# Using Novel Small Scale Mechanical Testing to Link the Mechanical Properties and Deformation Mechanisms of High-Dose Activated Inconel X-750

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As fuel-assembly hold-down springs, control guide-tube support pins, jet pump beams, and core internal bolts within light water reactors and fuel channel annulus spacers in modern CANDU reactors. Radiation effects on Ni-based alloys are highly dependent on the neutron energy spectrum and temperature in the reactor core with which they operate. The high-dose material presented in this study ($T_{irr\ avg}$ = 180 °C and $T_{irr\ avg}$ = 300 °C) functioned in a high thermal-neutron flux spectrum where (n,α), (n,p), and (n,γ) transmutation reactions accounted for the bulk of the total displacement damage. This damage, plus contributions from fast-neutron direct collision cascades, causes the material to incur dose rates between 2 and 4 dpa/yr in service. In addition, the transmutation reactions generate high internal helium and hydrogen gas contents, > 2.6 at% He and > 0.5 at% H (Judge et al., 2013), in the highest dose Inconel X-750. The high helium content has been linked to helium grain-boundary embrittlement in the bulk component that leads to intergranular failure as shown in Figure P14 (Judge et al., 2015).

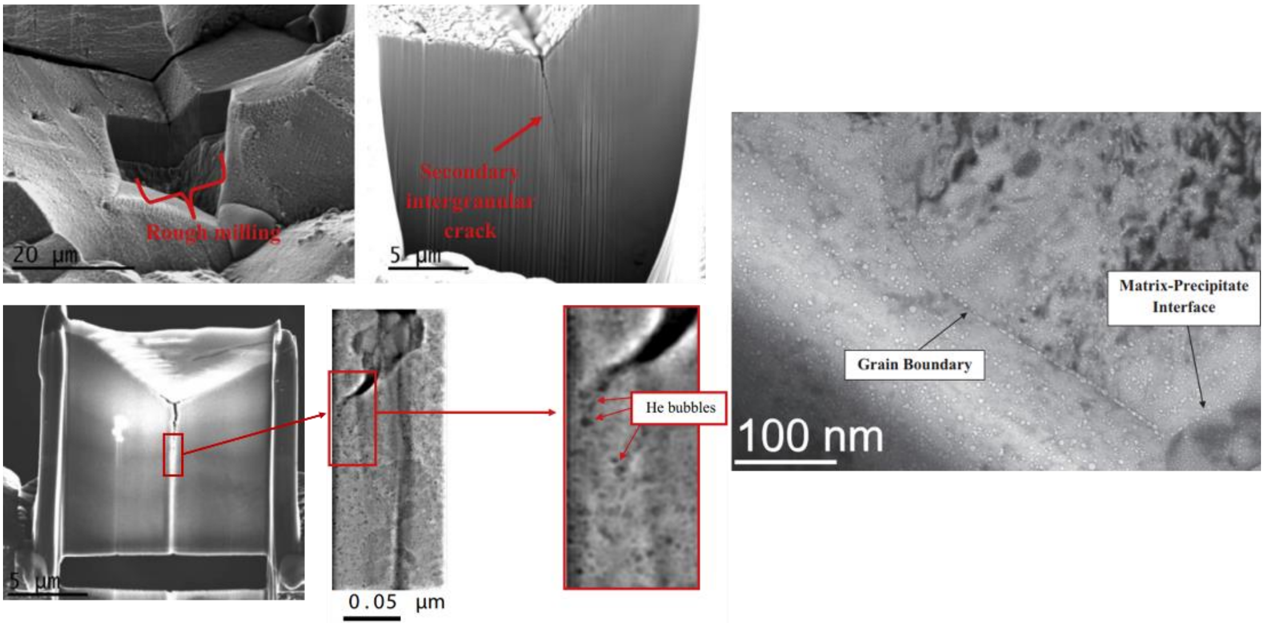


Figure P14: Direct evidence of helium grain boundary embrittlement linked to intergranular failure in high dose (53 dpa, 1.8 at% He) Inconel X-750 (Judge et al., 2015).

Previous post-irradiation experiments utilizing novel, micro-three-point bend testing quantified the flexural yield strengths of material irradiated to 53 dpa and 67 dpa at both 180 °C and 300 °C as shown in Figure P15, taken from (Howard et al., 2015; 2018). Differences in the yielding behavior of the high dose material at the two irradiation temperatures can be attributed to differing helium bubble hardening mechanisms. High temperature material with average bubble sizes > 2 nm forces dislocations to change course more than in low temperature material with average bubble sizes ~1 nm. This is reflected by large yield-strength increases in high-temperature material, whereas there is little difference in the yield strengths of non-irradiated, 53 dpa, and 67 dpa material irradiated at 180 °C.

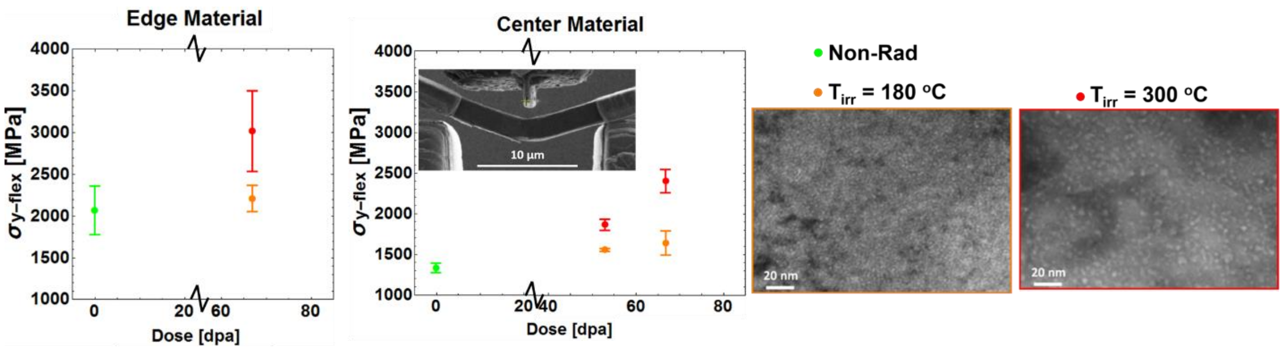


Figure P15: Flexural yield strengths of high dose, Inconel X-750, micro-three-point bend specimens (Howard et al., 2015; 2018 and their associated matrix helium bubble microstructures (Judge et al., 2015).

Assessing the mechanical properties beyond yielding via this testing technique was rather difficult because the specimens could not be tested to ultimate failure. There were a few indications of cracks along grain boundaries in specimens irradiated to 67 dpa after they yielded via deformation slip bands seen in SEM test videos, but more precise, direct evidence of failure strengths, degradation mechanisms, and ductility parameterization was still desired.

New processes developed at CNL utilizing the Fuel and Materials Cells (FMC) in combination with an active FEI Versa Focused Ion Beam (FIB) workstation and post-test TEM analysis led to the development and refinement of a second, novel, push-to-pull, micro-tensile, post-irradiation examination small scale mechanical test. Sample preparation techniques target specific boundaries of interest by coupling EBSD analysis with nanomanipulator lift-outs of active volumes of material (~1.25 µm x ~1 µm x ~2.5 µm). Micro-tensile testing of high-dose material irradiated to 80-85 dpa provides strong evidence for a mixed-mode failure mechanism involving both dislocation slip bands/channels which develop in the grain interior and grain boundary failure. Grain interior deformation shears and elongates helium bubbles such that they coalesce, leading to channel fracture (Figure P16a). Grain-boundary inclusions have also been shown to initiate cracks within the grain boundary, fracturing the boundary (Figure P16b). Micro-tensile testing also quantifies the mechanical properties of high-dose Inconel X-750 in terms of its critical resolved shear stress, yield strength, failure strength, and total elongation.

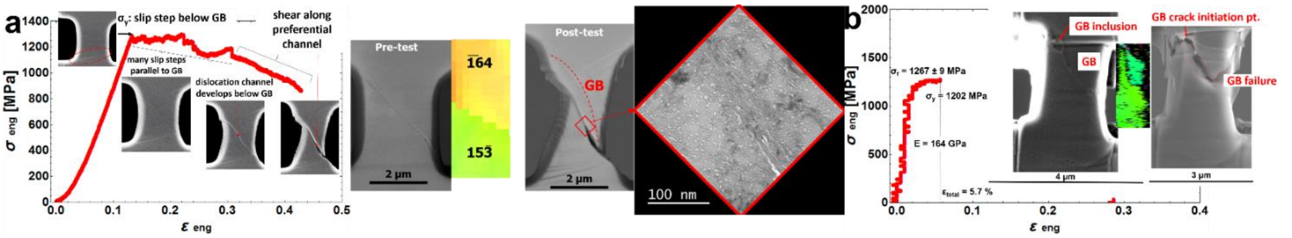


Figure P16: Micro-tensile specimens exhibiting (a) channel fracture and (b) intergranular fracture

## References


Howard, C., et al. (2015). Characterization of Neutron Irradiated CANDU-6 Inconel X-750 Garter Springs via Lift-Out Three-Point Bend Tests. In HOTLAB 2015 – Annual Meeting on hot laboratories and remote handling.

Howard, C., Judge, C. D., Poff, D., Parker, S., Griffiths, M., & Hosemann, P. (2018). A novel in-situ, lift-out, three-point bend technique to quantify the mechanical properties of an ex-service neutron irradiated inconel X-750 component. *Journal of Nuclear Materials*, *498*, 149-158.

Judge, C., Griffiths, M., Walters, L., Wright, M., Bickel, G., Woo, O., ... & Garner, F. (2013). Embrittlement of Nickel Alloys in a CANDU Reactor Environment CANDU (CANadian Deuterium Uranium)® is a registered trademark or Atomic Energy of Canada Limited. In *Effects of Radiation on Nuclear Materials: 25th Volume*. ASTM International.

Judge, C. D., Gauquelin, N., Walters, L., Wright, M., Cole, J. I., Madden, J., ... & Griffiths, M. (2015). Intergranular fracture in irradiated Inconel X-750 containing very high concentrations of helium and hydrogen. *Journal of Nuclear Materials*, *457*, 165-172.