EFFECT OF CLEAVAGE PLANES ORIENTATION ON LOCAL STRENGTH OF SPHEROIDIZED STEEL

B. Strnadel[x], E. Mazancová[xx], K. Mazanec[x]

This paper examines how the local cleavage strength of spheroidized steels depends on the orientation of cleavage planes in the matrix, relative to the applied stress. This work has led to the formulation of a new criterion for the propagation of microcracks, nucleated in carbide particles, into the matrix. The criterion implies a certain limit for the angular misalignment or disorientation between the perpendicular to the cleavage plane and the applied stress direction; when the angle exceeds this limit, the microcrack can no longer spread across the carbide-ferrite interface.

INTRODUCTION

Many low-temperature failures of spheroidized ferritic steels are caused by transgranular cleavage. Low-temperature transgranular cleavage of these steels has been experimentally proved to be initiated by slip-induced microcracking of carbides. During local plastic deformation, some carbides crack; but this cracking leads to cracking of the matrix only if the applied

[x] Institute of Metals Science, Technical University of Ostrava, 708 33 Ostrava, Czechoslovakia
[xx] Research Institute, The New Metallurgical Works, 707 02 Ostrava-Kunčice, Czechoslovakia

stress exceeds the local cleavage strength, defined by Curry and Knott (1) as:

$$\sigma_f(2r) = [\pi E \gamma_{eff}/[2(1-\nu^2)r]]^{1/2} \quad (1)$$

where 2r is the size of a microcrack nucleated in a carbide; γ_{eff} is the effective surface energy of the matrix; E is Young's modulus; and ν is Poisson's ratio. However, not all carbide particles where microcracks have nucleated are equally effective cleavage sources. If the cleavage planes in the matrix are favourably orientated relative to the cleavage plane in the carbide particle, the microcrack will cross the particle-matrix interface more easily than where there is substantial misalignment between these planes. An equally important factor for the spread of microcracks across a particle--matrix interface is the orientation of the perpendicular to the $\{100\}_F$ cleavage plane relative to the direction in which the applied stress is acting.

LOCAL CLEAVAGE STRENGTH

Equation (1) presents a local criterion for the propagation of a microcrack from the carbide particle where it was nucleated into the ferrite matrix: the applied stress σ must not be smaller than $\sigma_f(2r)$. This criterion, however, is valid only if applied stress acts in a direction perpendicular to the cleavage plane is at an angle β to the direction of the applied tensile stress, as is indicated in Figure 1, then only the normal component of that stress, σ_N, will assist microcrack propagation:

$$\sigma_N = \sigma \sin\alpha \cos\beta = \sigma \cos^2\beta \quad (2)$$

where $\alpha = \pi/2 - \beta$ is the angle between the local stress direction and the projection of that direction into the cleavage plane. It follows from equations (1) and (2) that for every magnitude of σ there is a certain critical size of microcracks at which they can spread from the carbide particle where they were nucleated into the matrix:

$$2r_f(\sigma_N) = \pi E \gamma_{eff} / [(1-\nu^2)\sigma^2 \cos^4\beta] \qquad (3)$$

In other words, if the local tensile stress around the carbide particle surpasses $\sigma_f(2r)$, cleavage may take place even in planes with perpendiculars offset from the applied stress direction by an angle of $\beta > 0$. However, if a microcrack is to spread into the matrix, this angle must not exceed a certain limit, β_{max}, which equation (2) suggests is dependent on the size of the largest carbide particle or of the microcrack nucleated in that largest particle:

$$\beta_{max} = \arccos[\sigma_f(2r_{max})/\sigma]^{1/2} \quad \text{for} \quad \sigma_f(2r_{max}) < \sigma \qquad (4)$$

As long as $\sigma_f(2r_{max})$ remains greater than σ, the microcrack will not cross the particle-matrix interface, i.e., it will remain stationary.

ELEMENTARY PROBABILITY OF CLEAVAGE AHEAD OF A PRE-CRACK TIP

Figure 1 shows the situation where the perpendicular to the cleavage plane P, with a random orientation relative to the direction in which tensile stress σ is acting, is projected uniformly into a sphere of unit radius $\vec{e}$. Obviously, the elementary probability of misalignment angle $\Psi(\beta)d\beta d\omega$ is proportional to the elemental area $e^2 \sin\beta d\beta d\omega$. This yields the following expression for the probability density of a misalignment or disorientation angle:

$$\Psi(\beta) = D\sin\beta \qquad (5)$$

Constant D can be derived from the normalization condition:

$$\int_0^{\beta_{max}} \Psi(\beta)\,d\beta = 1 \qquad (6)$$

Insertion from equation (5) into equation (6), and application of equation (4), now renders:

$$\Psi(\beta) = \sigma^{-1/2}\left[\sigma^{-1/2} - \sigma_f^{-1/2}(2r_{max})\right]^{-1} \sin\beta \qquad (7)$$

Godse and Gurland (2) have formulated the probability density of the size of microcracks nucleated in carbide particles, at any given magnitude of applied stress σ, as a function of the probability density of the carbide particle size $\varphi(2r)$, as follows:

$$\xi(2r) = \varphi(2r)\left[1 - \phi(2r_f(\sigma))\right]^{-1} \qquad (8)$$

where $\phi(2r_f(\sigma)) = \int_0^{2r_f(\sigma)} 2\varphi(2r)$ is the distribution function of the carbide particle size.

If we assume that the radial and tangential components of the stress field ahead of a pre-crack tip conform to the elastic-plastic model devised by McMeeking (3),

$$\sigma_i(x,\theta) = \sigma_Y\left[\left(\frac{1-\nu^2}{I_N}\right)\left(\frac{K_I}{\sigma_Y\sqrt{x}}\right)^2\right]^{1/(N+1)} \tilde{\sigma}_i(N,\theta) \quad \text{for} \quad 2\delta \leq x \leq 10\delta \qquad (9)$$

then the isostressed volume element ahead of a pre--crack tip, as indicated in Figure 2, is defined by

$$\delta V_i(\sigma) = \frac{2(N+1)bK_I^4(1-\nu^2)^2\sigma_Y^{2(N-1)}\delta\sigma}{I_N^2\,\sigma^{(2N+3)}} \int_0^{\pi} \left[\tilde{\sigma}_i(N,\theta)\right]^{2(N+1)} d\theta \qquad (10)$$

where index $i=x,\theta$ denotes the radial and tangential directions of the stress components; b is the characteristic width of the fracture front, which according to Evans (4) equals several grain sizes; K_I is the stress intensity factor; N is the work hardening coefficient, which can assume any value between unity and infinity; I_N is a dimensionless parameter; and $\tilde{\sigma}_i(N,\theta)$ is an angular function dependent on the work hardening coefficient. We can now assess the elementary probability that at least one of the microcracks in volume $\delta V_i(\sigma)$ ahead of a pre-crack tip will spread into the matrix: in the first approximation, it follows from the preceding considerations that this will be

$$\delta F^{i}(\sigma) = \exp\left[-2N_{Vp}\delta V_i(\sigma)\int_{2r_f(\sigma)}^{2r_{max}}\int_0^{\arccos[\sigma_f(2r)/\sigma]^{1/2}} \xi(2r)\Psi(\beta)\,d\beta\,dr\right] \tag{11}$$

where $N_{Vp} = N_V f_p [1-\phi(2r_f(\sigma))]$ is the volume density of microcracks nucleated in an isostressed volume element defined by $\delta V_i(\sigma)$; N_V is the volume density of carbide particles there; and f_p is the fraction of eligible microcracks participating in the fracture process.

CHARACTERISTIC DISTANCE

The first accepted definition of the characteristic distance was that distance, ahead of a pre-crack tip, over which redistributed applied stresses exceed the cleavage strength (5). Evans (4) modified this to mean the radial dimension, from the pre-crack tip, where the initial cracking event is most probable. This concept enables us to determine the characteristic distance from the following condition:

$$\frac{d\delta F^{i}(\sigma)}{d\sigma}\,\frac{d\sigma}{dx} = 0 \tag{12}$$

Insertion from equations (7) and (8) into equation (11) then allows us to derive from equation (12) the following relationship for characteristic distance x^{*}:

$$\int_{2r_f(\sigma)}^{2r_{max}} 2\sigma_f^{1/2}(2r)\varphi(2r)\,dr = \sigma^{1/2}\left[1-\phi(2r_f(\sigma))\right]\frac{[(4N+5)/(4N+6)]\sigma_f^{-1/2}(2r_{max}) - \sigma^{-1/2}}{\sigma_f^{-1/2}(2r_{max}) - [(4N+7)/(4N+6)]\sigma^{-1/2}} \tag{13}$$

If we transfer the right-hand side of this last equation to its left side, we can, for $\sigma_f(2r_{max}) \ll \sigma$, define the following function:

$$R(x^{*},T) = \int_{2r_f(\sigma)}^{2r_{max}} 2\sigma_f^{-1/2}(2r)\varphi(2r)\,dr + \frac{4N+6}{4N+7}\sigma^{-1/2}\left[\phi(2r_f(\sigma))-1\right] \tag{14}$$

Function R is dependent on temperature T because σ is a function of $\sigma_Y(T)$, as follows from equation (9), and

$\sigma_f(2r)$ is a function of $\gamma_{eff}(T)$. The local differential of function R implies that

$$\frac{dx^*}{dT} = \frac{U_1(x^*,T)\,\frac{\partial \sigma_Y}{\partial T} - U_2(x^*,T)\,\frac{\partial \gamma_{eff}}{\partial T}}{\frac{\partial \sigma}{\partial x^*}} \tag{15}$$

where $U_1(x^*,T)$ and $U_2(x^*,T)$ are positive functions of the characteristic distance and of the temperature. Since we know that $(\partial \sigma_y)/(\partial T) < 0$, $(\partial \gamma_{eff})/(\partial T) > 0$, and $(\partial \sigma)/(\partial x^*) < 0$, we may infer from equation (15) that the characteristic distance grows with the temperature.

DISCUSSION AND CONCLUSIONS

This paper analyses the conditions governing the propagation of microcracks from the carbides where they were nucleated into the matrix. The approach differs from previous (1), (2) and (4) by taking into account not only the size of the nucleated microcracks, but also the way the orientation of potential cleavage planes in the matrix affects the local strength. The authors adopt a new parameter: the misalignment between the perpendicular to a potential cleavage plane and the direction in which the applied stress is acting. They show, in equation (3), that this factor can substantially increase the critical size of microcracks. In other words, microcrack propagation into the matrix is facilitated, and hence the critical microcrack size is diminished, when this misalignment between the stress direction and the perpendicular to a potential cleavage plane is small. On the assumption that the orientation of potential cleavage planes in a matrix is entirely random, the authors have established the probability density of a misalignment angle or disorientation angle β. This figure and the probability density of microcrack sizes nucleated in carbide particles are then exploited for calculating the elementary probability of cleavage occurring in an isostressed volume element ahead of a pre-crack tip, for the radial and the tangential stress components, by means of equation (11). The conditions underlying the characteristic distance calculations were derived from the Evans concept (4), as is evident in equation (13).

REFERENCES

(1) Curry, D.A. and Knott, J.F., Metal Sci., Vol.12, 1978, pp. 511-514.

(2) Godse, R. and Gurland, J., Acta Metall, Vol.37, 1989, pp. 541-548.

(3) McMeeking, R.M., J. Mech. Phys. Solids, Vol. 25, 1977, pp. 357-381.

(4) Evans,A.G.,Metall.Trans.A,Vol.14A,1983,pp.1349-1355.

(5) Ritchie,R.O., Knott, J.F. and Rice, J.R.,J. Mech. Phys. Solids, Vol. 21, 1973, pp. 395-410.

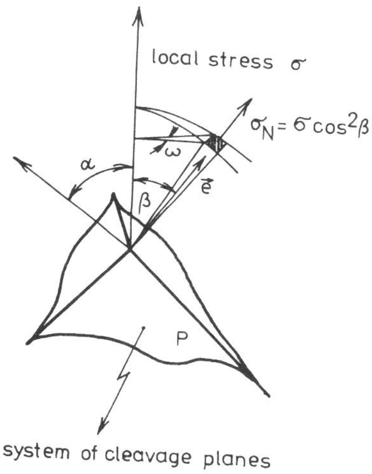

Figure 1 Scheme of cleavage plane orientation

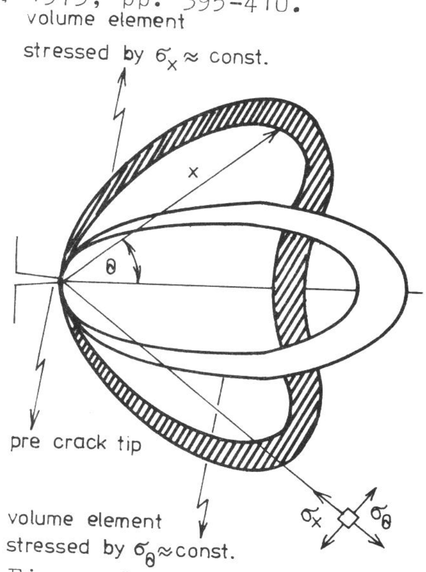

Figure 2 Scheme of iso-stressed volume elements