function applied to the real dislocation towards the crack inner region for each opening mode J ,¹⁴⁾

$$f_J = 2 \frac{d\delta_J}{dx_1}, \quad (6)$$

where f_J is the distribution function in mode J and δ_J is the crack opening displacement induced by the dislocation, using the fact that $\int_{-\xi}^{+\xi} f_J(x_1) dx_1 = -b$. The force components are determined for each mode by summation of the interactions between the real dislocation and each infinitesimal dislocation arc of the distribution.

The second term represents the force due to the external field and can be expressed as

$$F_{a1} = -\frac{\partial W_{ad}}{\partial \xi} = -\frac{2K_a K_d}{H}. \quad (7)$$

This interaction term is a function of K_a , hence the distance of the application point of load P to a point on the crack surface. The above made assumption that $\partial/\partial\xi = -\partial/\partial x_1$ is no longer valid if the distance between dislocation and the point on the crack surface is not small when compared to the preceding distance.

This relation shows that the dislocations shielding the crack ($K_a K_d < 0$) are displaced towards the positive side of the x_1 axis and the dislocations inducing an anti-shielding effect on the crack ($K_a K_d > 0$) are displaced towards the inverse sense if the slip plane is parallel to the crack plane.

Figure 6 illustrates this remark. The crack is substituted by a stacking of fictitious dislocations (represented by the bigger symbols in Fig. 6(a)). To place a real dislocation in front of the crack (Figs. 6(b) and (c)) consists of the introduction of an image distribution (smaller symbols) for which the Burgers vector is null and hence the sign is chosen to globally attract the real dislocation.

One observes that the stress concentration is weaker in case (b) than in case (a), the real dislocation is repulsive since the image force is directed towards the positive side of axis x_1 . The stress concentration is stronger in case (c) than in case (a) and the image force is always attractive towards the crack.

The preceding conclusions apply once the F_{a2} component does not play a significant role in the process, *i.e.*, once the dislocation slides within a plane parallel to the crack plane. This imposes an orientation on the crystallographic scheme and, in part, on the loading modes (essentially, modes II and III). Once the slip planes are inclined, the F_{a2} component may be relevant.

It is important to remark that all bi-dimensional analyses

Fig. 6 Crack dislocation interaction forces.

assume the dislocations slide within a plane containing the crack edge. However, the probability of this occurrence is really faint. Experimental observations made by the Nancy Group reveal plastic zones composed of dislocation loops in planes that are oblique to the crack edge (see Fig. 7).

3.2 The three-dimensional approach

In the reference system xyz linked to the crack shown in Fig. 7, x is the direction of propagation, y is the direction normal to the crack plane and z is the direction normal to the large faces of the sample. The origin is fixed at point of emission, E , of the dislocation, *i.e.*, the source position on the crack edge. Let the infinitesimal forces dP , dR and dQ act on point M with coordinates $(x, 0, z)$ which lies on the crack surface (the semi-infinite plane $x < 0$ shown in Fig. 8) and surrounded by the infinitesimal area $dx \cdot dz$. The infinitesimal stress intensity factors dK_I , dK_{II} and dK_{III} induced at a point N on the crack edge ($x = y = 0, z = z_0$) are given by

$$dK_I = \frac{\sqrt{2}}{\pi^2} dP F_1, \quad (8a)$$

$$dK_{II} = \frac{\sqrt{2}}{\pi^2} \left\{ dQ F_1 + \frac{2\nu}{2-\nu} [dQ F_2 + dR F_3] \right\} \quad \text{and} \quad (8b)$$

$$dK_{III} = \frac{\sqrt{2}}{\pi^2} \left\{ dR F_1 + \frac{2\nu}{2-\nu} [dQ F_3 + dR F_2] \right\}, \quad (8c)$$

where one has the weighting functions.¹⁵⁾

Fig. 7 X-ray topography showing a three-dimensional feature of the dislocation loop; (b) definition of the position of the dislocation loop with respect to the crack plane.

Fig. 8 The reference systems with respect to the crack.

$$F_1 = \frac{\sqrt{-x}}{x^2 + (z_0 - z)^2}, \quad (9a)$$

$$F_2 = \frac{\sqrt{-x}[x^2 - (z_0 - z)^2]}{[x^2 + (z_0 - z)^2]^2} \quad \text{and} \quad (9b)$$

$$F_3 = \frac{2(z_0 - z)\sqrt{-x^3}}{[x^2 + (z_0 - z)^2]^2}. \quad (9c)$$

If σ_{yx} , σ_{yy} and σ_{yz} are the stress components induced at a point $M(x, 0, z)$ of an infinite continuum medium by a dislocation loop emitted at E , the superposition theorem leads to $dP = +\sigma_{yy}(dx dz)$, $dQ = +\sigma_{yx}(dx dz)$ and $dR = +\sigma_{yz}(dx dz)$. Integrating the above equations over the area of a semi-infinite crack one can determine the stress intensity factor at a point $N(0, 0, z_0)$, z_0 being the distance between points N and E . This can be found in the form

$$K_I(z_0) = \frac{\sqrt{2}}{\pi^2} \int_{-\infty}^0 \int_{-\infty}^{+\infty} \sigma_{yy} F_1 dx dz, \quad (10a)$$

$$K_{II}(z_0) = \frac{\sqrt{2}}{\pi^2} \int_{-\infty}^0 \int_{-\infty}^{+\infty} \left\{ \sigma_{yx} \left[F_1 + \left(\frac{2\nu}{2-\nu} \right) F_2 \right] + \left(\frac{2\nu}{2-\nu} \right) \sigma_{yz} F_3 \right\} \quad \text{and} \quad (10b)$$

$$K_{III}(z_0) = \frac{\sqrt{2}}{\pi^2} \int_{-\infty}^0 \int_{-\infty}^{+\infty} \left\{ \sigma_{yz} \left[F_1 - \left(\frac{2\nu}{2-\nu} \right) F_2 \right] + \left(\frac{2\nu}{2-\nu} \right) \sigma_{yx} F_3 \right\}. \quad (10c)$$

One must remember that the stress components are given by¹⁶⁾

$$\begin{aligned} \sigma_{\alpha\beta} = & -\frac{\mu}{8\pi} \oint_C b_m \varepsilon_{im\alpha} \frac{\partial}{\partial X'_i} \nabla'^2 R dX'_\beta - \frac{\mu}{8\pi} \oint_C b_m \varepsilon_{im\beta} \frac{\partial}{\partial X'_i} \nabla'^2 R dX'_\alpha \\ & - \frac{\mu}{4\pi(1-\nu)} \oint_C b_m \varepsilon_{imk} \left(\frac{\partial^3 R}{\partial X'_i \partial X'_\alpha \partial X'_\beta} - \delta_{\alpha\beta} \frac{\partial}{\partial X'_i} \nabla'^2 R \right) dX'_k. \end{aligned} \quad (11)$$

3.2.1 Integration technique

The above equation for the stress components may be recognized to follow a pattern (see Appendix in Ref. 16))

$$\int_{+\frac{\pi}{2}}^{-\frac{\pi}{2}} \frac{f(\eta) d\eta}{R_0^k \Delta^k}, \quad (12)$$

which are expressed in terms of complete elliptic integrals of the first and the second kind, generally denoted by $K(p)$ and $E(p)$, where p is a geometric parameter relating the size of the loop and the position of a point $M(x, 0, z)$ relative to the loop in the range $0 \leq p \leq 1$. By an adequate arrangement of those equations, all stress components can be determined as functions of parameter p , thus creating a surface defined

over the semi-infinite plane $x \leq 0$ for each stress component. Since even p is determined over that plane, a surface is obtained for several values of p , leading to the term *iso-p contours*.

With the iso-p contours (see Fig. 9 for an experimental case analyzed in this work), a mesh is obtained and the stress components are analytically determined at each node. This result may be used arbitrarily to suitably interpolate the stresses. The stress intensity factors K_I are, then, numerically integrated over the area influenced by the loop stress field for points equally spaced along the crack edge.

3.2.2 Dislocation growth criteria

The necessary condition for the growth of a loop under the applied stress field is expressed by

$$\mathbf{F} \cdot (\xi \times \mathbf{Z}) < 0, \quad (13)$$

where ξ is a unit vector for a clockwise line orientation around the normal to the slip plane $\mathbf{Z}$, where the Peach-Kohler force $\mathbf{F}$ per unit length of dislocation equals $\sigma \cdot \mathbf{b} \times \xi$. This growth condition is restricted to

$$\tau = \mathbf{Z} \cdot (\sigma \cdot \mathbf{b}) > 0. \quad (14)$$

In the coordinate system attached to the crack geometry (see Fig. 10), with the crack front z and crack propagation direction x normal to the crack plane y , each component of stress around the crack tip has the form

$$\sigma_{ij} = \frac{K_I f_{ij}(\phi)}{\sqrt{2\pi r}}, \quad (15)$$

where r and ϕ are the polar coordinates of the point being considered. The isotropic angular function $f_{ij}(\phi)$ can be found in.¹⁷⁾ The resolved shear stress τ is derived from this tensor as

$$\tau = \frac{K_I H(\Phi)}{\sqrt{2\pi R}}, \quad (16)$$

where R and Φ are the polar coordinates in the slip plane (where $F = 0$ along X , which is the intersection between the glide plane and the crack plane). The result of the calculations are given in the form of equal resolved shear stress contours (ERSSC) with (see Fig. 11)

$$G(\Phi) = |H(\Phi)|^2, \quad (17)$$

Where $G(\Phi)$ is a function representing the equal stress contours.

Fig. 9 Iso-p contours along the crack edge where ρ' is the diameter of the dislocation loop.

Fig. 10 Definition of the coordinate systems attached to the crack geometry (x, y, z) and to the glide plane orientation (X, Y, Z).

Fig. 11 Iso-stress contour in the slip plane for the case analyzed in this work. Solid lines indicate the position of positive stresses and dashed lines the negative stresses (where loops do not grow).

A positive, or negative sign is assigned to each lobe of these highly anisotropic contours indicating that the loop is growing (or shortening) for that particular (b, Z) or $(-b, -Z)$ couple.

The previous qualitative description for mode I can be generalized: since shielding is necessarily associated with the dislocation displacement field u , three different opening modes ($J = \text{I, II or III}$) can be induced according to the u -direction. The shielding condition $K_a K_d < 0$ still holds true for each mode where K_a and K_d stand for the stress intensity factors induced by the external loading and the dislocation, respectively, for each mode J . For an infinite parallel to z , of Burgers vector b , located at (r, ϕ) , the latter can be expressed in the following way

$$K_d^J = \frac{\mu b_j k_{Ji}(\phi)}{2(1-\nu)\sqrt{2\pi r}}. \quad (18)$$

The ϕ dependent matrix coefficients $k_{Ji}(\phi)$ for a semi-

infinite crack can be found in.^{11,12)}

3.2.3 An example of shielding calculation

The following case was observed experimentally in mono-crystal silica samples, the Burgers vector being characterized by X-ray techniques associated with etch pits in the induced plastic region. Configuration is as shown in Fig. 7(b) with an inclined loop in an inclined plane for a Burgers vector $\mathbf{b} = (a/2)[101]$ and

$$\mathbf{x} = [\bar{1}10], \quad \mathbf{z} = [\bar{1}\bar{1}2], \quad \mathbf{Z} = [\bar{1}11], \quad (19)$$

for a position angle $\alpha = 30^\circ$.

This is a general condition, with no symmetries implied. Neither the Burgers vector nor the loop center lay on the crack propagation plane. Figure 9 shows a curve of iso-stress characterizing the relative position of the loop for which resolved stress $\tau > 0$, a condition for the loop expansion.

Figure 12 shows the shielding distribution $K_d(z_0)$ along the crack edge in reduced coordinates for the three opening modes. There, one notices that, in mode I, $K_{dI} < 0$, thus characterizing shielding. Also, in mode III, $K_{dIII} > 0$ and, in mode II, a change in sign occurs. Remarkable localized aspect of shielding is observed around the emission point. This indicates that, in order to effectively protect the crack against brittle fracture, one must have an adequate distribution of emission sources along its width such that the average value of shielding be significant. The curve shown is for a $\rho' = 50b$. When this value is increased, so does shielding and the localized effect becomes stronger, such that its average value alongside the crack edge does not change. Calculations show that the distance affected by the loop varies about $\rho^{3/4}$.

Contrary to the bi-dimensional model, the plastic zone development increases K_d , since the considered loops expand but keep their shielding segments close to the crack edge due to the strong attraction acting on them. However, distant segments keep moving away from the crack.

Studies made on the growth dynamics and the loop multiplication mechanism^{19,20)} point out that one sole emission source can multiply itself and provoke the appearance of other sources along the crack edge neighborhood. This is caused by the cross-slip effect occurring in adjacent slip planes. The loop segments sliding on other planes may touch the crack edge on a different point thus producing a step effect that gives rise to a new emission source. This phenomenon of

multiplication results in an avalanche of emission sources that may accelerate the material brittle-ductile transition by the rapid growth of the plastic zone.

3.3 Relaxation rate due to the emitted loop

The magnitude of the image force f_i on the loop of dislocation is

$$f_i = G_d = \frac{\int K_D^2(z_0) dz_0}{H}. \quad (20)$$

For the analyzed case, one observes the localized effect of this image force over the emission point.

The total crack extension force, G , is the summation of all external forces due to the applied field, G_a , the image force due to the loop dislocation in all opening modes J , G_d , and the variation of the deformation energy

$$G = \sum_J G_{aJ} + \sum_J G_{dJ} + \frac{\partial}{\partial \xi} (P \cdot \delta_{dJ})' = \sum_J \frac{(K_{aJ} + K_{dJ})}{H_J}. \quad (21)$$

For a mode I loading condition, one has

$$\begin{aligned} G &= \frac{(K_{aI} + K_{dI})^2}{H_I} + \frac{K_{dII}^2}{H_{II}} + \frac{K_{dIII}^2}{H_{III}} \\ &= G_A + \sum_J \frac{K_{dJ}}{H_J} + 2 \frac{K_A K_{dI}}{H_I}. \end{aligned} \quad (22)$$

One can make

$$\frac{G - G_a}{G_a} = \frac{\Delta G}{G_a} = \left(\sum \frac{k_{dJ}^2}{H_J} + 2 \frac{k_{dIII}^2}{H_{III}} \right) \frac{G_o}{G_a}, \quad (23)$$

with $G_o = \mu\sqrt{b}$, $K_{dJ} = G_o k_{dJ}$ and $K_A = G_o k_a$. The relaxation rate depends on z and in the loop size. Shielding may occur if one considers $k_{dI} < 0$ and to attain relaxation one must have a meaningful k_{dI} when compared with $\sum k_{dJ}^2$. Since $k_{dI} < 1$, $\sum k_{dJ}^2$ are equivalent to second order magnitude. However, this may not be true for large loops. As a consequence, the existence of different modes from the plastic zone induced opening mode may affect total relaxation. This implies that shielding effect may be sensibly reduced or even nullified by parasite induced modes even if the acting opening mode leads to a shielding effect.

The average relaxation rate along the crack edge is

$$\left(\frac{\Delta G}{G_a} \right)_{av} = \frac{1}{L} \int_{-\frac{L}{2}}^{+\frac{L}{2}} \frac{\Delta G}{G_a} dz. \quad (24)$$

For the example being analyzed, Figs. 13 and 14 shows the reduced crack extension force and the relaxation rate curves for different values of the applied stress field, with $k_a = \frac{K_a}{G_o}$.

Since the intensity and the sign of K_{dJ} , be it in the acting (Mode I in the equation) or in the parasite modes (II and III), are functions of the loop position in the slip plane, one verifies that a given Burgers vector may induce a shielding effect in an angular sector while inducing an anti-shielding effect on another, as shown in Fig. 15 (see Ref. 2)), where the calculations have indicated a shielding effect for the right side sector and anti-shielding for the left side sector for the same Burgers vector and the same slip plane.

Fig. 12 Reduced shielding distribution along the crack front for the different opening modes I, II and III.

Fig. 13 Reduced crack extension force as a function of distance along the crack front.

Fig. 14 Relaxation $(G - G_a)/G_a$; k_a are the reduced applied stress intensity factor.

Fig. 15 Different positions for the loop dislocation in the same slip plane.

3.4 Dislocation emission criteria

One of the problems to be solved in the nucleation and the development of a plastic zone is to answer some sliding systems are activated and others remain inactive, that is, what

criterion determines the emission of a dislocation loop within certain gliding system and in a certain position.

A Schmidt factor criterion was used by Michot and George²¹⁾ where equal-stress contours were employed, as shown in Fig. 11 in the example treated herein. In this criterion was proposed that the system preferentially nucleated would that presenting the greater stress. However, this criterion was not in agreement with a great number of experimental observations. Besides, the criterion does not take into account the non-homogeneity of the shear stress acting on the slip plane. Hence, a new criterion was proposed in which the work done by the applied forces to develop a loop, W , was used. It was considered the initial formation of the loop when the dislocation is supposed to form a circular ring. In the experiments, it was observed that the loop so formed was fixed to a point on the crack edge, for which the work was obtained by integrating the expression $\delta^2 W = \tau b R dR d\phi$ resulting in

$$W = \eta(\alpha) K_1 b \rho^{3/2}, \quad (25)$$

where ρ' is the loop radius and

$$\eta(\alpha) = \frac{2}{\pi} \int_{-\pi/2+\alpha}^{+\pi/2+\alpha} H(\Phi) \cos(\Phi - \alpha)^{3/2} d\Phi \quad (26)$$

is a function of the dislocation loop, as shown in Fig. 16.

This criterion has proved to be still inadequate, since it ignores the line energy induced by the variations on the different orientations assumed by the loop relative to the crack free surface. Oliveira²⁾ proposed an emission criterion based on the maximum relaxation, that is, the loop emission is the one that produces the greatest possible relaxation rate. The first results have shown that this criterion is certainly indicative but not necessarily fulfilled in practice, since shielding is totally independent of the applied stress field.

An optional emission direction must result from the minimization of the balance between the elastic energy of the loop and the work done by the external forces.

4. Conclusions

The understanding of the shielding mechanism induced by plastic zone is extremely important in predicting the mechanical behavior of cracked samples. The experimental proof is shown in Fig. 17, in which one can see the apparent toughness variation of a pre-deformed material. The plastic zone emission at the crack edge and its influence on the brittle-ductile transition of the material asks for a thorough investigation and

Fig. 16 Elementary work integration principle.

Fig. 17 Evolution of the material toughness with the level of pre-deformation (creep conditions) at the crack tip.

a broader consideration in the modeling process, such as a detailed three-dimensional formulation to allow the conditions for the emission, the development the multiplication and the saturation phases to take place. It is believed that a criterion based on energy minimization should be pursued.

REFERENCES

- 1) A. A. Wells: B.R. Weld J. **10** (1963) 563–570.
- 2) M. A. Loyola de Oliveira: PhD Thesis, INPL, France (1994).
- 3) N. Louat and K. Sadamanda: Acta Metall. Mater. **40** (1992) 2677–2682.
- 4) J. Weertman: Acta Metall. Mater. **26** (1978) 1731–1738.
- 5) R. Thomson: J. Mater. Sci. **13** (1978) 128–142.
- 6) S. J. Chang and M. Ohr: J. Appl. Phys. **52** (1981) 7174–7181.
- 7) A. B. Bilby, A. H. Cottrell and K. H. Swinden: Proc. Roy. Soc. A **272** (1968) 304–314.
- 8) J. R. Rice and R. Thomson: Philos. Mag. **29** (1974) 73.
- 9) B. S. Majumdar and S. J. Burns: Int. J. Fract. **21** (1983) 229.
- 10) G. Michot: Trans. Tech. Publ. **17–18** (1989) 55–98.
- 11) H. O. K. Kirchner and G. Michot: Mater. Sci. Eng. **79** (1986) 169.
- 12) I.-H. Lin and R. Thomson: Acta Metall. **34** (1986) 187.
- 13) G. Michot, M. A. Loyola de Oliveira and A. George: Mater. Sci. Eng. **A176** (1994) 99–109.
- 14) J. C. M. Li: Dislocation in Solids, Some Recent Advances—AMD **63** (1986) 35–43.
- 15) G. C. Sih and H. Liebowitz: Philos. Mag. A **64**, 4 (1991) 931–934.
- 16) J. P. Hirth and J. Lothe: *Theory of Dislocations*, 2nd Ed. (Krieger Pub., Malabar, 1982).
- 17) M. A. Loyola de Oliveira: Acta Mater. **46** (1998) 1371.
- 18) A. George and G. Michot: Mater. Sci. Eng. A **164** (1993) 118.
- 19) A. L. P. Amaral: MSc Thesis, UFES, Brazil (1998).
- 20) G. Michot and M. A. Loyola de Oliveira: Mater. Trans. **42** (2001) 14–19.
- 21) G. Michot and A. George: Inst. Phys. Conf. Series **104** (1989) 385–396.