MODELING OF THE DAMAGE EVOLUTION AT THE GRANULAR SCALE IN POLYCRYSTALS UNDER COMPLEX CYCLIC LOADINGS

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Summary A multi-scale model of damaged elasto-inelastic behavior is proposed to predict the plastic fatigue life for FCC metallic polycrystals under multiaxial loading paths. This model is expressed in the time dependent plasticity for a small strain theory. It is assumed that the damage variables initiate and then evolve at the grain level where the phenomenon of the localized plastic deformation occurs. The totally damaged polycrystal is defined by a probabilistic approach.

INTRODUCTION

A multi-scale model of the early fatigue damage initiation already proposed has been tested under different loading situations [1-3]. Based on the isotropic damage concept, this model assumed that the intragranular damage evolves when the accumulated slip reaches a given critical value (threshold). Its evolution is only governed by the inelastic energy at the slip system level. The multi-scale model has correctly predicted the fatigue life under different complex cyclic loadings. However, this developed approach has demonstrated some restrictions because it can only describe those materials like the Waspaloy [3] in which the damage initiation takes always place at the slip system level. It is obvious that the adopted assumptions make this approach quite limited in its application for a number of metals. Hence, to generalize such an approach and then increase its applicability, it is assumed now that the damage is modeled at the granular level using the rational framework of continuum damage mechanics. This allows to describe several types of defects in the granular level like the cavity and in levels lower than the granular (e.g., dislocations, lattice defects, etc.). A new damage criterion is also developed to faithfully describe the experimental results, notably those related to the effect of the loading path on the fatigue life. Furthermore, from the physical viewpoint, it is not possible to damage all the grains in the polycrystal to determine the fatigue life; the Weibull's law is thus used by which the overall fatigue life becomes function of the calculated probability.

THE MULTI-SCALE MODEL

It is assumed that the damage variables (d^g) initiate and then evolve at the well-plastified grains in the polycrystal. The associated generalized thermodynamic force (Y^g) is determined as a total granular energy being decomposed into elastic and inelastic part. The damage variable is coupled with elasto-inelastic constitutive equations of the multi-scale elasto-inelastic model used in [3]. It is well known that micro-crack initiation takes place at the end of stage I of fatigue. Then, the micro-cracks propagation can be observed during the stage II up to the final fracture of the fatigued specimen. An attempt is made here to model micro-crack initiation especially at the end of stage I of the fatigue. Despite the heterogeneous local damaged behavior on the granular level, the isotropic damaged behavior concept is adopted neglecting the anisotropy due to damage effect. The model is expressed in the self-consistent framework of time dependent plasticity for a small deformation theory. Based on slip theory, a granular damage scalar variable (d^g, Y^g) is introduced at the granular level for FCC crystalline structure. Its rate is supposed to be mainly characterized in term of energy and is defined by:

$$\dot{d}_g = \frac{\left(\overline{Y}^g\right)^{S_0^g}}{S_g} \frac{H\left(p_g - p_g^{th}\right)}{\left(1-d_g\right)_{m_g}} \sum_{s=1}^{N_{sys}} \dot{\lambda}_s \qquad (1) \qquad \text{with} \qquad p_g^{th} = \gamma_g^{th} \left(1 - \frac{N_{sp}}{N_{st}}\right)^n \qquad (2)$$

where p^g is the granular accumulated plastic strain, S^g, S_0^g and m_g are material constants characterizing the damage mechanism at the granular level. H is the classical Heaviside function. It is important to note that a recent work [4] shows that the fatigue damage initiation criterion ($p_g^{th} = \gamma_g^{th}$) gives some fatigue lives fairly far from the experimental observations notably under complex loadings. Therefore, a new damage criterion should be not only function of the granular accumulated strain, but also of the nature of the loading situation. Such a new criterion under which the fatigue damage cannot be nucleated is given in (2). γ_g^{th} represents a threshold of the granular accumulated plastic strain, N_{sp}: the number of the activated plastic slip, N_{st}: the total number of slip system in the polycrystal. In order to model the totally damaged polycrystal, it is assumed that this phenomenon is governed by a probability law. The later follows the Weibull's law. Thus, it is supposed that a polycrystal can be damaged, if its damaged energy (ψ) attains a critical value (ψ_u). The totally damaged polycrystal condition takes place when the probability is almost equal to one.

$$p_f = 1 - \exp\left[-\frac{1}{V_0} \int_V \left(\frac{\psi - \psi_u}{\psi_0}\right)^n dV\right] \qquad (3)$$

where V_o is the polycrystal's volume. ψ_o and n are material parameters.

APPLICATION OF THE MODEL

The main goal of this paragraph is to qualitatively describe the overall damaged-inelastic behavior of polycrystals in multiaxial low-cycle fatigue. All the numerical simulations are conducted by employing a polycrystal of 400 grains. Different cyclic loading paths are used in this investigation, namely: uniaxial tension-compression (TC) and biaxial tension-torsion with various out-of-phase angles: $\phi=0°$ (TT0), $\phi=30°$ (TT30), $\phi=45°$ (TT45), $\phi=60°$ (TT60) and $\phi=90°$ (TT90) and butterfly test. These tests are carried out under strain-controlled condition with the maximum von-Mises equivalent strain. The influence of the loading paths on the fatigue lives is obviously pointed out in Table 1. In fact, the obtained results show (Table 1 and figure 1) that the fatigue life decreases remarkably with increasing ϕ. Also, it reveals, in general, that d^g (for $d^g \geq 0.6$) decreases with the increasing of the applied loading complexity.

Type of loading	Nomber of plastifed systems/grain	Number of grains with dg=0.1	Number of grains with dg=0.3	Number of grains with dg=0.6	Number of grains with dg=0.95	Fatigue lives N_f (number of cycles)
TC	**2.14**	234	122	68	44	**802**
TT00	2.16	189	82	34	2	773
TT30	2.20	236	110	59	23	744
TT45	2.37	259	134	66	33	598
TT60	2.82	192	131	63	28	486
TT90	3.02	149	105	47	21	412
Butterfly	**4.16**	121	77	34	17	**215**

Table 1: Influence of the loading path on the fatigue lives

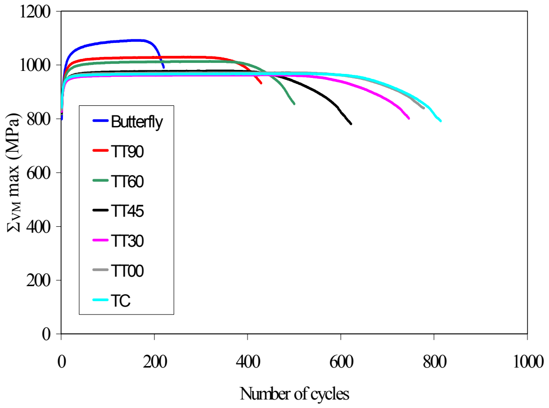

Figure 1: Predicted evolution of the overall maximum stress up to the final fracture of the polycrystal under different loading paths

As a typical example, figure 2 displays the maximum overall stress evolution during TT90 up to final damaging of the polycrystal when the probability (P_f) is near 1.

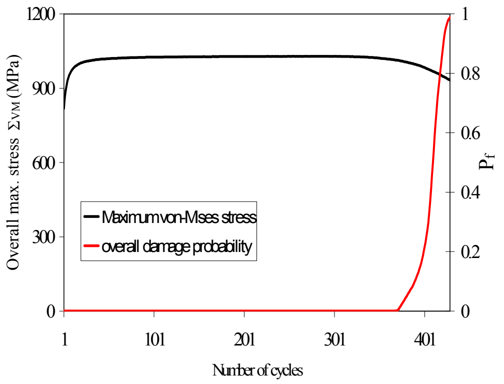

Figure 2: Predicted evolution of the maximum overall von-Mises stress and probability in TT90 up to final damaging of the polycrystal.

CONCLUSIONS

The proposed model reproduces successfully the inelastic fatigue behavior of polycrystals. It can naturally describe the overall cyclic stress-strain evolution using a local damaged constitutive equation. It gives a fairly well agreement with the experimental observations particularly for non-proportionality effect of the loading paths on the plastic fatigue life.

References

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