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Combining porous plasticity with Coulomb and Portevin-Le Chatelier models for ductile fracture analyses

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ABSTRACT

For large void volume fraction, the Rousselier porous plasticity model transforms naturally into a coalescence model, in the whole range of stress triaxiality, in agreement with the necessary kinematic coalescence condition (NKCC). It enables to model slant fracture in notched tensile or cracked specimens. Nevertheless, void coalescence is not the single mechanism involved in slant fracture. That is why it is necessary to combine porous plasticity with other models. In this paper, the Coulomb fracture model and the Portevin-Le Chatelier (PLC) model (or dynamic strain aging: DSA) are formulated at the slip system scale. The Coulomb model combines the resolved normal and shear stresses for each slip plane and direction. For DSA, we postulate that each slip system has its own history of dislocation pinning and unpinning by solute atoms. The models are fully coupled in the framework of classical polycrystalline plasticity. A Reduced Texture Methodology (RTM) is used to provide the computational efficiency needed for numerical applications. The RTM approach involves a significant reduction of the number of representative crystallographic orientations. The models are applied to a notched tensile specimen taken from a 6260 aluminum alloy thin-walled extrusion. Fractographic examinations show a combination of dimples and large smooth areas on the slant fracture surface (mixed fracture). It highlights the need for combined fracture models. The PLC model gives very sharp oscillations of the macroscopic plastic strain rate, associated with moving plastic strain rate bands. It leads to a significant reduction of ductility compared to porous plasticity alone.

1. Introduction

Ductile damage may be defined as the cause of failure processes involving a significant amount of dissipation. Various mechanisms can be involved:

1. plastic deformation diffuse macroscopic localization, like necking in round tensile specimens or in thin sheets
2. shear fracture due to strain localization in shear bands,
3. dimple fracture due to micro-voids initiation, growth and coalescence,
4. adiabatic softening and dynamic effects at high strain rates (these effects as well as creep mechanisms at high temperature are not considered in this paper).

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Necking (1) generally comes first. Therefore, a good modeling of large strain plasticity is a prerequisite for the analysis of the other mechanisms. An accurate modeling of *initial* anisotropy (if any), anisotropic *hardening* and non-proportional loadings is obtained with self-consistent polycrystalline plasticity (Luo and Rousselier, 2014). In this framework, a Reduced Texture Methodology (RTM) is used to provide the computational efficiency needed for finite element (FE) analyses. The RTM approach involves a significant reduction of the number of representative crystallographic orientations (usually 3 texture components and 12 orientations are sufficient for an orthotropic metal) and a specific parameter identification procedure including the texture parameters. An explicit integration algorithm is used for the material model.

At very low stress triaxiality, shear fracture (2) can be observed with no void damage on the fracture surfaces of a shear specimen taken from a thin 6260 aluminum extrusion (Rousselier and Luo, 2014). The Coulomb fracture model *at the slip system scale* is in agreement with experimental data. At higher stress triaxialities, void damage can occur at a very late stage of localized deformation, according to in situ 3-D X-ray computed tomography (XCT) of a thin 2198 aluminum compact tension specimen slant fracture (Morgeneyer et al., 2014). The fracture event is shear strain localization (2), it is not void damage. In these two examples, the underlying plastic softening mechanism is not known. The Portevin-Le Chatelier (PLC) phenomenon could be involved (Clausen et al., 2004; Wang et al., 2011).

With flat notched tensile specimens, that present higher stress triaxialities than the shear specimen, a mixed mechanism (2 + 3) is observed for the aluminum extrusion. The Coulomb fracture model has been combined with fully coupled porous plasticity in the RTM framework (Rousselier and Luo, 2014). The experimental and numerical results are in good agreement with regard to fracture strains and locations, macroscopic and microscopic features. In the present paper, a well-known dynamic strain aging (DSA) model (Kubin and Estrin, 1985; McCormick, 1988) for the Portevin-Le Chatelier (PLC) phenomenon is formulated *at the slip system scale*. The combination of this model with porous plasticity is numerically investigated.

More generally, the ability of porous plasticity to model strain localization in shear and slant fracture is questioned. That is why a return to some basics in ductile fracture modeling is presented in Section 2. In Section 3, the results of FE analyses of the notched tensile specimen with various combinations of the material models are discussed.

2. Return to some basics in ductile fracture modeling

2.1. Void growth

Initially, ductile fracture of metals was mainly investigated with fracture mechanics specimens, i.e. cracked geometries. Specimens with a machined crack are cyclically loaded in order to obtain a very sharp crack tip (A in Fig. 1a, O in Fig. 1b). The fatigue precrack tip radius approximately is the same as the fatigue striations width, i.e. smaller than $r_0 = 1$ μm. The specimen is then monotonically loaded. The crack tip radius drastically increases, up to approximately $r = 100$ μm. At some load, a ductile crack propagates from the blunted crack tip. Dimples can be seen on the fracture surface B in Fig. 1a. The blunted crack tip is called "stretch zone" (SZ). The stretch zone width (SZW) is more or less equal to the crack tip radius. Although dimples can exceptionally be seen in the SZ (C in Fig. 1a), the *new* surface (OF in Fig. 1b) of the blunted crack tip is not created by void growth and coalescence. The mechanism is similar to the one observed on the surface of tensile specimens at large strains, with the initially smooth surface roughened by the emergence of coarse slip bands. This mechanism, obviously related to the presence of a free surface, cannot be modeled with bulk plasticity (BP). It can be referred to as "surface plasticity" (SP). Both macroscopic and crystal plasticity models only consider slips in a 3D volume. Anyway, the deformation $\Delta r/r_0 \approx r/r_0 \approx 100$ is beyond the scope of any classical plasticity model. Only Discrete Dislocations Dynamics (DDD) could be an effective tool for SZ modeling, but the computational cost is beyond actual means.

In steel, void growth ratios R/R_0 were measured by Benzerga et al. (2004a) on sections of notched round bars loaded in tension. They varied between 3 and 10 under longitudinal loading and between 2 and 50 under transverse loading, depending on triaxiality level and growth direction. In high-purity copper, XCT of smooth tensile specimens gives void elongation ratios

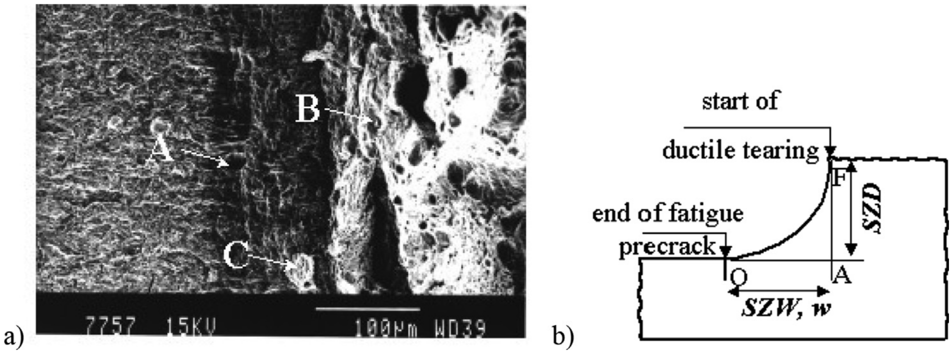

Fig. 1. Stretch zone at the tip of a fatigue crack in steel, loading direction Y, thickness direction Z: a) scanning electron microscopy (SEM) of the fracture surface, plane XZ, b) Crack tip section, plane XY.