Void growth and coalescence in irradiated materials

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VOID GROWTH AND COALESCENCE IN IRRADIATED MATERIALS

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Abstract: 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 protons. Micron-scale holes drilled through the thickness of these samples subjected to uniaxial loading conditions allow a detailed description of void growth and coalescence. Comparisons of experimental results to analytical and numerical results tend to indicate that, for voids of typical size on the order or higher than the grain size, accounting for irradiation macroscopic hardening is sufficient to model void growth and coalescence in irradiated materials

1. Introduction

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. One key ingredient for structural analysis of nuclear power plant core components is the fracture behavior of the material. 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.

2. Experimental setup

Pure copper foils (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 was performed to emulate neutron irradiation. 15 µm diameter cylindrical voids were drilled through the thickness of tensile samples (machined from the thin foils) using Focused Ion Beam (FIB) atomic milling (Figs. 1a, 2). 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. 1b). Such model experiment - first proposed in [2] - allows a detailed characterization of the ductile fracture mechanisms of void growth and coalescence. Experimental results on both unirradiated and irradiated materials are compared to 3D Finite Element simulations and to analytical results (McClintock growth model [3] and Thomason-like coalescence criterion [4]).

3. Results and Conclusions

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 model) 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 mode

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promoting localization - are sufficient to describe the effect of irradiation of the ductile behavior of irradiated materials.

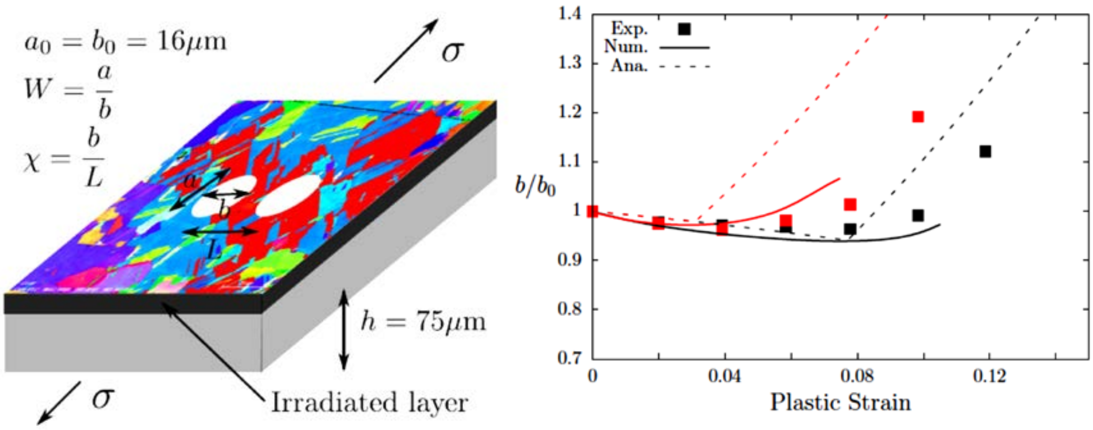

Figure 1. (a) Cylindrical holes drilled with FIB in a 75 um thick pure copper foil subjected to uniaxial tension (b) Comparison between experimental results, finite element simulations and analytical results (black: unirradiated, red: irradiated)

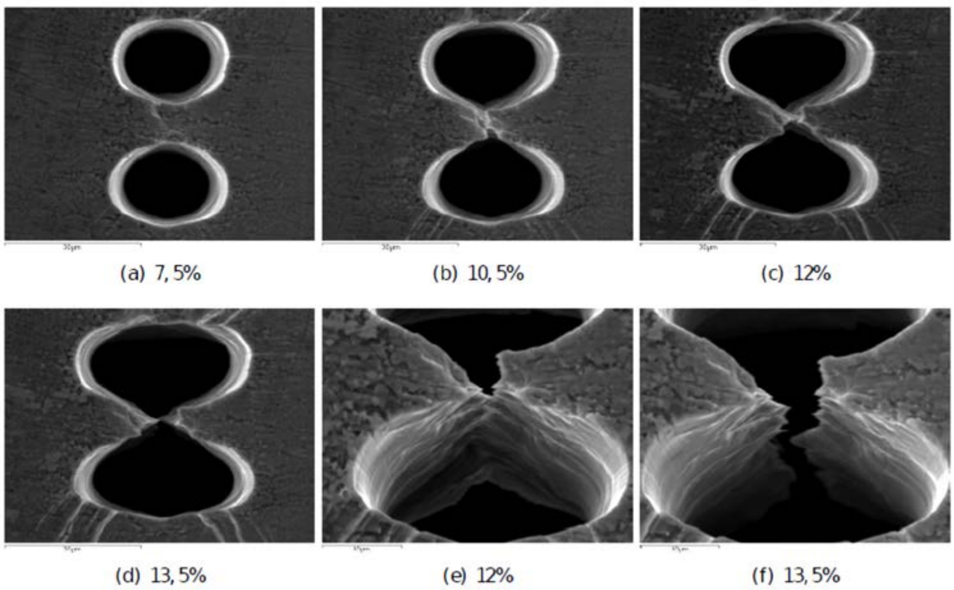

Figure 2. Typical observations of growth and coalescence of two cylindrical holes at different plastic strain

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