PHYSICAL AND MECHANICAL MODELLING OF TIME-DEPENDENT FRACTURE

B. Z. Margolin*, V. A. Shvetsova* and A. G. Gulenko*

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

INTRODUCTION

Analysis of mechanical, metallographic and fractographic research results obtained by many authors under consideration of time-dependent fracture in inert environment shows the followings. If the critical fracture parameters depend on strain rate, then fracture occurs on intercrystalline mechanism, otherwise, fracture is transcrystalline. Fracture process may be described as competition between damages on grain boundaries and in grain: the fracture mechanism is determined by that damade which gives a lower value of critical fracture parameters. Critical fracture parameters and material fracture mechanism at 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 - cycle number N_f or plastic strain ε_f do not depend on strain rate ξ. Curve 2 corresponds to intercrystalline fracture, which is characterized by critical parameter sensitivity to strain rate. At strain rate $\xi=\xi^*$ a transition from transcrystalline

* Central Research Institute of Structural Materials "Prometey", Saint-Petersburg, Russia.

to intercrystalline fracture takes place: for $\xi>\xi^*$ the critical state is controlled by damage accomulation in grain and critical fracture parameters do not depend on ξ. For $\xi<\xi^*$ critical state is controlled by damage accumulation on grain boundaries, critical parameters of fracture become dependent on ξ.

PHYSICAL-AND-MECHANICAL MODEL OF INTERCRYSTALLINE FRACTURE

The void nucleation and growth on grain boundaries is considered. Material is represented as aggregate of unit cells which have size equal to the average grain diameter and include adjacent grain boundaries. Stress-strain state of unit cell supposed to be uniform. It is assumed that unit cell fracture is an elementary act of fracture.

Fracture Condition

Critical strain responsible for unit cell fracture is determined as a strain, by which an accidental deviation in void area on grain boundary results in strain localization and thus in plastic collapse of unit cell without its loading increase. The conditions to achieve critical strain may be formulated as

$$\delta F|_{q=const} = 0 \qquad (1)$$

where $F=S_n\sigma_1$, $S_n=1-S$, $q=\sigma_1/\sigma_{eq}$. It is supposed that local variation of strain does not result in the change of stress state triaxiality, therefore equation (1) may be rewritten as

$$\sigma_{eq}\,\delta S_n + S_n\delta\sigma_{eq}=0 \qquad (2)$$

where $\delta\sigma_{eq} = g'(\varepsilon^p_{eq})\delta\varepsilon^p_{eq}$.

For mathematical formulation of the model it is necessary also to introduce the equations describing void nucleation and growth on grain boundaries.

Void Nucleation

Two competing processes should be taken into consideration: grain boundary slip 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 slip and thus, brings down the possibility of void nucleation

$$k = \frac{d\rho}{d\varepsilon_{eq}^{p}} = (B_1(\xi^{p})^{-(n+1)} + B_2(\xi^{p})^{-1})(\rho_{max} - \rho) * \exp(-B_3(\xi^{p})^{-2n}) \text{ ....(3)}$$

Void Growth

On the base of investigations of Chen and Argon (1), Needleman and Rice (2) equation, which describes void growth by three-axial stress state and sign-alternating loading was obtained (Margolin and Shvetsova (3)).

$$\frac{dR}{d\varepsilon_{eq}^{p}} = R[\mathrm{sign}(\sigma_n)(f_1(\Lambda_q / R) - 3/8) + \chi(\sigma_0) f_2(|q_0|)] \text{ ....(4)}$$

where

$$f_1(\Lambda_q / R) = 0.5(\Lambda_q / R)^3 \left[\ln\left(\frac{R + \Lambda_q}{R}\right) + \left(\frac{R}{R + \Lambda_q}\right)^2 * \left(1 - 0.25\left(\frac{R}{R + \Lambda_q}\right)^2\right) - 3/4 \right]^{-1}$$

$$\Lambda_q = |q|^{1/3} \Lambda; \quad q_0 = (\sigma_0 / \sigma_{eq}); \quad f_2 = 0.28 \exp(1.5 |q_0|),$$

COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS

On the base on the developed model the analysis of various materials lifetime by static and cyclic loading was performed.

The verification of the model by static loading was carried out by the analysis of critical state of iron, 304 austenitic steel and nickel alloy (CrNi55MoWZr) by uniaxial and multiaxial stress states by using original test results and test data in (Cane (4), Chen and Argon (5)). Calculation results at 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 also carried out for three-axial stress state when the second and the third principal stresses were equal. Calculation results are in good agreement (Fig. 2) with the empirical relation obtained on the base of large number of experiments (Contesti et al (6)).

t*f/tf= (S1/ eq) ....(5)

Effect of hydrostatic compression on lifetime is demonstrated in Fig. 3 as applied to nickel alloy. It is shown tha both lifetime and critical plastic strain increase at hydrostatic compression. Such phenomenon is caused by hydrostatic compression effect on void evolution: total void area under uniaxial loading is smaller at loading with hydrostatic compression.

Lifetime calculation according to model was also performed as applied to 304 stainless steel at cyclic loading with symmetric cycle and strain range of 2% at temperature T=873K. Effect of strain rates on both fracture mechanism and lifetime was studied. Results calculated according to model were compared with the available experimental results (Yamaguchi and Kanazawa (7)) (Fig. 4).

SYMBOLS USED

B_1, B_2, B_3	= coefficients, depending on grain boundary diffusion parameters
$g(\varepsilon^p_{eq})$	= stress-strain at static and cyclic loading (MPa)
n, α_1, α_2	= material constans
R	= void radius (mm)
S	= void area per the unite area
t^*_f , t_f	= specimen lifetime at three-axial stress state and at uniaxial loading (h)
ε^p_{eq}	= equivalent plastic strain
ε_f, N_f	= critical strain and lifetime (cycle)
Λ	= Needleman-Rice's length parameter (mm)
ξ, ξ^*	= strain rate (s^{-1}) and transition strain rate (s^{-1})
ξ_p	= equivalent plastic strain rate (s^{-1})
ξ_s	= steady-state creep rate (s^{-1})
ρ	= void number per boundary area unite (mm^{-2})
ρ_{max}	= maximum number of nucleation sites per area unite (mm^{-2})

σ_1 = maximum principal stress (MPa)

σ_0 = hydrostatic component of stress tensor (Mpa)

σ_{eq} = equivalent stress (MPa)

$\chi(\sigma_0)$ = unit step function

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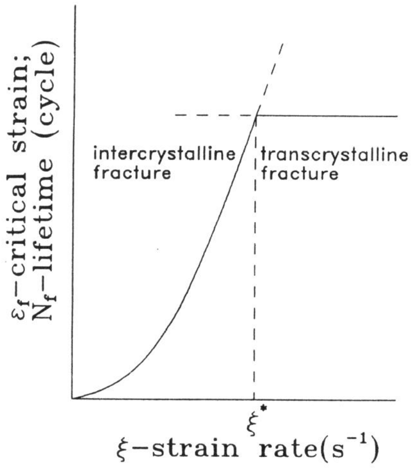

Figure 1. Strain rate effect on critical fracture parameters.

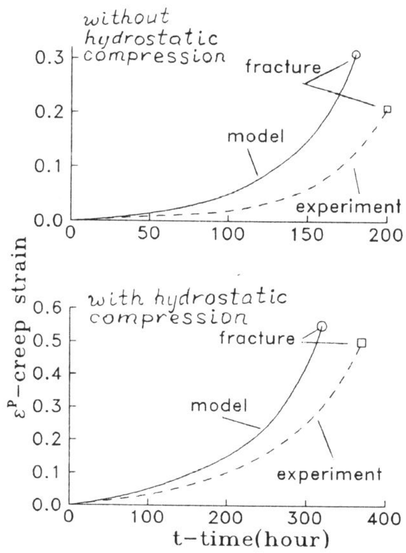

Figure 3. Creep curves under uniaxial loading.

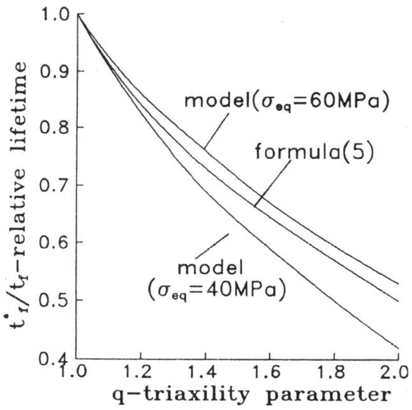

Figure 2. Calculation results accoding to the model and to the formula (5).

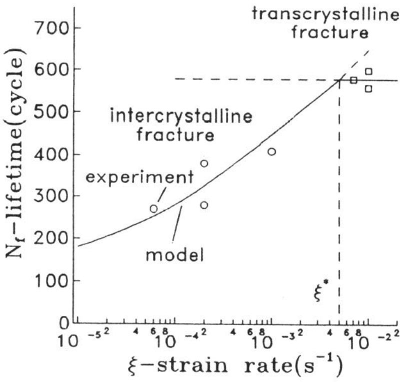

Figure 4. Lifetime dependence on strain rate.