MODELLING OF SURFACE DAMAGE AND FRACTURE OF POLYCRYSTALLINE COPPER UNDER PLASTIC FATIGUE

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On the basis of experimental data for OHFC copper the modelling of surface fatigue microcrack initiation and growth, as well as of the fatigue macrocrack propagation is attempted. Statistical and energetic approaches are applied. Special attention is given to the influence of the precycling on the fatigue durability of the material.

INTRODUCTION

There is an extending interest in the fatigue damage processes of metallic materials in connection with many contemporary industrial applications. In the elastoplastic regime, cyclic damage is frequently characterized by the initiation and growth of a population of surface microcracks. These microcracks grow and interact until the formation of a predominant macrocrack. Further propagation of this macrocrack into the bulk material produces its failure (Suresh (1), Anderson (2), Miller (3), Chaboche (4)). Modelling of such damage processes is required for estimating residual fatigue resistance accounting for previous loading history and physical damage mechanisms related to the material characteristics. The present work constitutes an attempt of modelling surface fatigue damage and fatigue failure of polycrystalline copper on the basis of experimental data. Experiments were previously carried out by Ghammoury (5) with cylindrical specimens of polycrystalline copper subjected to low cycle fatigue under global plastic strain amplitude E_p = const, resulting in symmetric tension-compression global stress amplitude Σ_M. For the material

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considered (OFHC copper, 99.95 % pure, mean grain diameter 45 μm) stochastic initiation and growth of surface intergranular fatigue microcracks is observed. At a certain cycle level $N=N_g$, the predominant fatigue crack is formed. This crack initiates and enters into the specimen bulk with an intergranular mesomechanism up to a level $N=N_T$. Above this level, up to the failure of the specimen ($N = N_R$) the leading mesomechanism is transgranular. A special attention is paid here to characterize the influence of a precycling on the subsequent fatigue durability of the material.

SURFACE FATIGUE MICROCRACK GROWTH - STATISTICAL APPROACH

Under the experimental conditions, summed up in the introduction and for a given initial number of cycles $N_{(0)}$, surface fatigue cracks with depth $a_{\ell(0)}$ and width $L_{\ell(0)}$, are formed (see Figure 1).

For all cycles $N \in [N_0, N_T]$, $N_0 = \inf \{N_{(0)}\}$, the ratio a_ℓ/L_ℓ is assumed to be constant. The stochastic distributions of the initial depth $a_{\ell(0)}$ and of the corresponding rate of microcrack propagation $V_{\ell(0)}$ for $N = N_{(0)}$, as well as of the depth a_ℓ and of the rate V_ℓ for given number of cycles N are observed (5).

On the basis of attentive microstructural analysis we assume that the resistance of the material against the microcrack penetration r_ℓ follows a Boltzmann like statistical law. The process of microcrack propagation is activated when the actual energy e_ℓ exceeds the initial energetic barrier $e_{\ell(0)}$ i.e.

$$r_\ell = r_{\ell(0)} \exp\left\{-\frac{\Delta e_\ell}{K_B T_0}\right\} = r_{\ell(0)} \exp\left\{-\lambda_\ell \left(N - N_0\right)\right\} \tag{1}$$

when : $\Delta e_\ell = e_\ell - e_{\ell(0)}$, $e_\ell = \sigma_\ell^p \bar{\varepsilon}_{cum}^p(N)$,

$$e_{\ell(0)} = \sigma_\ell^p \varepsilon_{cum}^p \left(N_{(0)}\right), \quad \lambda_\ell = \frac{4K_\ell \bar{\varepsilon}_p^\alpha}{K_B T_0}, \quad \sigma_\ell^p = K_\ell \bar{\varepsilon}_p^{\alpha-1}, \tag{2}$$

where K_B is the Boltzmann constant, T_0 is the initial temperature, K_ℓ and α are the material constants ; in the Manson-Coffin law $\alpha \approx 2$, Suresh (1) ; σ_ℓ^p is the local stress, corresponding to r_ℓ ; ε_p is the mean local plastic amplitude over the surface of the specimen while $\bar{\varepsilon}_{cum}^p(N)$ is the mean accumulated plastic strain after N cycles. The rate of the microcrack propagation V_ℓ is inversely proportional to the material resistance r_ℓ and :

$$V_\ell = V_{\ell(0)} \exp\left\{\frac{\Delta e_\ell}{K_B T_0}\right\},\ a_\ell = a_{\ell(0)}\left[\exp\left\{\frac{\Delta e_\ell}{K_B T_0}\right\} - 1\right],\ V_{\ell(0)} = a_{\ell(0)}\lambda_\ell \qquad (3)$$

where $\frac{\Delta e_\ell}{K_B T_0} = \lambda_\ell\,(N - N_0)$, $V_{\ell(0)}$ is the initial value for $N=N_0$. According to our previous assumption $a_{\ell(0)}$, $V_{\ell(0)}$, a_ℓ, V_ℓ, λ_ℓ have statistical distribution depending on density d. The experimental envidence (5) allows the following form :

$$\begin{array}{ll} 0 \le x \le x_1 & x_1 \le x \le x_{max} \\ d = d_{max} - a_0 x^2 & d = b_0\,(x_{max} - x)^2 \\ a_0 = (d_{max} - d_1)/x_1^2, & b_0 = a_0 x_1/(x_{max} - x_1) \end{array} \qquad (4)$$

In Fig. 2 an example for the distributions of λ_ℓ (d), $V_{\ell(0)}$ (d) is given for $E_p = 2.10^{-3}$.

PROPAGATION OF THE PREDOMINANT FATIGUE CRACK – ENERGETIC APPROACH

The preponderant fatigue crack initiates for $N = N_g$ with depth $a = a_g$. For the copper under consideration in the cycle interval $N \in [N_g, N_T]$, resp. $a \in [a_g, a_T]$ the mesoscale crack propagation mechanism is still intergranular. For the second stage $N \in [N_T, N_R]$, resp. $a \in [a_T, a_R]$ the mesomechanism becomes transgranular. a_R is the depth corresponding practically to the fatigue failure N_R. We assume, by the reasoning analogous to the one in the foregoing that the mesomechanism of the predominant fatigue crack propagation obeys also the statistical law of Boltzmann exhibiting activation character with activation energy $(e - e_g)$, resp. $(e - e_T)$. e_g is the energetic barrier for the intergranular mechanism and e_T the corresponding barrier for the transgranular mechanism.

According to this assumption we consider a macroscale level with the corresponding energy $e = \sigma^p \varepsilon^p_{cum}$ (N) where $\sigma^p = K E_p^{\alpha-1}$, K being a macroscopic material constant, $\varepsilon^p_{cum} = 4N\,E_p$, e_g and e_T are the macroscopic energetic barriers. The rates of the predominant fatigue crack propagation during the two stages are $V_a^{(m)} = da^{(m)}/dN$ with m = I , II. $a^{(m)}$ is the macroscopic depth of the crack after N cycles, while $a^{(m)}/L^{(m)}$=const. Then :

Stage I : $N \in [N_g, N_T]$, resp. $a \in [a_g, a_T]$

$$V_a^{(I)} = V_g \exp\left\{\frac{e - e_g}{K_B\ T_0}\right\}, \quad a^{(I)} = a_g \exp\left\{\frac{e - e_g}{K_B\ T_0}\right\},$$
$$a_g = \frac{V_g}{\lambda_p^{(I)}}, \quad \left\{\frac{e - e_g}{K_B\ T_0}\right\} = \lambda_p^{(I)}\left(N - N_g\right) \tag{5}$$

Stage II : $N \in [N_T, N_R]$, resp. $a \in [a_T, a_R]$

$$V_a^{(II)} = V_T \exp\left\{\frac{e - e_T}{K_B\ T_0}\right\}, \quad a^{(II)} = a_T \exp\left\{\frac{e - e_T}{K_B\ T_0}\right\},$$
$$a_T = \frac{V_g}{\lambda_p^{(II)}}, \quad \left\{\frac{e - e_T}{K_B\ T_0}\right\} = \lambda_p^{(II)}\left(N - N_T\right) \tag{6}$$

Taking into account that $L^{(II)} = a^{(II)}/C$, $C = \text{const.}$, we express :

$$L^{(II)} = L = L_T\ \exp\left\{\lambda_p\left(N - N_T\right\}\right.$$
$$\lambda_p = \lambda_p^{(II)},\ L_T = a_T/C.$$

For $\lambda_p = \beta_0/N_R$, $\beta_0 = \text{const.}$, we obtain the expression of the unified relation $L = N/N_R$ for every $E_p = \text{const.}$ (Suresh (1), Ghammouri (5), Alain (6)). In a sense, this is a proof that the assumed activation mechanism for the predominant crack propagation is physically reasonable.

INFLUENCE OF PRECYCLING ON THE MATERIAL FATIGUE DURABILITY

A number of experiments with OFHC copper (5) show that the precycling could increase or decrease the fatigue durability N_R in comparison with the reference value $N_{R(r)}$.

The degree of this influence depends on : (a) the relation between the constant amplitudes in the two processes $\varphi = E_{ph}/E_p$ (the index h is reserved for the precycling) ; (b) the surface treatment after the precycling without surface polishing (N_p) and with polishing (N_p). We attempt to describe both processes, introducing the following parameters ; η_T – characterizing the influence of the precycling on the energetic barrier e_T ; η_h – characterizing the material structural changes in the whole specimen after N_h preliminary cycles.

For the first process :

$$a_h = a_{Th} \exp \left\{ \lambda_{ph} (N_h - N_{Th}) \right\}, \quad N_h > N_{Th} \tag{7}$$

For the second process we have :

$$a = a_h \exp \left\{ \lambda_p \overline{N} + \lambda_{ph} (\eta_T \ N_{Th} - \eta_h N_h) \right\}, \quad \overline{N} = N - N_h \tag{8}$$

Fatigue durability for the case without surface polishing :

$$\overline{N}_R^{'} = \frac{1}{\lambda_p} \ \ln \frac{a_R}{a_h} + \lambda_h \ (\eta_h N_h - \eta_T N_{Th}), \ \lambda_h = \frac{\lambda_{ph}}{\lambda_p} = \frac{K_h}{K} \ \varphi^{\alpha} \tag{9}$$

Fatigue durability for the case with surface polishing :

$$N_R^{''} = N_{R(r)} + \lambda_h \ (\eta_h N_h - \eta_T N_{Th}), \ N_{R(r)} = N_T + \frac{1}{\lambda_p} \ \ln \frac{a_R}{a_T} \tag{10}$$

The analysis of the relations (9) and (10) allows the following estimations :

$$\begin{cases} \text{(a) If } \ \eta_h N_h > \eta_T N_{Th}, \ \overline{N}_R^{'} > \overline{N}_{R(r)} = N_{R(r)} - N_h \ \text{ and } \ \overline{N}_R^{''} > N_{R(r)} \ ; \\ \text{(b) If } \ \eta_h N_h < \eta_T N_{Th}, \ \overline{N}_R^{'} < \overline{N}_{R(r)} \ \text{ and } \ \overline{N}_R^{''} < N_{R(r)} \end{cases} \tag{11}$$

The above relations reflect well the experimental results concerning the increase or the decrease of the fatigue strength. The model presented enables to interpret many other effects, as e.g. the deviation from the unified relation $(L–N/N_R)$ in the case of two successive processes, Ghammouri (5). The parameters η_T and η_h can be determined by the following procedure : (i) preliminary cyclic process with E_{ph}=const. until $N=N_h>N_{Th}$ then (ii) two cyclic processes with different $E_p(1)$=const., $E_p(2)$=const. until $N_R(1)$ and $N_R(2)$:

$$\begin{aligned} \varphi^{\alpha}(1) \ (\eta_h N_h - \eta_T N_{Th}) = \Delta N_R(1), \quad \Delta N_R(1) = \overline{N}_R^{''}(1) - \ N_{R(r)}(1) \\ \varphi^{\alpha}(2) \ (\eta_h N_h - \eta_T N_{Th}) = \Delta N_R(2), \quad \Delta N_R(2) = \overline{N}_R^{''}(2) - \ N_{R(r)}(2) \end{aligned} \tag{12}$$

On the basis of the results obtained the authors are performing further work concerning the mesostructural analysis of the phenomena studied in preceding sections.

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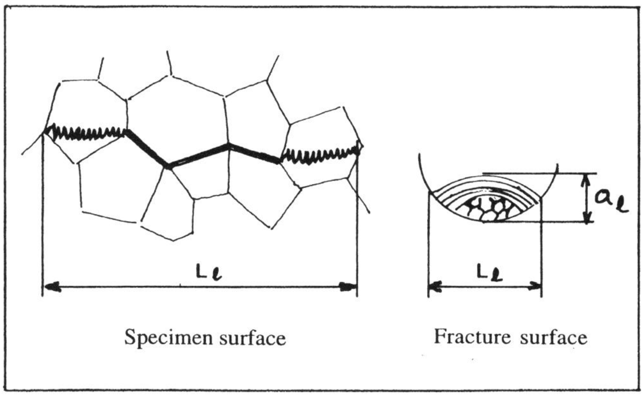

Figure 1 Schematic view of damage processes.

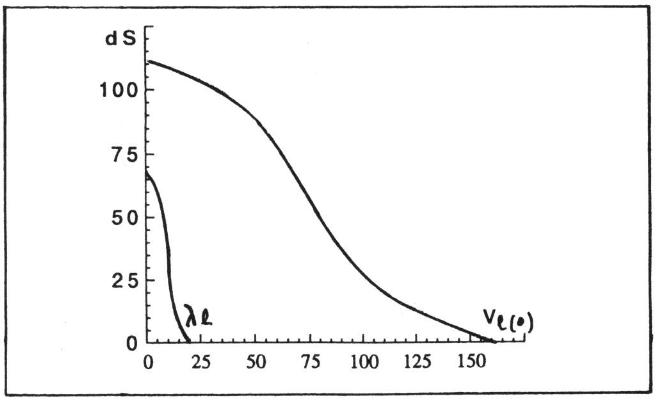

Figure 2 Distribution of initial $V_{\ell(0}$ and λ_ℓ values.