Void growth and coalescence in irradiated materials
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Background and Objectives

Structural materials used in nuclear environment are subjected to high energy particles irradiation - e.g. neutrons - leading to the creation of crystalline defects - e.g. dislocation loops, stacking faults - and associated evolution of mechanical behavior such as hardening, loss of strain hardening capability, strain localization.

Ductile fracture toughness through void growth and coalescence - a key ingredient for safety structural analysis - decreases dramatically with irradiation.

- Are there specific mechanisms such as strain localization associated with the ductile fracture of irradiated materials?
- Are the available models sufficient to describe void growth and coalescence in irradiated materials?

Materials and Methods

\[ a_0 = b_0 = 16\mu m \]
\[ W = \frac{a}{b} \]
\[ X = \frac{b}{L} \]
\[ h = 75\mu m \]

Polycrystalline thin copper films of 75\mu m thickness
- Proton-irradiation on one side up to 20\mu m
- Focused-Ion Beam (FIB) drilling of pairs of cylindrical holes
- Uniaxial loading conditions

Void growth and coalescence are assessed on each side (unirradiated and irradiated) through monitoring the evolution of holes dimensions with strain under Scanning Electron Microscope (SEM).

Experimental results are compared to 3D Finite Element (F.E.) simulations (accounting for the stress-strain behavior of both unirradiated and irradiated layer), and to analytical results:

McClintock growth model: Pre-coalescence
\[ a + b = (a_0 + b_0)[1 + p(1 + 2\sqrt{3})/4] \]
\[ a - b = (a_0 + b_0)\sqrt{3}p \]

Post-coalescence
\[ a + b = (a_0 + b_0)\exp[\Delta\nu_c(1 + \sqrt{3}\sinh(\sqrt{3}))] \]
\[ a - b = (a_0 + b_0)[(a_0 - b_0)/(a_0 + b_0)]\exp[2\sqrt{3}\sinh(\sqrt{3})\Delta\nu_c] \]

Thomason-like (necking) coalescence criterion
\[ \frac{\sigma}{\sigma_0} = \frac{1}{3}(1 - \chi)\left[1 + \left(\frac{1}{2W}\chi\right)^2\right] \]

Experimental and Numerical results

- Evolution of stress-strain behavior with irradiation
  - Significant hardening \[\Delta\sigma_{ys} = 130\text{MPa}\]
  - Decrease in strain-hardening
  - Increase in localization at grain scale

- Void growth and coalescence
  - Accelerated void growth and coalescence in the irradiated layer, consistent with:
    - F.E. simulations
    - Analytical models (McClintock, Thomason)
  - No significant influence of strain localization at the grain scale

Conclusions

Model experiments have been performed to assess void growth and coalescence in irradiated material in order to gain insight into the ductile fracture behavior of materials used in nuclear environment:

- Proton-irradiation emulating neutron-irradiation; hardening, loss of strain-hardening capability
- FIB-drilled holes on both unirradiated and irradiated material

Assessment of experimental results with analytical and numerical models tends 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.

References