A PROBABILISTIC MODEL FOR CLEAVAGE FRACTURE OF POLYCRYSTALLINE METALS CONTAINING A DISPERSION OF BRITTLE PARTICLES

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A probabilistic "weakest link" type brittle fracture model has been developed accounting for microcrack nucleation from slip-induced cleavage of a particle or inclusion, propagation to the surrounding grain and subsequent propagation to neighbouring grains. The model is intended for making microstructure-based fracture analysis with a local approach. An application of the model to the prediction of the critical cleavage fracture stress of a bainitic steel is presented.

INTRODUCTION

The origin of brittle fracture of polycrystalline metals failing by cleavage is most frequently associated to the slip-induced cracking of some non-metallic brittle particle or inclusion (a carbide in ferritic steels). When the size of the particles is under the grain size of the metallic matrix, the nucleating event of a macroscopic failure results from the successive ocurrence of three simple events: slip-induced cleavage of a particle, transmission of the microcrack to the neighbouring grain across the particle/matrix interface and propagation of the grain-size microcrack to the neighbouring grains across the grain boundaries. On the basis of this scheme, a statistical "weakest link" fracture model has been developed that takes into account the presence of two independent distributions of structural elements, isolated particles and matrix grains, with two barriers for cleavage propagation, the particle/matrix interfaces and the grain boundaries, characterized by a crack arest capability well

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over the crack propagation resistance on the cleavage planes of the crystalline lattices of the two phases. An application of the model to the prediction of the fracture stress of a bainitic steel is presented.

A relatively large number of statistical models for brittle fracture of polycrystalline metals have been already published (e.g., Curry and Knott(1), Beremin (2), Wallin et al. (3), Strnadel et al. (4), Lin et al. (5) and Godse and Gurland (6)). Most of them assume macroscopic failure to be propagation-controlled (ref. (6) represents an exception) and, in general, the critical stress or toughness level of the material at a given temperature is assumed to be dominated by the size-distribution of one particular constituent of the microstructure, the carbide size or the grain size, with the other constituents playing an indirect or minor role. In the present model, the nucleation event is associated to the particle distribution and particles and grains play a combined role at the propagation stage. Thus, it represents a generalization in respect to most previously published models.

OUTLINE OF THE MODEL

On the "weakest link" hypothesis, the "active zone" of the piece or specimen under load (its plastic zone) is divided in a number of volume elements, δV, so that the failure of one of them causes the macroscopic failure of the piece. Each volume element is characterized by its stress state, σ_{ij} (K), where K represents the macroscopic loading state, and by its plastic state, $\bar{\epsilon}$ (K). Let N_v^m be the number of potential failure nuclei of type m per unit volume and F_m the failure probability of the nuclei m under the local stress σ_{ij} in the active zone. The failure probability of the piece is

$$\phi(K) = 1 - \exp\left[-\int_0^V \sum_m N_v^m \, F_m [\sigma_{ij}(K), \bar{\epsilon}(K)] \, dV\right] \qquad (1)$$

where the integral is extended to the "active volume".

Microcrack Nucleation

With the exception of the most brittle cases (some hexagonal and refractory metals), cleavage failure is initiated in metals by the slip-induced cracking of a non-metallic particle. For fine particles, the cracking is not solely determined by the applied stress, σ_{ij}, but rather by the microstresses associated with local strain heterogeneities. Then, the probability of fracture of a particle will depend on its size, c, on the plastic state and on the size of the grain which contains the particle, D:

$$p = p\,(\sigma_{ij},\ \epsilon,\ c,\ D) \qquad (2)$$

The actual form of (2) is unknown. For fine particles, we have assumed that their fracture is mainly a consequence of their intersection with slip bands, which gives a direct proportionality of p on particle size, c:

$$p = \alpha c/\bar{c} \quad , \quad c \le \bar{c}/\alpha \qquad (3)$$

$$p = 1 \quad ; \quad c > \bar{c}/\alpha$$

Microcrack propagation

Microcrack propagation from the particle to the metallic matrix or across the matrix grain boundaries is assumed to be driven by the local stress state. Spherical shape of the particles or grains has been assumed so that microcracks are penny-shaped. In general, the local stress state induces mixed modes of loading on the microcrack and propagation has been considered to occur for any overcritical size, t

$$t > t^* = (\beta\, K^B_{Ia} / \sigma_{eff})^2 \quad , \quad \beta = 1{,}25 \qquad (4)$$

where K^B_{Ia} is the local stress intensity factor for crack arrest corresponding to the concerned boundary (Hahn, (7)). A critical energy release rate criterion under mixed mode conditions is assumed so that the effective stress for the penny-shape crack is, in the absence of anisotropic effects.

$$\sigma_{eff}\,(\sigma_n > 0) = [\sigma_n^2 + (4\,\tau^2/(2 - \nu)^2]^{1/2} \qquad (5)$$

σ_n and τ being, respectively, the resolved normal and shear stresses on the crack face (Shih, (8)).

Random orientation of the crack nuclei has been considered, although, for simplicity, coplanar crack propagation has been assumed. For any particular crack orientation, the failure probability is then,

$$\phi = 1 - \exp\left[-\int^{V} [N_v^g F_g\,(c^* \le c \le D^*) + N_v^c\, F_c\,(c \ge D^*)]\ dV\right]$$

$$F_g(c^* \le c \le D^*) = \int_{D^*}^{\infty}[1-\exp[-N_v^c \frac{\pi\, D^3}{6}\, F_c(c^* \le c < D^*)]]\,m(D)\ f_g(D)\ dD$$

$$F_c\ (c^* < c \le D^*) = \int_{c^*}^{D^*} p(c)\ m(c)\ f_c(c)\ dc \qquad (6)$$

where f_g and f_c are the size distribution functions (diameters in volume) of, respectively, carbides and grains and m is an orientation factor related with the position randomness of the cracks in the particles or grains.

The critical sizes c^* and D^* are calculated according to eq. (4). Obviously, when the crack arrest capacity of the grain boundaries, $K^{f/f}_{la}$ is not higher than that of the particle/matrix boundary, $K^{c/f}_{la}$, only the particle size distribution is decisive for the failure load, the grain size distribution playing no role.

APPLICATION

The model has been applied to the prediction of the critical cleavage stress, σ_f, of a 533B bainitic steel when measured in tension with specimens of 1724 mm^3 of uniformly stressed active volume (cylindrical specimens of 7,6 ϕ x 38 mm). The distributions of volume diameter of carbides and bainite packets of the steel were obtained using standard techniques of Quantitative Stereology (fig. 1). Four-parameter gamma functions were fitted to the experimental data. Figure 2 shows examples of results for different values of the microfracture parameters. The figure is using a Weibull plot and it can be seen that the predicted probabilities are well represented by a two-parameter Weibull distribution function in the range shown (5% $\leq \phi \leq$ 95%). The "accepted" values for K^B_{la} of carbide/ferrite and ferrite/ferrite interfaces are , respectively, 2,5 MPa $\sqrt{m}$ and 5 MPa $\sqrt{m}$ (Hahn (7)). There is much uncertainty on their exact value. Superposed to the theoretical predictions experimental data obtained with 7,6 ϕ x 38 mm tensile specimens deformed at 77 K at $4 \cdot 10^{-4}$ s^{-1} are also shown in fig. 2. It can be seen that using K^B_{la} values close to those commonly accepted, there is a reasonable agreement of the data with the theoretical predictions for both the average σ_f value and the Weibull modulus, m (variability of the results).

CONCLUSIONS

- A probabilistic model of the "Weakest link" type has been developed for predicting the brittle (cleavage) fracture of polycrystalline metals containing a dispersion of brittle particles or inclusions.

- An applicaton of the model to the prediction of the distribution of the critical cleavage stress of a bainitic steel gives reasonable agreement with the experimental frequency of cleavage stresses.

- The model can be used, in a first stage, for the assessment of the local (microscopic) fracture parameters and then for a local approach to brittle fracture problems.

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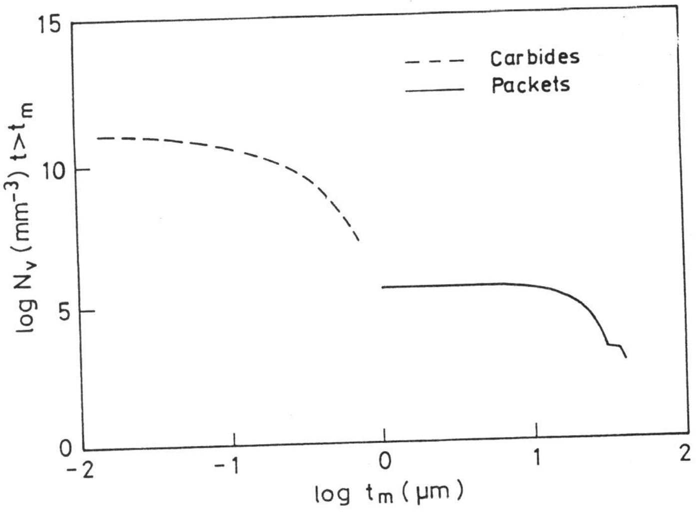

Fig. 1. Measured distributions of diameters (in volume) of carbides and bainitic packets in a SA 533B grade 1 steel.

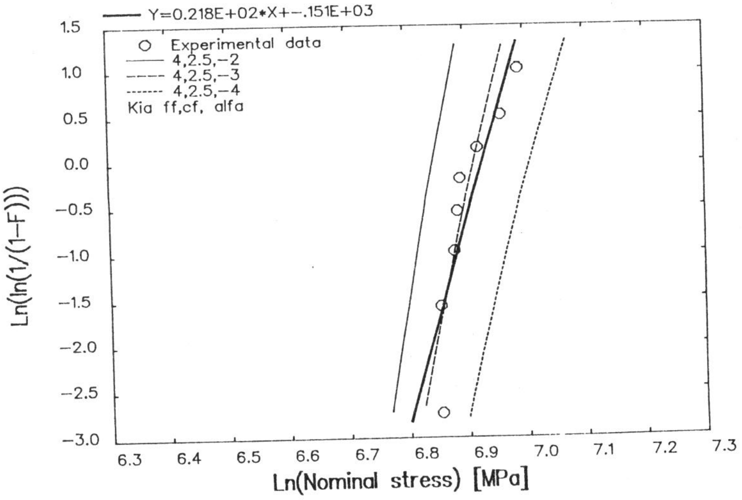

Fig. 2. Calculated probabilities of critical cleavage stress for tensile specimens with 1724 mm^3 of active zone ($K^{c/f}_{la}$ = 2,5 MPa $\sqrt{m}$, $K^{f/f}_{la}$ = 4 MPa$\sqrt{m}$, -4 < log α < -2). Superposed: experimental data.