NEW CRITERION OF FATIGUE FRACTURE INITIATION AND CRACK GROWTH MODEL IN PEARLITIC STEELS

G.P.Karzov*, B.Z.Margolin*, V.A.Shvetsova*

Strain-power criterion of fatigue fracture initiation is formulated for bcc-metals, in particular, for perlitic steels on the base of some physical and mechanical ideas about damage cumulation under cyclic loading. Fatigue crack growth model which allow to describe the crack path and rate into inhomogeneous stress field at various stress ratio factors is proposed.

INTRODUCTION

The most equations describing fatigue fracture initiation may be represented in the form $\varphi(\Delta\varepsilon, N_f)=0$. Influence maximum stress σ_{max} on fatigue lifetime is taken into account mainly on the base of Goodmen and Peterson type empirical equations for high cycle fatigue only. For low cycle fatigue the equations taking into account strain asymmetry only and ignoring σ_{max} influence are usually used. It should be noted that the most equations describing fatigue failure don't logically lead to methods for fatigue lifetime prediction at nonstationary loading. By this various empirical cumulative damage rules are used.

In the most cases fatigue crack growth models, don't allow to explain test results existed. For example, under mode II loading of cracked body the crack growth rate is defined by the value of the maximum strain range, localized ahead the fatigue crack tip, but the crack

---

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

propagation direction appears to be perpendicular to the direction of the maximum normal stress action, where plastic strain range is small.

In present work the strain-power criterion of fatigue fracture initiation is formulated for bcc-metals, in particular, for perlitic steels on the base of some physical and mechanical ideas about damage cumulation under cyclic loading. Moreover fatigue crack growth model which allow to describe the crack path and rate into inhomogeneous stress field at various stress ratio factor R is proposed.

Under cyclic loading process of fatigue fracture of polycrystalline bcc metal grain may be divided in three stages: microcrack nucleation in grain or on boundaries of fragmental (or cellular) dislocation substructure arising under cyclic deformation; microcrack stable growth; unstable microcrack growth and hence fracture initiation in grain scale. Under low cycle failure the lifetime of the first stage is very small as related to the lifetime, corresponding to fatigue fracture initiation (Kotsanda (1)). Number of cycles associated with the stage of stable microcrack growth determines practically lifetime up to fracture initiation in grain. At reaching the critical length microcracks are propagating by unstable manner to dislocation substructure boundaries which to this moment may become barriers, arresting microcracks. Then in the present or next cycle coalescence microcracks in grain happens by a break of ligaments (Fig.1).

Disagreement between a real path of fatigue crack and the maximum damage region, where this path is to pass due to a theoretical prediction may be decided in the following way (Margolin and Shvetsova (2)). In many cases numerous microcrack nucleation happens under fatigue. Several microcracks in each cell may be an initiators of grain fracture simultaneously. The most fast rate of microcrack coalescence is observed in a plane, perpendicular to the direction of the maximum normal stress action (Fig.1), path of microcrack, placed in this plane (section A-A) being straight. It is clear that at the equal rate of microcrack unstable growth a more quick failure initiation takes place exactly in this plane. A growth of microcracks with linear paths leads to unloading of the tips of microcracks propagating on curvilinear paths and as a result to their arrest. Hence, a real path of fatigue crack happens in the direction, perpendicular to the orientation of the maximum normal stress.

THE STRAIN-POWER EQUATION FOR FATIGUE FAILURE

The following principal positions are used to obtain the strain-power equation.

1. Material is considered as an aggregate of unit cells, the size of which is equal to average grain diameter.

2. Numerous microcrack nucleation is realised. One of the places, where microcrack nucleation and growth up to unstable state occur, is localized in the plane perpendicular to the direction of the maximum normal stress action.

3. Lifetime to fatigue failure initiation is determined by the stage of microcrack growth from the nucleus microcrack length l^{o} to the critical length l_f.

4. Nucleus microcracks are geometrically similar irrespective of cyclic loading level, i.e. a ratio of nucleus microcrack length to their blunting l^0/δ^0 is constant.

5. The microcrack growth rate dl/dN is determined by equation

$$\frac{dl}{dN} = c \cdot (\Delta\varepsilon_{eq}^{p})^{n} \cdot l$$

6. The maximum fatigue microcrack blunting δ during microcrack growth is decribed by equation

$$\delta = b \cdot (\Delta\varepsilon_{eq}^{p})^{m} \cdot l^{k}$$

The following strain-power equation for fatigue failure initiation at stationary loading was obtained

$$\ln\frac{S_m}{\sigma_{max}} = c_0(\Delta\varepsilon^{eff})^{n} \cdot N_f \quad \text{.....................................(1)}$$

where $\Delta\varepsilon^{eff} = (\Delta\varepsilon_{eq}^{p}) + A(\Delta\varepsilon_{eq}^{e})^{q}.$

The strain-power equation for fatigue failure initiation at nonstationary loading has a form

$$\ln\left[\frac{S_m}{\sigma_{max}}\left(\frac{\Delta\varepsilon_f^{eff}}{\Delta\varepsilon_1^{eff}}\right)^{m/2}\right] = c_0\sum_{j=1}^{k}(\Delta\varepsilon_j^{eff})^{n} \cdot N_j \quad \text{..(2)}$$

where k - block number, in which fracture happens; Nj - loading cycle number in j-block; σ_{max} - the maximum stress in k-block.

It is shown in Fig.2, that calculation results by equation (2) for two-block loading are well argeed with experimental data by Collins (3) and at the same time the calculation by linear cumulative damage rule leads to considerable errors.

FATIGUE CRACK GROWTH MODEL

Fatigue crack growth is considered as a discrete process in which every elementary increment of crack length is equal to unit cell size.The model is based on the obtained by authors (2) approximational solution of cyclic elastic-plastic problem about stress-strain state near the crack tip at loading on both I mode and I and II modes simultaneously and on the strain-power equation (2). Performed calculations show that at triaxial stress state the strain range near the crack tip depends on both load range (in this case ΔK) and K_{max}. At mixed loading II mode contribution in strain range is larger than I mode. Obtained results allows to predict fatigue crack growth rate and ΔK_{th} at arbitrary loading asymmetry and mixed loading without some empirical parameters. Comparison of some calculated and experimental results is shown in Fig.3 and 4.

ANALYSIS OF JUMPS OF FATIGUE CRACK

As mentioned above, cyclic deformation leads to material dislocation substructure formation, the boundaries of which may be barriers for unstable propagated microcracks. If microcrack is arrested by these boundaries, then fatigue crack growth is stable. Otherwise jumps of fatigue crack happen, that is observed at $\Delta K = K_{fc}$. The role of any substructural boundaries as a barriers may be formulated as the following condition $G(d) < \gamma$ or $\sigma_{max}\sqrt{\pi d} < P$, where P is constant, d is cell size. Therefore value S_c at which microcrack overcomes substructural boundaries may be obtained from the equation $S_c = P/\sqrt{\pi d}$, where $S_c = S_c(\Delta\varepsilon, N)$. Stable growth of fatigue crack is observed if near the crack tip $\sigma_{max} < S_c$, unstable growth at $\sigma_{max} \geq S_c$.

The possibility of brittle jumps of fatigue crack was analysed for Cr-Ni-Mo-V steel after various heat treatment. It was shown that for Cr-Ni-Mo-V steel after special heat treatment imitating radiation embrittlement jumps of fatigue crack occur at $K_{fc} = 1500 H/mm^{3/2}$. This calculation results are well argeed with experimental data by Troshchenko et al. (4).

SYMBOLS USED

A, c, c_0, q, k, m, n = material constants

G = elastic energy release rate (N/mm)

ΔK, K_{max} = range and maximum value of stress intensity factor (SIF) ($H/mm^{3/2}$)

ΔK_{th}, K_{fc} = threshold SIF and critical value of SIF, corresponding to fatigue crack jumps ($H/mm^{3/2}$)

l = microcrack length (mm)

N_f = number of cycles to fracture initiation (cycle)

S_c = critical brittle fracture stress (MPa)

S_m = material constant (MPa)

γ = effective surface energy (N/mm)

$\Delta\varepsilon_{eq}^{e}, \Delta\varepsilon_{eq}^{p}$ = equivalent elastic and plastic strain range

REFERENCES

(1) Kotsanda, S., "Fatigue of Metals", Metallurgia, Moscow, U.S.S.R., 1990 (in Russian).

(2) Margolin, B.Z., Shvetsova, V.A., Problemy prochnosti, No. 4, 1990, pp. 12-21 (in Russian).

(3) Collins, J.A., "Failure of Materials in Mechanical Design. Analysis. Prediction. Prevention", A Wiley Intercience Publication, New-York, U.S.A., 1981.

(4) Troshchenko, V.T., Pokrovski, V.V., Prokopenko, A.V., "Metal fracture toughness under cyclic loading", Naukova Dumka, Kiev, U.S.S.R., 1987 (in Russian).

(5) Otsuka, A., Mori, K. and Miyada, T., Eng. Fract. Mech., Vol. 7, 1974, pp.429-439.

(6) Gao, H., Brown, M.W. and Miller, K.J., Fatigue Eng. Mater. and Struct., Vol. 5, No. 1, 1982, pp.1-17.

(7) Tanaka, K., Eng. Fract. Mech., Vol. 6, 1974, pp.493-501.

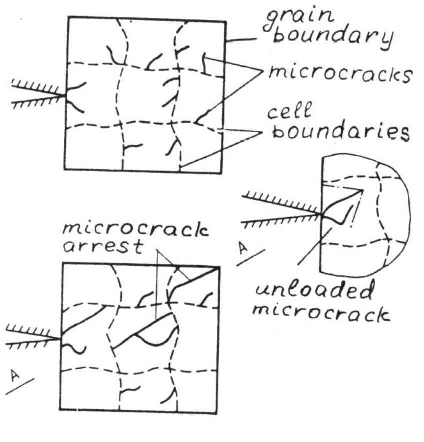

Figure 1. Fatigue failure of a grain (scheme).

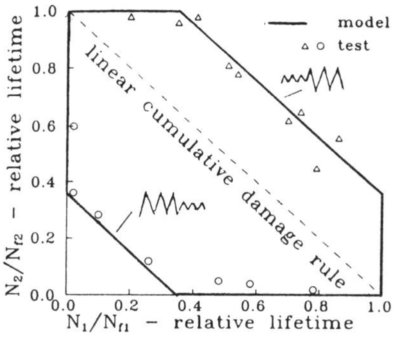

Figure 2. Damage cumulation at two-block loading.

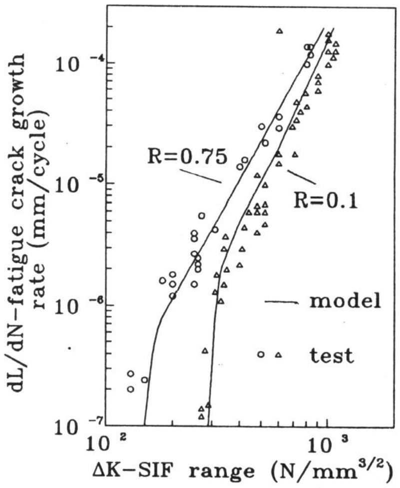

Figure 3. Fatigue crack kinetics at various R.

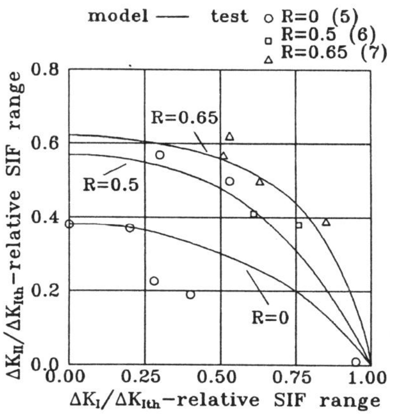

Figure 4. Threshold SIF at mixed loading.