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Technical note

IDENTIFICATION DAMAGE MODEL FOR THERMOMECHANICAL DEGRADATION OF DUCTILE HETEROGENEOUS MATERIALS

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The failure of ductile materials subject to high thermal and mechanical loading rates is notably affected by material inertia. The mechanisms of fatigue-crack propagation are examined with particular emphasis on the similarities and differences between cyclic crack growth in ductile materials, such as metals, and corresponding behavior in brittle materials, such as intermetallic and ceramics. Numerical simulations of crack propagation in a cylindrical specimen demonstrate that the proposed method provides an effective means to simulate ductile fracture in large scale cylindrical structures with engineering accuracy. The influence of damage on the intensity of the destruction of materials is studied as well.

Key words: damage, manufacturing, thermal and mechanical fatigue.

1. Introduction

Ductile fracture is the failure of a solid material due to nucleation, coalescence and growth of cavities induced by plastic deformation. There are several ways, from empiric relationships [1, 2] to porous media stiffness modeling [3], developed to study this phenomenon in order to predict when a workpiece will fail under given stress-strain state. For damage evolution caused by large plastic deformation, Lemaitre and Chaboche developed the first and simplest model [4-8], which considers a linear evolution of isotropic damage with plastic strain in a uniaxial stress state condition. This model was later expanded by other authors, adding new capabilities such as dealing with anisotropic damage [9], or with non-linear damage evolution [10-14]. A reliable prediction of the material damage behavior in a forming process crucially depends on the appropriate identification of damage parameters, which are used in simulations. It has been repeatedly reported that during a forming process, mechanical properties of the material change, which causes a decrease in its strength due to microstructural changes [15]. When the material is subjected to cyclic loading at high values for stress or strain, damage develops together with cyclic plastic strain after a period of incubation preceding the phases of nucleation and propagation of microcracks. Considering the thermal dependence of material characteristic with the temperature, fatigue evaluation may be affected by this intrinsic dissipative phenomenon. Lemaitre's damage model is

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developed for plane stress cases. A fully coupled elastic-plastic-damage subroutine is developed and implemented into an explicit code. The effect of temperature on damage detection results was detected early. Eigen frequency changes caused by temperature effects on different structures were described in the works of Peeter and Deroek [16], Farrar [17] or Ralbovsky [18]. The effect of temperature was considered as an obstacle for damage detection. Various methods for removing this effect were proposed, Deroeck [19], Hu [20] and many other scientists.

The main goal of the performed work is to understand and further quantify the influence of controlled high thermal gradients in thermomechanical cycling on the damage and failure behavior of the material system.

2. Materials

The material considered in this study is F114 Carbon Steel. The main mechanical and thermal properties of tested specimen are summarized in Tab.1. The geometry of the steel is shown in Fig.1 to obtain a thermal stress loading under homogeneous uniform temperature distribution; the steel was restrained against axial expansion by creating an interaction boundary condition at its outside edge. In order to determine thermal strain in the analysis we need the thermal expansion coefficient α. Poisson's coefficient does not depend on temperature and takes a constant value $\upsilon=0.3$.

A displacement boundary condition was applied at the outside extremity of the tensile specimen. The displacement was smoothly ramped up in the first portion of the test and then held constant.

Table 1. Mechanical and thermal properties of the tested specimen.

F114 Carbon steel parameters	Values
Tensile modulus MPa	*7850*
Tensile strength (Nmm-2)	*600-750*
Yield stress (MPa)	*315*
Mass thermal capacity (Jkg-1K-1)	*460*
Thermal conductivity (Wm-1K-1)	*47-58*

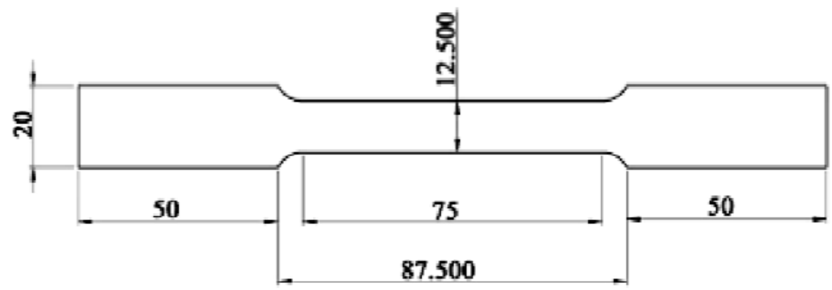

Fig.1. Geometry of F114 Carbon Steel.

3. Theoritical background

The continuum damage variable introduced by Kanchanov is defined as the relationship between the sectional area of voids A_v and the overall sectional area A_0 of a given surface in a volume element. Assuming the hypothesis of isotropic deterioration of the material, the damage can be written as

$$D = \frac{A_v}{A_0} = 1 - \frac{A_{eff}}{A_0} \tag{3.1}$$

where A_{eff} is the effective resisting area. It may be observed that this definition is the same as the micro-void area fraction used is some micromechanical theories, such as McClintock's [21]. The damage variable can assume any value between *0* and *1*, covering from a virgin state to a completely damaged reaches a critical value $D_c < 1$, when the effective area can no longer resist the applied load, loading to the formation of a macroscopic crack.

According to Lemaitre's damage model and strain equivalence principle, any constitutive equation for a damaged material may be derived in the same way as for the virgin material, replacing the stress tensor σ by the effective stress tensor $\tilde{\sigma}$, defined by

$$\tilde{\sigma} = \frac{\sigma}{1 - D}. \tag{3.2}$$

This is also the effective stress in compression if the microcracks and microcavities remain open. However, it is frequently observed that the cracks that open in tension, resulting in loss of load carrying area and stiffness, may partially close and increase the load bearing area and stiffness under thermomechanical loads. One important consequence of this assumption is that one can define an effective elastic modulus of the damaged material, giving an indirect way to measure the damage in a solid, by monitoring the evolution of the Young modulus with increasing strain

$$D = 1 - \frac{\tilde{E}}{E}. \tag{3.3}$$

$\tilde{E}$ is the effective elastic modulus and E is the elastic modulus for the undamaged material.

Using the thermodynamic of irreversible processes as the basis [8], CDM treats the damage as an internal thermodynamic state variable, and so its evolution can be derived assuming the existence of a potential of dissipation ϕ and an associated variable *Y*, called the damage strain energy release rate and defined as [8]

$$-Y = \frac{\sigma_{eq}^2}{2E(1-D)^2}\left[\frac{2}{3}(1+\nu)\sigma + 3(1-2\nu)\left(\frac{\sigma_H}{\sigma_{eq}}\right)^2\right]. \tag{3.4}$$

$\sigma_{eq} = \sqrt{2/3}\left\|\sigma^D\right\|$ is the von Mises equivalent stress, σ^D is the deviatoric stress tensor, ν is Poisson's ratio and $\sigma_H = \left(1/3\right) tr(\sigma)$ is the hydrostatic stress. The coupled constitutive equation for the plastic material is derived using the hypothesis of strain equivalence stated before. Further, Lemaitre [8] shows that the damage evolution can be written as

$$\dot{D} = \frac{\partial \phi}{\partial Y}(1-D)\dot{p}, \tag{3.5}$$

with $p = \sqrt{2/3}\left\|\varepsilon^p\right\|$ defined as the accumulated plastic strain and ε^p being the plastic strain tensor. This is the governing equation for ductile damage evolution as derived in its original form (Lemaitre [8]). However, as it has been mentioned, Lemaitre's model has been extended for more general conditions. In the Lemaitre and Chaboche model, the hypothesis of isotropic damage, existence of a strain threshold for damage initiation and linear evolution of the damage with the accumulation of plastic strain leads to the following equation for damage evolution

$$\text{for } \dot{D} = \begin{cases} 0 & \text{for} \quad p < p_D \\ \frac{-Y}{S}\dot{p} & \text{for} \quad p \geq p_D \end{cases} \tag{3.6}$$

p_D : accumulated plastic strain threshold and

S: damage resistance parameter.

For the uniaxial stress state, and assuming that the elastic strain can be neglected in comparison to the total strain, the accumulated plastic strain can be considered equal to the principal strain. The damage increases until it reaches a critical value D_c which can be calculated with the following equation [10]

$$D_c = \frac{D_{lc}}{R_v}\left[\frac{\sigma_u}{\sigma_{eq}}(1-D)^2\right], \tag{3.7}$$

D_{lc} : is the critical damage for the uniaxial stress state and can be measured in a tensile test, σ_u is the ultimate stress and

$$R_v = \left[\left(2/3\right)(1+\nu) + 3(1-2\nu)\left(\sigma_H/\sigma_{eq}\right)^2\right], \tag{3.8}$$

R_v is called triaxiality factor, which accounts for the difference between the actual stress state and the perfectly uniaxial stress state.

This model was later implemented in the ABAQUS/Explicit solver using subroutine [22] following the numerical algorithm proposed by lee and Pour-Boughrat [23].

4. Numerical methods description

The explicit finite element calculation software, ABAQUS/ Explicit, was employed for the simulation of traction deformation and fracture of the F114 Carbon Steel. The size of mesh in the element model was *0.05mm×0.05mm* and *0.1mm×0.1mm* for the *1mm* and *3mm* sample, respectively. The mesh was then transitioned toward the boundaries using triangular elements and quad elements where bilinear mapping could be employed. The finite element analysis results are critical for identifying crack propagation parameters during a TMF cycle. The selected element type was an 8-node linear brick, of reduced-integration elements (C3D8R). In the finite element model, the specimen was simplified as a rigid body. The displacement load was applied on the top specimen along the 3- axis direction with the other degrees of freedom fixed. In the traction test, the steel cylindrical rod suffered damage. The boundary element method (BEM) simplifies the meshing process and has the ability to correctly characterize the singular stress fields near the crack front. The boundary conditions applied to this model were the result of a global/local approach where displacements and temperatures were taken from the results of the global model and applied to the boundaries of the local sub-model studied here. The thermal portion of the analysis should consist of at least two steps. The first step is a steady-state analysis in which the blade is brought from an initial temperature of *70°F* to a steady operating temperature distribution and then the other step simulates the cool down.

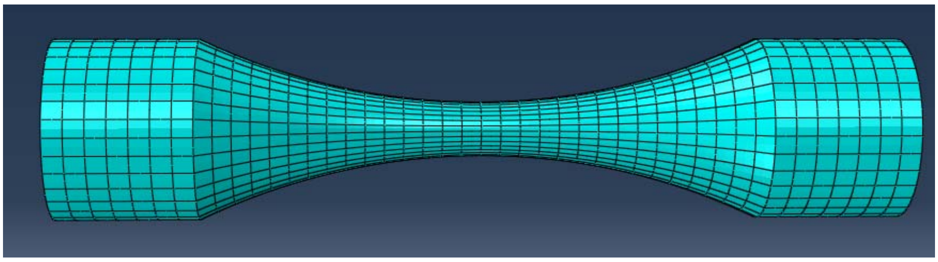

Fig.2. Coarse meshes.

5. Results and discussion

When a material is loaded at elevated temperature, for instance a temperature above 1/3 of the melting temperature, the plastic strain involves viscosity; that is, the material may be deformed at constant stress. When the stress is large enough, there are intergranular decohesions which produce damage and an increase of the strain rate through the period of tertiary creep. The damage can be determined by post-processing a reference structure calculation, performed in elasticity for quasi-brittle and high cycle fatigue applications and in elasto-plasticity for more ductile conditions. The reference calculation gives the stresses, strains and the plastic strains history with no damage at the mesolevel of classical continuum mechanics. As for ductile damage, the gradients of creep damage are similar to the visco-plastic gradients.

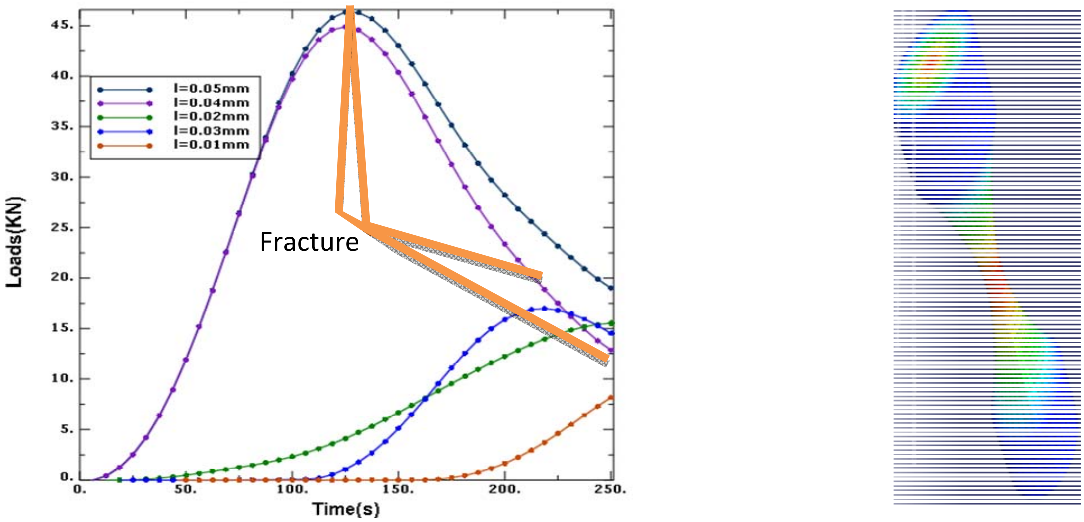

Fig.3. Influence of the length scale on the resulting deformation behavior of the cylindrical bar.

The results presented in Fig.3 prove that in the first *180* seconds the increase in force of only a few KN leads to the appearance of plastic deformation. In the case of the intrinsic length scale more than *l=0.03mm*, a rapid increase in force occurs 20 seconds after the beginning of plastic deformation. The final failure line started to run from one of the higher temperature regions in the early stage of plastic deformation, although these points often become indistinctive in the middle stage of plastic deformation. Thus, the failure-starting point can be predicted in the early stage of plastic deformation. To demonstrate the influence of the intrinsic length scale in the model, simulations have been performed with five different values: *0.01*, *0.02*, *0.03*, *0.04* and *0.05* [*mm*]. The evolution of the damage variable field obtained by the finite-element analysis is illustrated in Fig.3. The reason for faster damaging at the center lies in the fact that damage growth in ductile metals is strongly dependent on the stress triaxiality ratio which is highest at the center of the specimen. The damage rate is slightly smaller than the rate of effective plastic strain, as the displacement increases the stress state at the center of the specimen and causes the damage to increase exponentially whereas the equivalent plastic strain rate remains approximately constant.

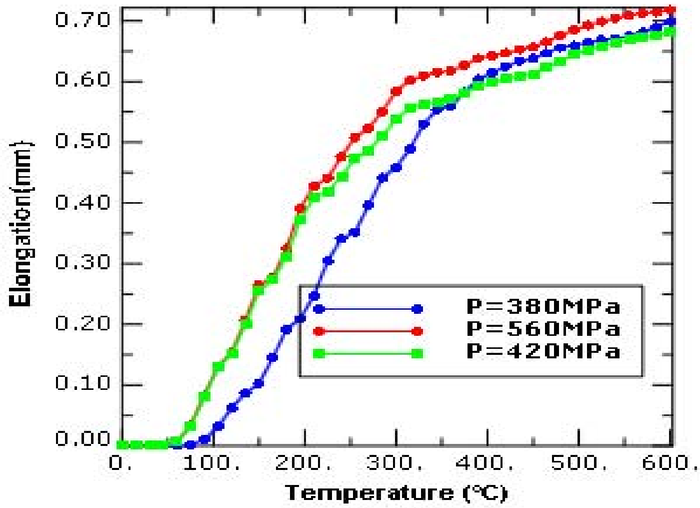

Fig.4. Elongation tensile evolution with thermal and mechanical loadings.

The results presented in Fig.4 show that the temperature variation can influence the behavior of the structure in two manners. First, thermal expansion must be considered in the elasticity law. Second, the possible dependence of material properties with respect to the temperature imposes us to consider this effect in the time discretization of the equations. With increasing temperature there is a decrease of compressive strength, density, thermal conductivity and thermal diffusivity in steel because of an increase in porosity and permeability. The progressive softening during the loading reflects the internal degradation of the material response. The deformation can occur more easily at elevated temperatures, so more plastic deformation zone of a fatigue thermomechanical crack. Damage propagation and crack initiation and ductile fracture can be predicted successfully. The effect of damage on the hydrostatic strain as a function of temperature variation is shown in Fig.4.

6. Conclusion

In this paper, by using the Finite Element Analysis (FEA), the mechanical properties and damage parameters for F114 Carbon steel were identified. The fully coupled elastic-plastic-damage model was developed and implemented into an explicit code. It is concluded that the finite element analysis (FEA) combined with continuum damage mechanics (CDM) can be applied to predict ductile fracture in ductile materials.

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