MODELLING OF THE STRAIN RATE EFFECT ON THE LIFETIME OF AUSTENITIC STEELS UNDER CYCLIC LOADING AT THE HIGH TEMPERATURES

A.G. Gulenko*and B.Z. Margolin*

The model for prediction of material lifetime under cyclic loading has been elaborated on the basis of the proposed dependences for nucleation and growth of grain boundary voids, the kinematic hardening scheme and the plastic collapse criterion. The influence of various cyclic loading regimes on the lifetime has been studied numerically according to the proposed model. To verify the proposed model the comparison of the calculated and experimental results has been performed as applied to 304 stainless steel. It has been shown that the model allows one to predict the effect of the strain rate on the cyclic lifetime and to take into account a phenomenon of void healing in compression semi-cycle.

INTRODUCTION

Experimental studies show that fracture of the polycrystalline metals under cyclic loading over elevated and high temperature range has a series of peculiarities (Pineu (1)). For high strain rate in cycle ξ the failure mechanism is transcrystalline. In this case the cyclic lifetime N_f does not depend on ξ and, therefore the calculation of N_f may be carried out by the known equations for fatigue failure (Coffin (2), Manson (3)). As the strain rate is decreasing the transition from transcrystalline to intercrystalline failure is observed, the cyclic lifetime decreasing. For this case the lifetime depends on ξ and cannot be calculated by equation of Manson-Coffin type.

The purpose of the present paper is to elaborate a comparatively simple model for intercrystalline fracture under cyclic loading with various strain rates. In the proposed model the attemp to take into account main physical processes for cavitation intercrystalline fracture and, at the same time, to formulate the constitutive equations of plastic cyclic deformation and damage accumulation which may be easily used is undertaken. As fracture criterion in the present paper the plastic collapse criterion

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

proposed by authors in (Margolin et al (4)) is used. This criterion does not require to introduce of any empirical parameters such as the critical ratio of void radius to distance between two neighbouring voids or others.

FRACTURE CRITERION

The plastic collapse criterion proposed in (4) for fracture caused by void evolution is used in the present study as the intercrystalline fracture criterion. The polycrystalline material is represented as an aggregate of unit cells. Mechanical properties of the unit cell are taken as the average mechanical properties of the polycrystalline material. To analyse an evolution of voids on grain boundary the unit cell is taken as cube including the adjacent grain boundaries. The size of unit cell ρ_{uc} is never less than the grain size d_g. Critical state of unit cell with voids, i.e. fracture of unit cell, is defined as the plastic collapse of unit cell. Plastic collapse criterion is written as (4)

$$\left(\frac{\partial F_1}{\partial æ}\right)_q = 0 \text{ or } \frac{dF_{eq}}{dæ} = 0, \; æ = \int d\varepsilon^p_{eq}; \tag{1}$$

where F_1 - the maximum principal stress; F_{eq} - the equivalent stress for F_{ij}; F_{ij} - stresses for which the stress equilibrium equations are fulfilled; $q = \frac{F_1}{F_{eq}}$.

Following Kachanov (5) it is also introduced the effective stresses σ_{ij} which are calculated as (4)

$$\sigma_{ij} = \frac{F_{ij}}{1 - S_\Sigma}, \tag{2}$$

where S_Σ - the relative area of voids, i.e. area of voids per unit area of deformed grain boundary. Then the equation (1) may be represented in form

$$\frac{dF_{eq}}{dæ} = (1 - S_\Sigma)\frac{d\sigma_{eq}}{dæ} - \sigma_{eq}\frac{dS_\Sigma}{dæ}. \tag{3}$$

CONSTITUTIVE EQUATIONS

Nucleation of Voids on Grain Boundaries

Analysis for main processes of void nucleation on grain boundaries performed in (4) has shown the followings. Void nucleation rate $\alpha_{int} \equiv \frac{d\rho_{int}}{dæ}$ (here ρ_{int} - the number of voids per unit area of undeformed grain boundary) is mainly determined by the equivalent plastic strain rate ξ^p_{eq}. The function $\alpha_{int}(\xi^p_{eq})$ has a sloping maximum and decreases both as ξ^p_{eq} decreases and as ξ^p_{eq} increases. Such a shape of the function $\alpha_{int}(\xi^p_{eq})$ reflects two competing processes which determine the void nucleation: grain boundary sliding and vacancy diffusion near void nucleation seats. The first process leads to increase of the local stress σ_s near void nucleation seats. The second one accomodates the grain boundary sliding and, as a result, reduce σ_s . As shown in (4), the range of strain rates over which the function $\alpha_{int}(\xi^p_{eq})$ may be taken as constant function corresponds to $\xi^p_{eq} \approx 10^{-8}...10^{-5}s^{-1}$. In the present study cyclic loading with strain rates $\xi^p_{eq} \geq 10^{-5}s^{-1}$ will be considered. Over this range the function $\alpha_{int}(\xi^p_{eq})$ is approximated by the power law $\alpha_{int} = a(\xi^p_{eq})^m$ with material constants a and m<0.

Growth of Voids on Grain Boundary

Loading for triaxial stress state and alternating cyclic equation for growth of isolated spherical void caused by vacancy diffusion and plastic strain derived by generalizing the dependences of Rice-Tracey (6) and Chen-Argon (7) takes the form

$$\frac{dR}{Rd\ae} = \text{sign}(F_1)\left[\frac{1}{2}\left(\frac{\Lambda_q}{R}\right)^3 \cdot f\left(\frac{\Lambda_q}{R}\right) - \frac{3}{8}\right] + \chi(q_m)[0.56\sinh(1.5q_m)], \tag{4}$$

$$f\left(\frac{\Lambda_q}{R}\right) = \left[\ln\frac{R+\Lambda_q}{R} + \left(\frac{R}{R+\Lambda_q}\right)^2\left(1-\frac{1}{4}\left(\frac{R}{R+\Lambda_q}\right)^2\right) - \frac{3}{4}\right]^{-1}, \tag{5}$$

where $\chi(q_m) = \begin{cases} 1, \text{ if } q_m > 0 \\ 0, \text{ if } q_m \leq 0 \end{cases}$, $\Lambda_q = |q|^{1/3}\left(\frac{D_\Lambda \sigma_{eq}}{\xi^p_{eq}}\right)^{1/3}$; $D_\Lambda = \frac{\Omega D_b \delta_b}{kT}$; R - the void radius; $q_m = F_m/F_{eq}$; $F_m = F_{ii}/3$; σ_{eq} - the effective equivalent stress; Ω - the atomic volume; D_b - the coefficient of grain boundary diffusion; δ_b - the grain boundary thickness; k - Bolzman constant; T - the absolute temperature.

In eqn (4) the term in the first square brackets describes void growth caused by vacancy diffusion, the term in the second square brackets - by plastic strain.

Equation (4) has a clear physical matter. Let the considered void locate on grain boundary which is perpendicular to the maximum principal stress. Under tensile stress the vacancy flow is directed to void and void grows. It is clear, that for compressive stress the opposite process occurs. Therefore, for alternating cyclic loading growth and healing of void caused by vacancy diffusion are controlled by the sign of the maximum normal stress.

In contrast to diffusive void growth the void growth caused by plastic strain is irreversible process. Under the reverse loading the dislocation motion is, as a rule, no reverse and the plastic deformation is mainly provided by dislocation motion on the slip planes which do not coinside with the slip planes which work under the direct loading. As a result, under the reverse loading the void shape changes only, but the effective size does not change. As a clear example of such a process the fatigue crack growth may be also indicated, when the fatigue crack grows in tension semi-cycle and the crack length does not decrease in compression semi-cycle. Thus, the plastic void growth under cyclic loading may be schematized by the following way: the void size increases under tension and does not change under compression.

Elastic- Plastic Cyclic Deformation

The considered material is assumed to be cyclic stable material. Then, taking the linear law for strain hardening the behaviour of a material under cyclic loading may be described by the kinematic hardening scheme (Ishlinsky (8))

$$\beta_{eq} - \Phi(\xi^p_{eq}, T) = 0\,, \tag{6}$$

where the equivalent active stress $\beta_{eq}=\sqrt{\frac{3}{2}\beta_{ij}\beta_{ij}}$; the active stress deviator $\beta_{ij}=s_{ij}-\rho_{ij}$; the effective stress deviator $s_{ij}=\sigma_{ij}-\sigma_m\delta_{ij}$; $\sigma_m=1/3\sigma_{ii}$; the microstress deviator $\rho_{ij} = C(\varepsilon^p_{ij} - \varepsilon^p_m\delta_{ij})$; δ_{ij} - Kroneker symbol; material constant $C = \frac{2}{3}\frac{E_h}{(1 - E_h / E)}$ according to (8); E_h - harderning modulus for the linear stress-strain curve; E - Young's modulus; $\Phi(\xi^p_{eq}, T)$ - the yield surface function dependent of the plastic strain rate and temperature.

The associated flow rule is represented in form

$$d\varepsilon^p_{ij} - d\varepsilon^p_m\delta_{ij} = \frac{3}{2}\frac{d\varepsilon^p_{eq}}{\beta_{eq}}\beta_{ij}\,. \tag{7}$$

Consider periodic region of a material taken as a cube with the side size equal to the grain diameter d_g which contents three adjacent grain boundary facets. Then from the mass preservation law we have

$$d\varepsilon^p_m = \frac{1}{3}\frac{3dV_{gb}\cdot d_g^2}{(d_g^3 + 3V_{gb}\cdot d_g^2)} = \frac{dV_{gb}}{(d_g + 3V_{gb})}\,, \tag{8}$$

where V_{gb} – the void volume per unit area of undeformed grain boundary.

To perform numerical calculations according to the above equations FEM program has been elaborated.

RESULTS

According to the proposed approach the cyclic lifetime for 304 austenitic steel for $T=600^0C$ has been calculated. Uniaxial cyclic loading with symmetric cycle controlled by longitudinal strain has been analysed. The minimum and maximum values of longitudinal strain have been given as $\varepsilon_{min}=-0.01$ and $\varepsilon_{max}=0.01$. Calculations have been performed for two loading types (Fig. 1) A: $\xi_1=\xi_2=\xi$; B: $\xi_1<\xi_2$, where ξ_1, ξ_2 - the absolute values of the strain rate in semi-cycles of tension and compression.

The calculated results for the cyclic loading type A are represented in Fig. 2, in which experimental data (Yamaguchi and Kanazawa (9)) are also shown. As seen from Fig. 2, for the loading type A the cyclic lifetime increases as the strain rate increases. This reqularity is connected with that the relative void area increases with a less rate for loading with a larger strain rate (Fig. 3). This is explained by decreasing the contribution of diffusive processes in void growth and decreasing the void nucleation rate.

Calculation for the loading type B has been performed for two regimes: 1) $\xi_1=10^{-4}$ s^{-1} and $\xi_2=10^{-3}$ s^{-1}; 2) $\xi_1=10^{-5}$ s^{-1} and $\xi_2=10^{-3}$ s^{-1}. The calculated results are shown in Fig. 3. The calculated ratio of the lifetime N_{f_1} for the first regime to the lifetime N_{f_2} for the second regime $N_{f_1}/N_{f_2}=3.01$. The same ratio obtained from test data (Morishita et al (10)) is 2.70.

As seen from Fig. 2, for the cyclic loading type B the lifetime decreases as the strain rate in compression semi-cycle ξ_2 increases (the strain rate in tension semi-cycle ξ_1 is constant). Such a effect is explained by the healing of voids under compression. As an illustrative example for the void healing processes, the kinetics of the relative void area S_Σ for the A and B types are shown in Fig. 4.

REFERENCES

(1) Pineau, A. I., "Microstructural aspects of high temperature fatigue of structural materials", "Fatigue at High Temperature", Edited by R. P. Skelton, Applied Science Publishers LTD, London-New-York, 1983, pp.233-273.

(2) Coffin, L. F., Trans. ASME, Vol.76, No.6, 1952, pp. 273-291.

(3) Manson, S. S., NACA TN-2933, 1953.

(4) Margolin, B. Z., Karzov, G. P., Shvetsova, V. A. and Kostylev, V. I., Fatigue Fract. Eng. Mater. Struct., Vol.21, No.1, 1998.

(5) Kachanov, L. M., Izv. AN SSSR, OTN, Vol.8, 1958, pp.3-10.

(6) Rice, J. R. and Tracey, D. M., J. Mech. Phys. Solids, Vol.17, No.3, 1969, pp.201-217.

(7) Chen, I. W. and Argon, I. W., Acta Met., Vol.29, 1981, pp.1759-1768.

(8) Ishlinsky, A. Yu., Ukr. Matem. Zhurnal, Vol.6, No.3, 1954, pp.314-325.

(9) Yamaguchi, K. and Kanazawa, K., Metal. Trans. A., Vol.11, 1980, pp.1691-1699.

(10) Morishita, M., Taguchi, K., Asayama, T. et al, ASTM Spec. Tech. Publ., Vol.942, 1988, pp.487-499.

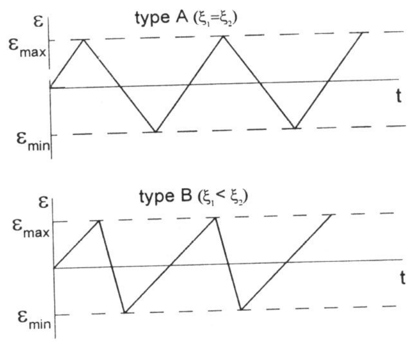

Figure 1. Cyclic loading of types A and B.

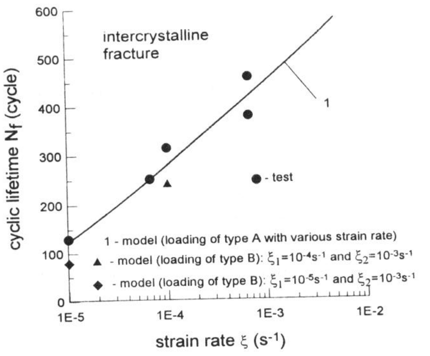

Figure 2. The lifetime of 304 stainless steel under cyclic loading vs strain rate.

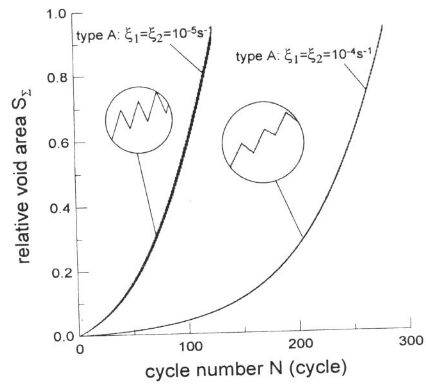

Figure 3. The relative void area S_Σ vs cycle number N for cyclic loading of type A.

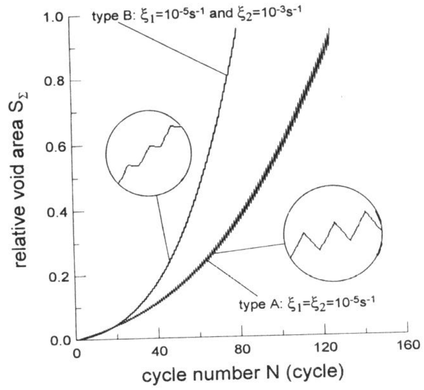

Figure 4. The relative void S_Σ vs cycle number N for cyclic loading of types A and B.