Void growth and coalescence in irradiated materials

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VOID GROWTH AND COALESCENCE IN IRRADIATED MATERIALS

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Summary Irradiation with high energy particles induces crystalline defects in metallic materials. These microstructural changes strongly modify the mechanical properties, leading in particular to significant hardening and strain localization at the grain scale. The effects of irradiation on the mechanisms of ductile fracture - void growth and coalescence - are assessed in this study based on model experiments. Pure copper thin tensile samples have been irradiated with ions, showing a strong increase of hardness. Micron-scale holes drilled through the thickness of these samples subjecting to uniaxial loading conditions allow a detailed description of void growth and coalescence. Results are compared to those obtained on unirradiated materials, as well as to theoretical and numerical predictions.

BACKGROUND

Materials used in the nuclear field undergo significant microstructural changes due to ballistic damages of high energy particles such as neutrons, ultimately leading to the formation of crystalline defects [1]. Typically observed defects are faulted dislocation loops, cavities and stacking fault tetrahedron. These microstructural changes lead to the degradation of mechanical properties such as increase of yield stress and decrease of strain hardening capabilities at the macroscopic scale, but also changes in deformation modes at the microscopic (grain) scale - from rather homogeneous deformation to localization in bands. One key ingredient for structural analysis of nuclear power plant core components is the fracture behavior of the materials. The aim of this study is thus to assess the ductile fracture mechanisms of irradiated metallic materials, based on model experiments of void growth and coalescence.

MATERIALS AND METHODS

Pure copper films (75 μm thick) are used in this study as a model material to study the effect of irradiation on ductile behavior, both at the unirradiated and irradiated states. Proton-irradiation have been performed to emulate neutron irradiation at the JANNuS facility [2], leading to the formation of crystalline defects. Increase of yield stress and decrease of strain-hardening capabilities have been quantified post to irradiation. 20 μm diameter voids were drilled through the thickness of tensile samples machined from the thin films using Focused Ion Beam (FIB) atomic milling (Fig. 1). Tensile samples were subjected to uniaxial loading conditions, and the evolution of the voids dimensions was measured using Scanning Electron Microscope (SEM) as a function of applied strain (Fig. 2). Such model experiment - first proposed in [3] - allows a detailed characterisation of the ductile fracture mechanisms of void growth and coalescence.

RESULTS AND DISCUSSION

For both unirradiated and irradiated materials, the evolution of voids dimensions and coalescence strains are shown to be in rather good agreement with theoretical predictions (McClintock growth model, Coalescence models) and in very good agreement with finite element simulations accounting for the evolution of mechanical properties with irradiation. Irradiated material exhibits a higher void growth rate compared to unirradiated material. For the void size used in this study, only the increase of yield stress and the decrease of strain-hardening capabilities - and not the change in deformation modes promoting localization - are thus sufficient to describe the effect of irradiation of the ductile behavior of irradiated materials. Lower void sizes are finally used to assess the potential effect of localized bands on void growth and coalescence.

References

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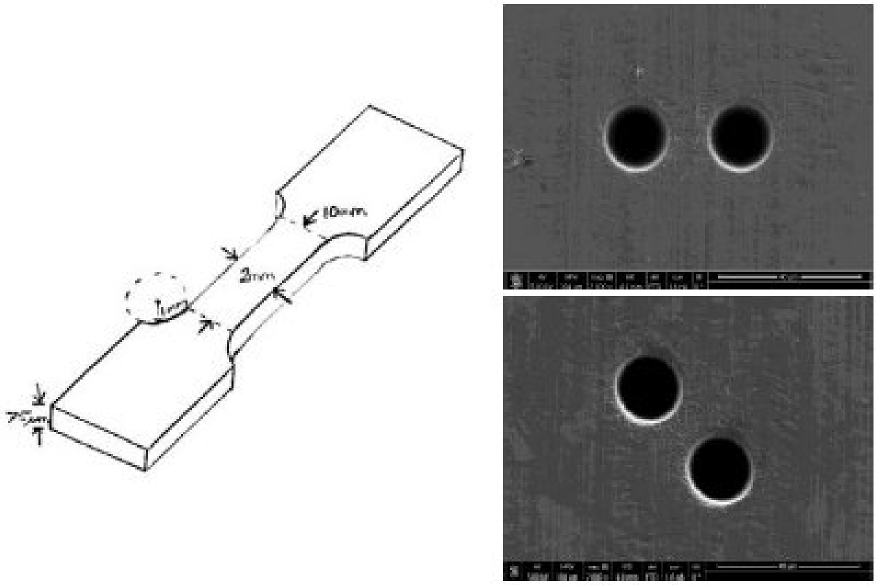

Figure 1: Tensile sample geometry and holes (20 μm diameter) drilled by FIB (Focused Ion Beam) through the thickness of the samples to assess void growth and coalescence.

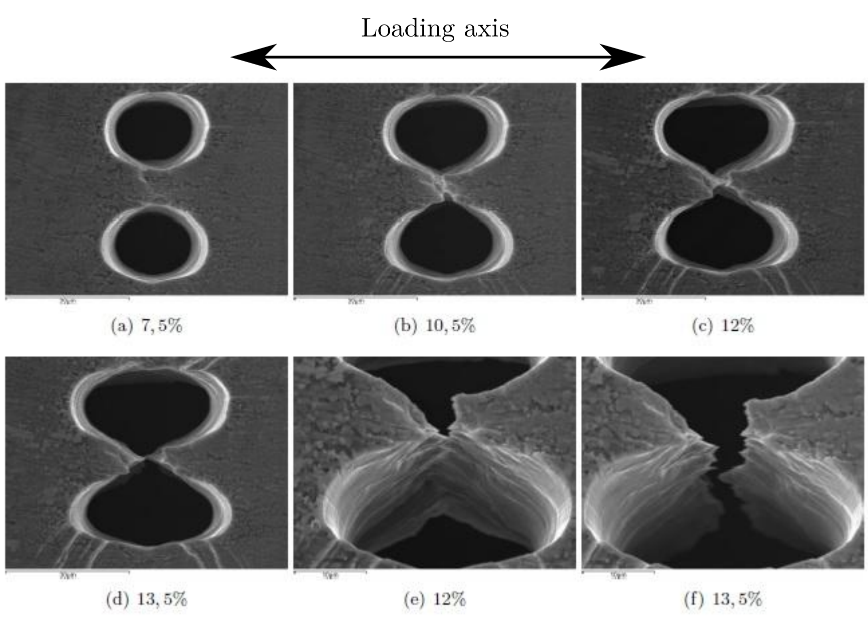

Figure 2: Typical SEM (Scanning Electron Microscope) observations of void growth and coalescence in pure copper in uniaxial loading conditions, as a function of macroscopic plastic strain.