PHYSICAL AND MECHANICAL MODEL OF INTERCRYSTALLINE FRACTURE BY STATIC AND CYCLIC LOADING

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ABSTRACT

A new physical and mechanical model of intercrystalline fracture in polycrystalline material has been developed. It is based on the analysis of void nucleation and growth caused by plastic strain and vacancy diffusion. The model permits to predict a component lifetime by long-term stationary and non-stationary loading under the conditions of three-axial stressed state.

KEYWORDS

Ductile fracture, transcrystalline, intercrystalline, voids, diffusive growth, plastic growth, plastic instability, micro-volume.

INTRODUCTION

Consider briefly experimental results illustrating strain rate effect on the parameters, controlling material critical state and compare them with mechanisms of damage accumulation and fracture. The main mechanism observed by various types of deformation when strain rate parameters influence on fracture characteristics is to decrease the critical values of these characteristics with the reduction of the effective strain rate. Thus, by creep tests in a definite temperature range creep rate decrease, caused by the reduction of applied stresses, may result in the decrease ef strain corresponding to specimen fracture (Sklenizka et al.,1987). Under the conditions of cyclic loading the reduction of effective strain rate (which is induced by frequency decrease, or exposure in a cycle, or cycle form) may cause sufficient reduction of number of cycles to fracture . Thus, in many cases the critical values of parameters determining the material fracture, become dependent on loading conditions. Fracture criteria are usually formulated by a traditional way - that is by the introduction of empirical relations of critical parameters versus strain rate (or time). However, such phenomenological models are of little use for result extrapolation of relatively short laboratory tests on real operation time, as well as for fracture description under conditions of three-axial stressed state by complex loading programs. In this connection many investigators apply to the analysis of physical mechanisms and concepts of damage accumulation by fracture, depending on time. The metallographic and fractographic analysis conducted by many authors (Čadek, 1987; Karzov et al., 1989a) showed that lifetime reduction by strain rate decrease was caused by the transition from transcrystalline to intercrystalline fracture. In other words, one may expect for a material revealing tendency to intercrystalline fracture by long-term static and cyclic loading, a sensitivity to rate parameters of deformation in respect of critical state characteristics. In this report an attempt is made to formulate physical and mechanical conception permitting to predict material lifetime by intercrystalline fracture under the conditions of rather arbitrary loading and three-axial stressed condition.

GENERAL THESIS

In most cases intercrystalline fracture is associated with damage development along grain boundaries according to the mechanism of void nucleation and growth and it passes ahead of damage accumulation process in a grain body according to the mechanism which is characteristic for a given strain type. It should be noted that recently obtained equations, describing intercrystalline and transcrystalline damage accumulation are not practically connected with each other. It is conditioned by the fact that the damage accumulation process is described in terms of mechanics of continua, when any damage parameter refers to infinite small material volume. Sometimes, the refusal from such interpretation of damage could be productive (Karzov et al., (1989a,1989b)). The consideration of damage in finite volume of material gives the possibility to analyse fracture initiation and development both in a grain and on grain boundary. In this case, fracture process may be described as competition between damage on boundaries and damange in grain and the fracture mechanism will be determined by the fact - which of these damages first reaches its critical value. In this connection, the analysis of critical parameters and material fracture type by long-term static and cyclic loading may be represented with a following scheme (Fig. 1). Line 1 in Fig. 1 corresponds to transcrystalline fracture. By this, critical parameters N_f and ε_f do not depend on strain rate ξ. Curve 2 corresponds to intercrystalline fracture, which is characterized by their critical parameter sensitivity to strain rate. According to the proposed scheme, fracture will be determined by that process which gives lower values of critical parameters. At strain rate $\xi=\xi_*$ a transition from transcrystalline to intercrystalline fracture takes place: for $\xi>\xi_*$ the critical state is controlled by damage accumulation processes in grain, and fracture characteristics do not depend on ξ. For $\xi<\xi_*$ intercrystalline damage determines fracture process, critical parameters of fracture become dependent on ξ. Various rate dependence of critical parameters by transcrystalline and intercrystalline fracture is associated with the different nature of physical processes,

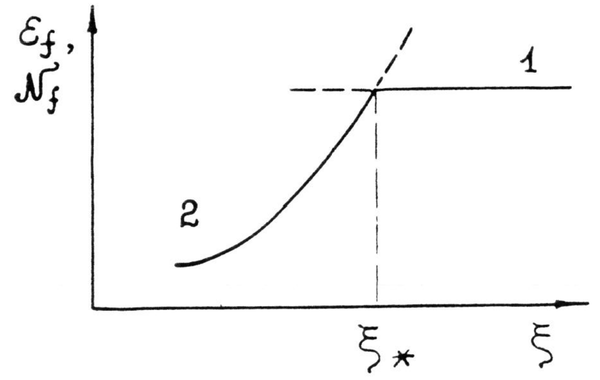

Fig. 1. Strain rate effect on critical characteristics, corresponding to transcrystalline (1) and intercrystalline (2) fracture (scheme).

resulting in the accumulation of intercrystalline and transcrystalline damages. As it was mentioned, under the conditions of consideration intergranular fracture is connected with void nucleation and growth on grain boundaries. Such damage is provided by two processes: grain boundary diffusion and plastic strain, and their correlation varies with the change of strain rate (Needleman, Rice, 1980). With the reduction of ξ the relative contribution of diffusion processes is increased, therefore by deformation with two different rates ξ_1 and ξ_2 ($\xi_1<\xi_2$) the damage accumulation rate, which may be expressed as $dS/d\varepsilon$ (S - void area per boundary area unit) will be higher by $\xi=\xi_1$: $\frac{dS}{d\varepsilon}\Big|_{\xi=\xi_1} > \frac{dS}{d\varepsilon}\Big|_{\xi=\xi_2}$. Thus, at lower strain rate the critical state will be reached sooner, and the values of xf or Nf parameters will decrease. By transcrystalline damage accumulation the role of diffusion processes is insignificant, because void nucleation and growth in grain is mainly associated with dislocation but not diffusion processes (Čadek, 1987). At $\xi=\xi_*$, diffusive growth of voids on grain boundaries may be disregarded as compared with their plastic growth. The stress, providing $\xi>\xi_*$ rate, is sufficiently high - material plastic strain is mainly realized by transcrystalline slip, grain boundaries sliding does not occur, that is, physical boundaries are not marked. Thus, transcrystalline fracture is most probable, as boundaries occupy a smaller volume, than grain body. The described regularities of intergranular fracture under long-term static and cyclic loading are assumed as a basis of the physical and mechanical model, considered below.

PHYSICAL AND MECHANICAL MODEL

The process of void nucleation and growth on grain boundaries in a structure element is considered. A structure element is a regular fragment of material volume with the dimension equal to the average grain diameter L, including adjacent grain boundaries (Fig. 2).

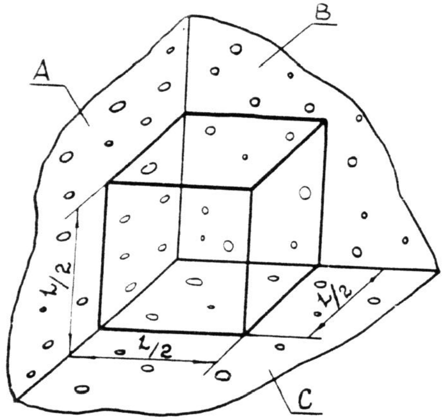

Fig. 2. Relative position of grain faces (A, B, C) with voids and a structure element, used in a calculation model (1/8 part of a structure element is shown).

Stress-strain state of structure element is supposed to be uniform. It is assumed that microvolume fracture is an elementary act of macrofracture. Critical strain responsible for macrofracture is determined as a strain, by which an accidental deviation in void area along a typical structure element section (grain boundary) results in strain localization in this section and thus leads to a element stability loss without its loading increase. The condition to achieve critical strain may be formulated as

$$\delta F|_{q_n=const} = 0 \; . \tag{1}$$

where $F = S_H \sigma_n$, $S_H = 1-S$, σ_n - normal stress, $q_n = \sigma_n/\sigma_{eq}$, σ_{eq} - equivalent stress. It is supposed that local strain variation does not result in the change of stress triaxiality, equation (1) may be written down as

$$\sigma_n \delta S_H + S_H \delta\sigma_{eq} = 0 \tag{2}$$

Parallel with macrofracture condition (1),(2) it is necessary to introduce the equation describing void nucleation and growth on grain boundaries for mathematical formulation of the model.

VOID NUCLEATION

Two competing processes should be taken into consideration: grain boundary sliding and diffusion at the sites of void nucletion. The first process leads to stress concentration increase and thus, to the increase of void nucleation rate, and the second - accomodates sliding and thus, brings down the possibility of void nucleation. As a result of the analysis carried out the following equation describing void nucleation

process has been obtained.

$$\varkappa = \frac{dJ}{\overline{d\varepsilon^p_{eq}}} = \left(B_1(\xi^p_{eq})^{-(n+1)} + B_2(\xi^p_{eq})^{-1}\right)\cdot(J_{max}-J) \; \exp(-B_3(\xi^p_{eq})^{-2n}) \; , \tag{3}$$

where J - void number per boundary area unit; J_{max} - maximum number of nucleation sites per area unit; $\overline{d\varepsilon^p_{eq}}$ - equivalent plastic strain increment; ξ^p_{eq} - equivalent plastic strain rate; B_1, B_2, B_3 - coefficients, depending on grain boundary diffusion parameters; n - material constant.

VOID GROWTH

In recent investigation and studies performed before (Kuklina, Margolin, 1990) an equation was obtained, which describes void growth by three-axial stress state and sign-reversed loading

$$\frac{dR}{\overline{d\varepsilon^p_{eq}}} = R(\mathrm{sign}(\sigma_n)\,(f_1(\Lambda_q/R) - 3/8) + X_1(\sigma_m) f_2(|q_m|)) \; , \tag{4}$$

where

$$f_2(\Lambda_q/R) = 0.5(\Lambda_q/R)^2 \left[\ln\frac{R+\Lambda_q}{R} + \left(\frac{R}{R+\Lambda_q}\right)^2 \left(1-0.25\left(\frac{R}{R+\Lambda_q}\right)^2 - 3/4\right)^{-1}\right];$$

$$\Lambda_q = |q_n|^{1/3}\Lambda; \quad \Lambda = \left(\frac{\Omega D_b \delta_b \sigma_{eq}}{kT\,\xi^p_{eq}}\right)^{1/3}; \quad q_m = (\sigma_m/\sigma_{eq});$$

$$f_2 = 0.28\exp(1.5|q_m|) \; ,$$

R - void radius; σ_m - hydrostatic stress component; Ω - atomic volume; D_b - grain boundary diffusion coefficient; δ_b - grain boundary width; k - Bolcman's constant; $X_1(\sigma_m)$ - unit step function.

ANALYSIS OF PLASTIC INSTABILITY

Let us return to equation (2) and determine its values. By supposing elastic-plastic character of material deformation at the moment of plastic stability loss of a structure element, we have

$$\delta\sigma_{eq} = \frac{\partial\sigma_{eq}}{\partial\varepsilon^p_{eq}}\,\overline{\delta\varepsilon^p_{eq}} \equiv g'(\varepsilon^p_{eq})\,\overline{\delta\varepsilon^p_{eq}} \; , \tag{5}$$

where $g(\varepsilon^p_{eq})$ - dependence, describing the diagram of static and cyclic deformation; ε^p_{eq} - equivalent plastic strain. An accidental deviation in void area is instantaneous and therefore the associated with it determinant increment δS will be conditioned only by plastic (athermic) strain (in this case, diffusion mass transfer is disregardly small). With the use of equation (4) it is not difficult to demonstrate that in the case of only plastic growth of void ($\Lambda/R \to 0$) $\delta S = AS\overline{\delta\varepsilon^p_{eq}}$, where $A = 0.56\cdot\exp(1.5\sigma_m/\sigma_{eq})$. As A is the value which does not depend on void size and taking into account, that at $\int\overline{d\varepsilon^p_{eq}} = \varepsilon$, $\varkappa\overline{d\varepsilon^p_{eq}}$ voids with initial radius R_0 are nucleated, we'll obtain

$$\delta S_H = -\delta S = -(AS + \pi\varkappa R_0^2)\,\overline{\delta\varepsilon^p_{eq}} \; . \tag{6}$$

Thus, the relations (3)-(6) permit to determine all values of the main equation (2).

THE COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS

Based upon the developed model, the analysis of various materials lifetime by static and cyclic loading has been performed. The experimental verification of the model by static loading has been carried out as an example by the analysis of critical state of two materials (iron (Cane, 1978), 304 austenitic steel (Chen, Argon, 1981) by uniaxial and multiaxial stressed state. Calculation results thus obtained by uniaxial loading are comparable with the well-known Monkman-Grant's correlation: $\xi_s t_f$= const. The calculated value of $\xi_s t_f$ parameter appeared to be slightly varied both for iron and the type 304 steel. Such result is in a good conformity with Monkman-Grant's correlation. For 304 steel the calculations of ε_f and t_f values were carried out for uniaxial loading as well as for three-axial stress state when the second and the third principal stresses were equal.

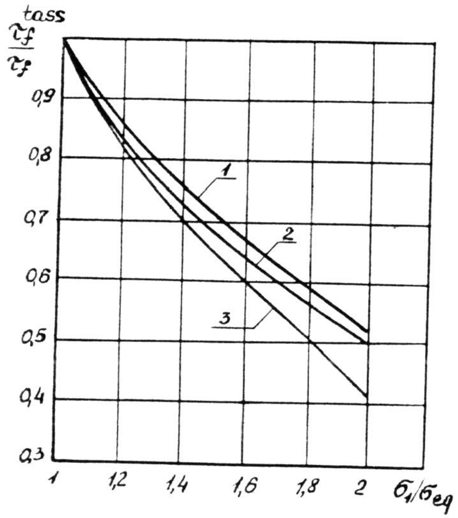

Fig. 3. The comparison of calculation results of relative lifetime t_f^{tass}/t_f according to the proposed model (1,3) and to the formula (7) (curve 2): 1,3 - numerical calculation results at σ_{eq}=60 MPa and σ_{eq}=40 MPa, respectively.

Calculation results are in good agreement (Fig. 3) with the empirical relation given below

$$t_f^{tass}/t_f = (\sigma_1/\sigma_{eq})^{-\alpha_1/(\alpha_2+1)} \tag{7}$$

where t_f^{tass}, t_f - specimen lifetime by three-axial stressed state and by uniaxial loading, respectively; σ_1 - principal

stress; α_1, α_2 - material constants. Fig.3 shows that relative lifetime t_f^{tass}/t_f calculated according to the developed model, practically does not depend on equivalent stress, but is only the function of stress state. The analysis of 304 stainless steel lifetime were conducted as related to strain rate under the condition $|\xi_1|=|\xi_2|$, and also in the case, when $|\xi_1|\neq|\xi_2|$ (ξ_1, ξ_2 - strain rate in semi-cycle of tension and compression, respectively). In all cases, symmetric cycle with strain range of 2% was analysed. Temperature of deformation is T=873K. These conditions are in accordance with the available experimental results in respect of 304 steel lifetime (Yamaguchi, Kanazawa, 1980; Morishita et al., 1988), it permits to compare them with calculation results. Fig. 4 gives the calculation results of lifetime N_f of uniaxial specimens (supposing, that material fracture is intercrystalline) versus strain rate ξ (curve 1).

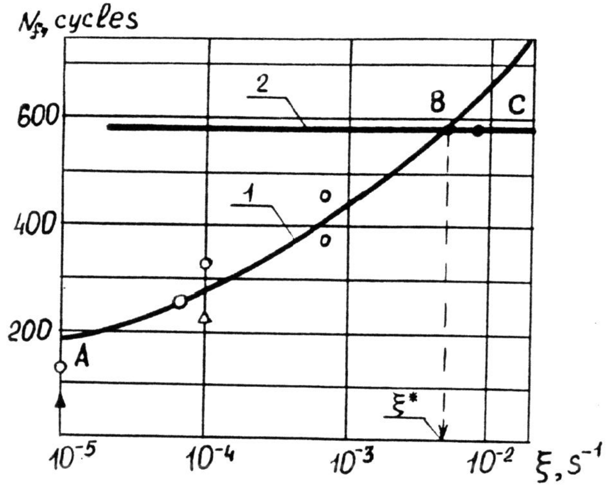

Fig. 4. Lifetime N_f dependence on strain rate ξ under cyclic loading of specimens made from 304 stainless steel with strain range of $\Delta\varepsilon$=2% : 1 -calculation according to the model of intercrystalline fracture at various ξ ($|\xi_1|=|\xi_2|=|\xi|$); Δ-calculation at $|\xi_1|=10^{-5}s^{-1}$, $|\xi_2|=10^{-3}s^{-1}$; Δ - calculation at $|\xi_1|=10^{-4}s^{-1}$, $|\xi_2|=10^{-3}s^{-1}$; 2 -lifetime by transcrystalline fracture; o, ● - experimental results by intercrystalline and transcrystalline fracture .

Curve 2, characterising transcrystalline fracture (Fig. 4) is constructed on the base of experimental results, given in (Yamaguchi, Kanazawa, 1980). Fig. 4 demonstrates a sufficiently good conformity of experimental and calculated lifetime data N_f in intercrystalline fracture zone, when $|\xi_1|=|\xi_2|$. Lifetime calculation was made on condition $|\xi_1|\neq|\xi_2|$ for two following

regimes. In the first regime $|\xi_1|=10^{-5} s^{-1}$; $|\xi_2|=10^{-3} s^{-1}$,
in the second - $|\xi_1|=10^{-4} s^{-1}$, $|\xi_2|= 10^{-3} s^{-1}$. By both loading
regimes strain range $\Delta\varepsilon$ is 2%. Calculation results showed that
with the increase of strain rate ξ_2 in absolute value (compres-
sing cycle part) at constant ξ_1 (tension cycle part) the life-
time to intercrystalline fracture initiation is decreased. Such
effect is associated with void healing by compression, and it is
good agreement with available experimental results. The relation
$(N_{f1}/N_{f2})_c$ (N_{f1} and N_{f2} - specimen lifetimes in the first and
in the second loading regimes, respectively), obtained by calcu-
lation, is equal to 3.01 and the relation, obtained from expe-
rimental data, is equal to 2.66. It is evident that disagree-
ment between $(N_{f1}/N_{f2})_c$ and $(N_{f1}/N_{f2})_e$ is unsufficient.

Thus, the comparison of calculated and experimental results by
various types of material loading permits to consider the pre-
diction of structure components lifetime with the use of the
developed model to be very perspective.

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