Nanomechanical Testing in Materials Research and Development V

Proceedings

Fall 10-5-2015

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High-Temperature Fracture Test Using Chevron-Notched Tungsten Microcantilevers

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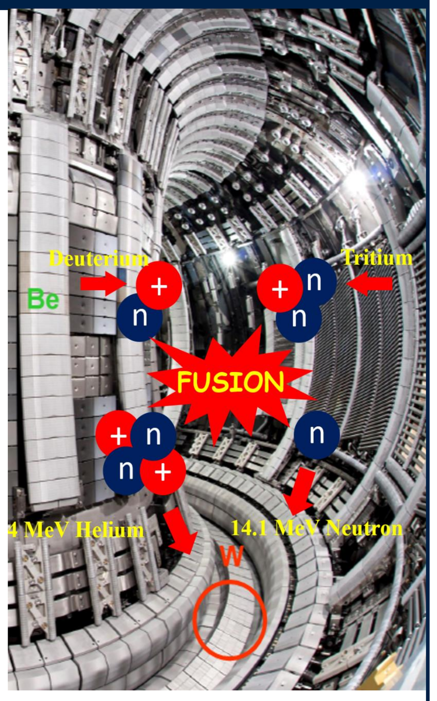
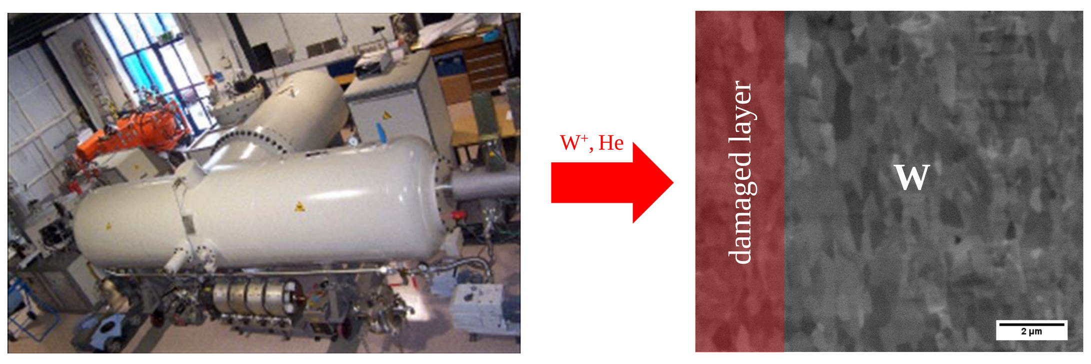
Introduction

Tungsten alloy, due to it's superior high-temperature strength, is currently the primary candidate material for the plasma facing components (PFCs) of the fusion divertor. Fusion reaction creates energetic neutron & helium, which bombards the tungsten PFCs and induces severe embrittlement. Ion-irradiation is often used as surrogates for the neutron damage, as it doesn't activate specimen and accumulates damage faster. However, the major drawback is the shallow damage layer. The goal of this work is to develop micro-scale fracture tests to measure the fracture behaviour of tungsten from the irradiated layer, in a fusion-relevant temperature.



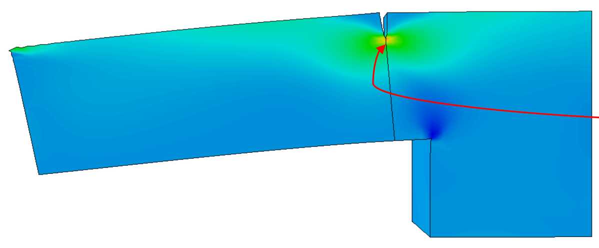
Cross-sectional view of the Joint European Torus at the Culham Centre of Fusion Energy



Ion-irradiation at the University of Surrey. The damaged layer is often in the micro-metre regime, depending on the type of ions and energy used

Micro-Fracture Testing

Combination of FIB-based sample preparation and nanoindentation allows fracture tests to be conducted at the micro-scale. Successful tests using linear-elastic fracture mechanics (LEFM) analysis had been done on brittle materials, where the plastic zone at the crack tip is small with respect to sample dimensions.

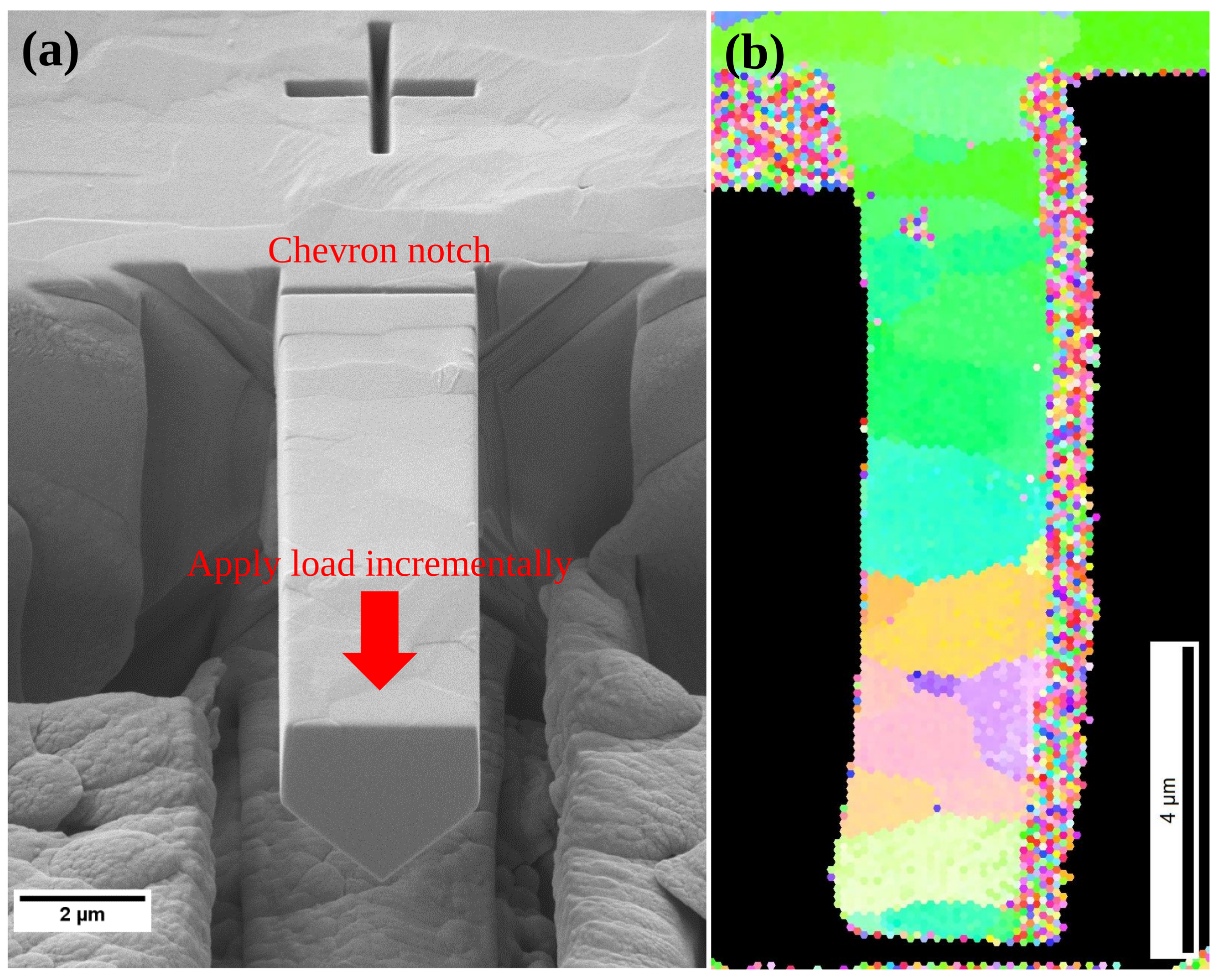


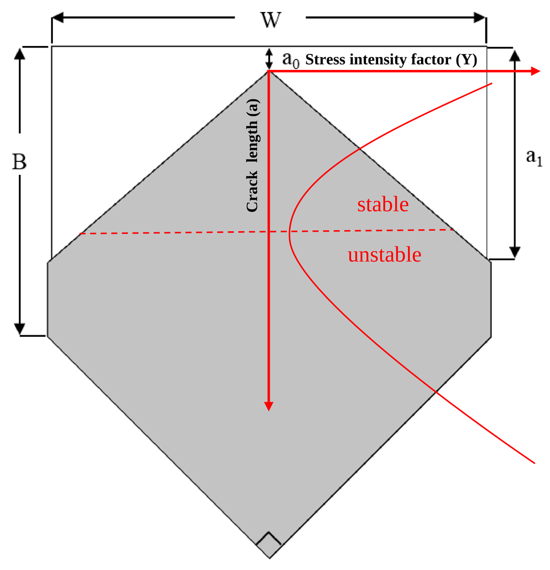
$$r_y = \frac{1}{2\pi}\left(\frac{K_I}{\sigma_{ys}}\right)^2$$

r_y : plastic zone radius

However, in semi-brittle tungsten, the plastic zone size is comparable with sample dimensions, LEFM is no longer applicable and elastic-plastic fracture mechanics (EPFM) analysis is necessary to evaluate the true fracture toughness. This work introduces a novel chevron notch design to the microcantilever to promote stable crack growth, which is a prerequisite for the EPFM approach.

Chevron-Notched Microcantilever



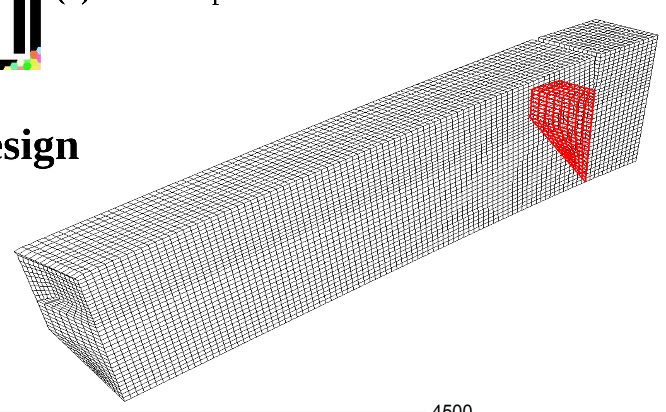


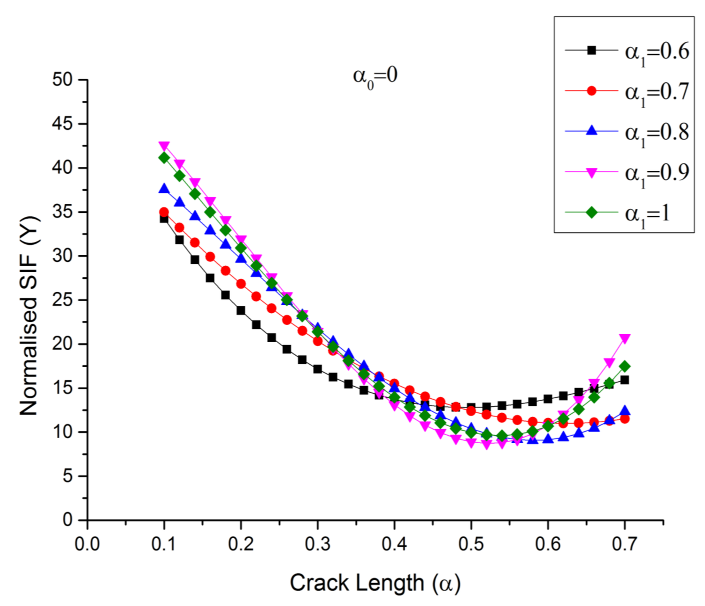
- Pre-cracking not needed
- Promote stable crack growth
- Well-defined crack geometry

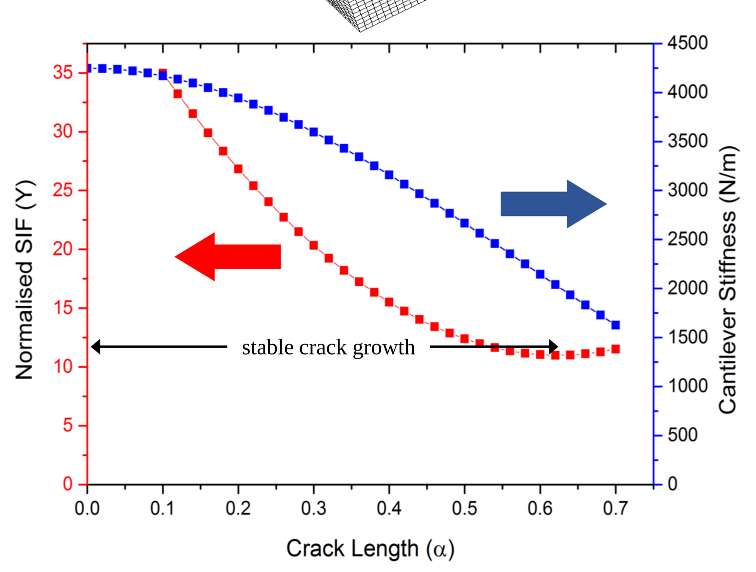
(a) SEM image of pentagonal WTa microcantilever
(b) EBSD map of the cantilever

Finite element modelling is used to optimise chevron notch design

- Finds chevron geometry with longest stable crack growth
- Cantilever stiffness can be plotted against crack length

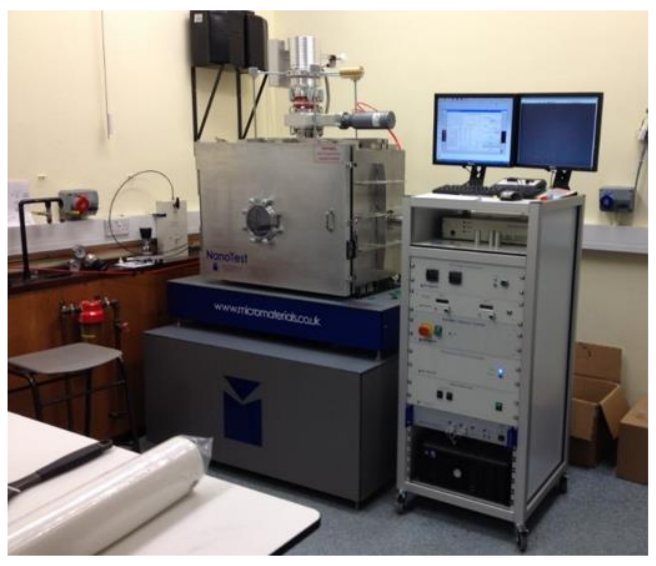


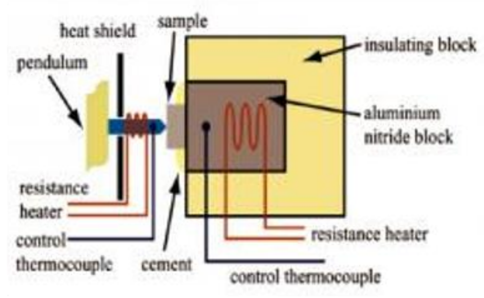


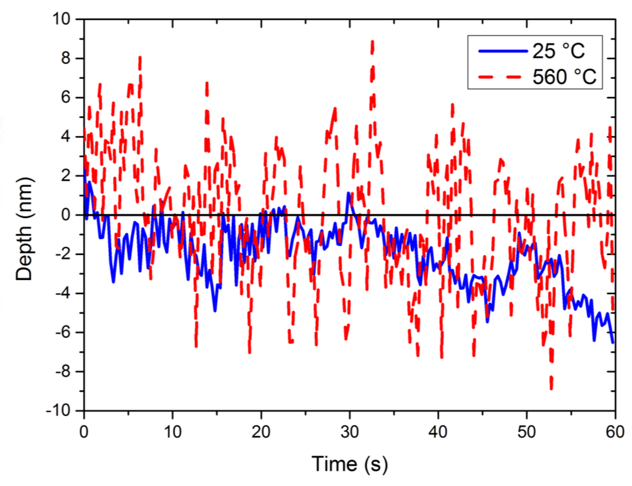


High-Temperature Nanoindentation

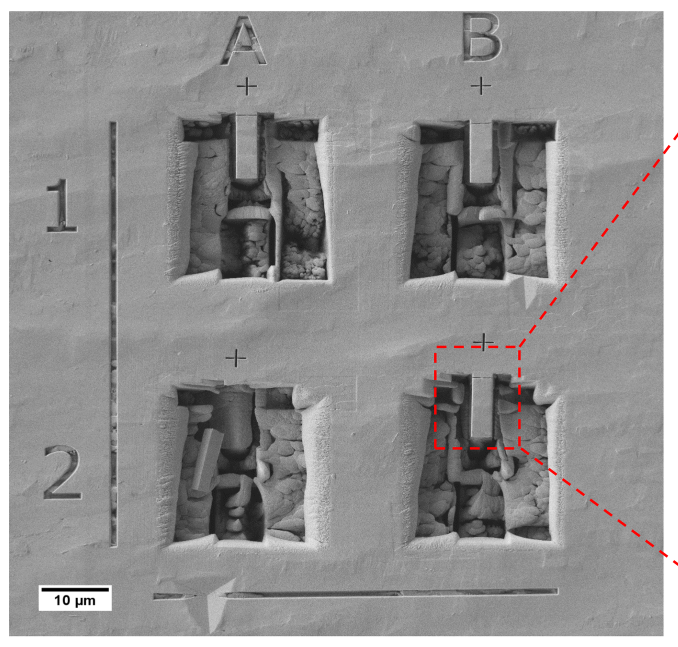
MicroMaterials® NanoTest Xtreme, a variable temperature nanoindenter (-100 to 950 °C) was used to conduct high-temperature micro-fracture tests under high vacuum environment. The temperature of the tip and sample were matched carefully to minimise the thermal drift issue (drift rate < 0.08 nm/s), which can cause great inaccuracy in tests with long contact time.

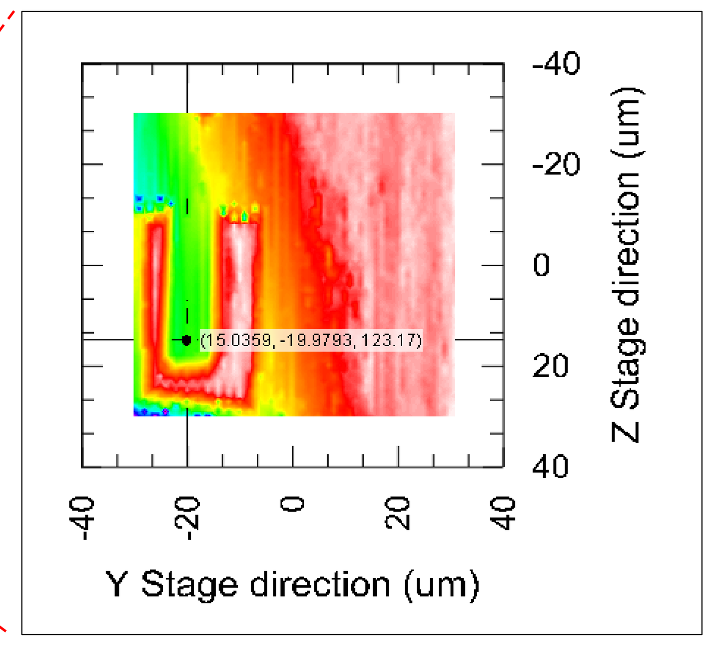






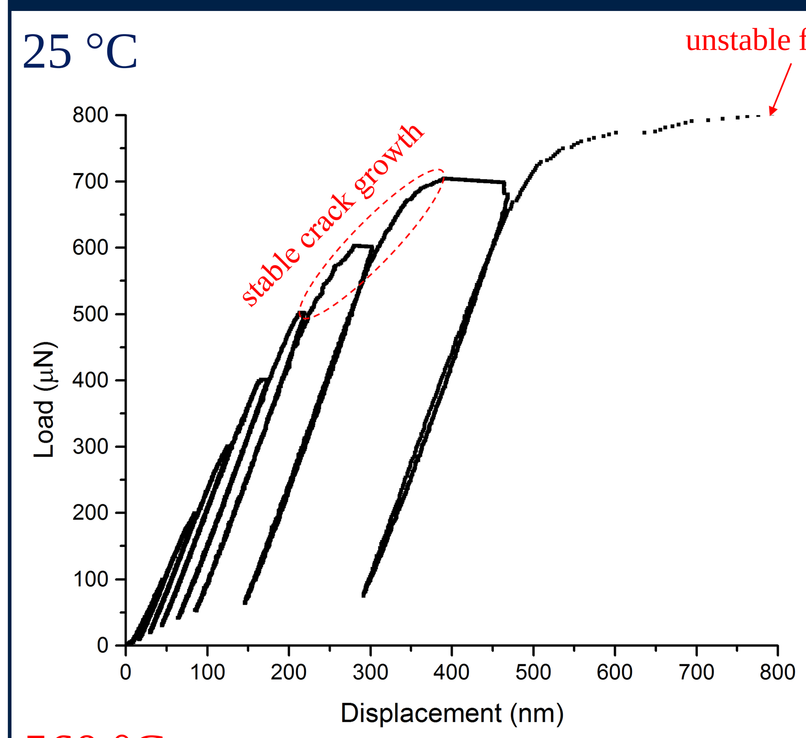
The indenter was first operated in imaging mode to generate a high-resolution surface scan, so the loading point can be precisely positioned. A partial load/unload method with a hold dwell period at each peak load was applied to measure the cantilever stiffness until unstable fracture occurs.

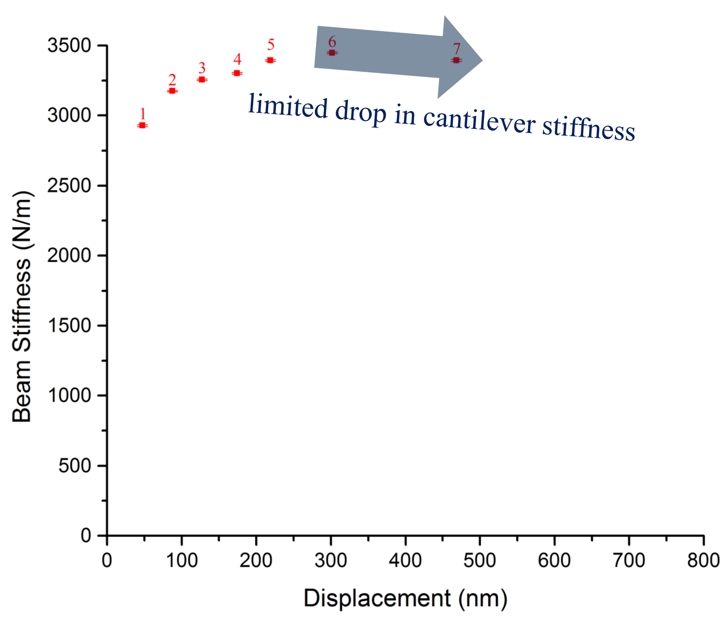


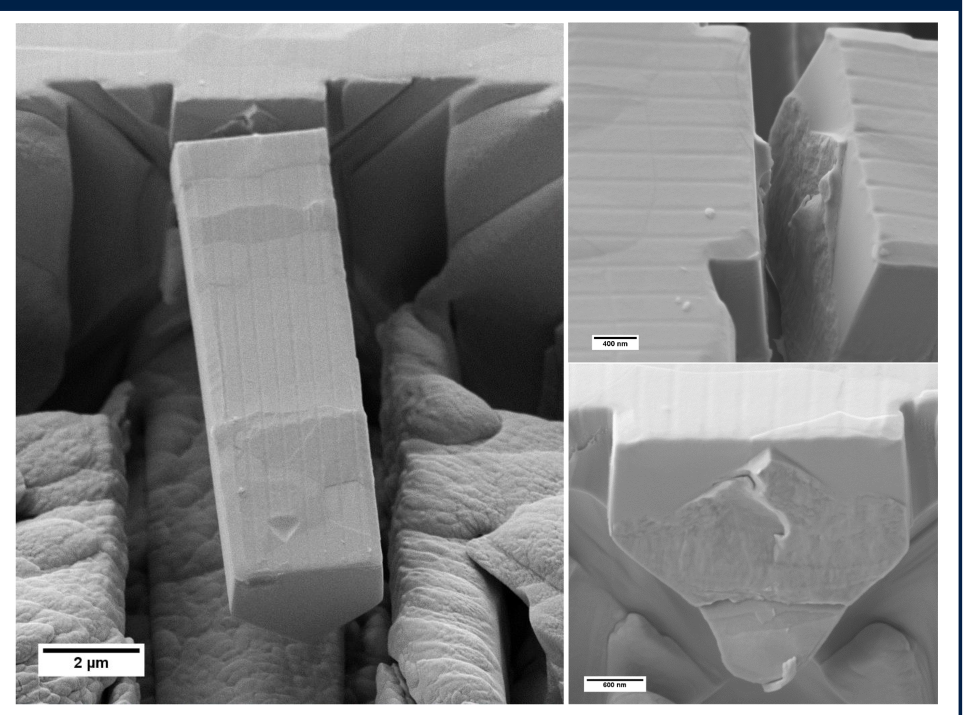


Experimental Results

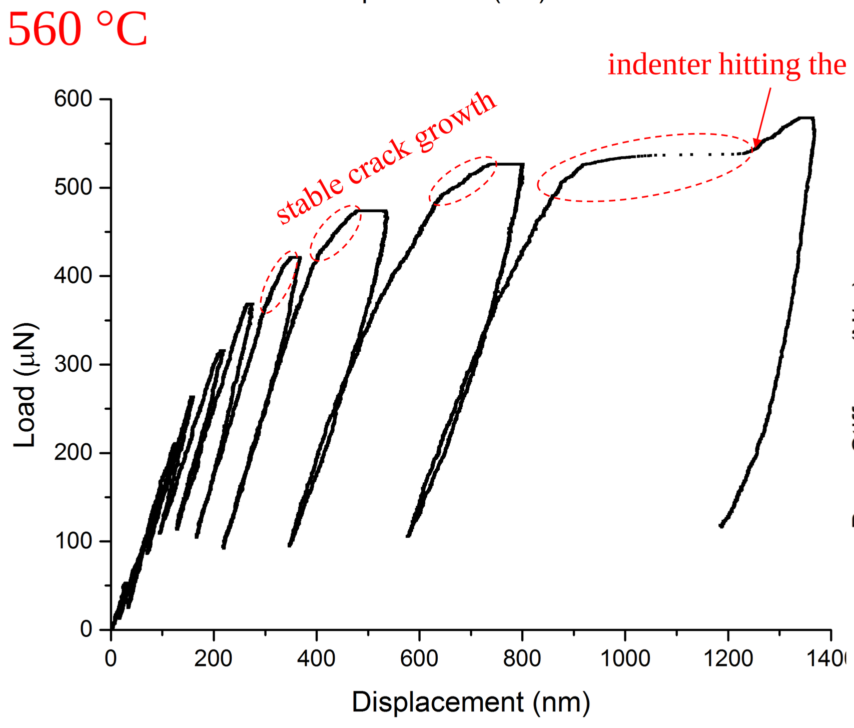
25 °C

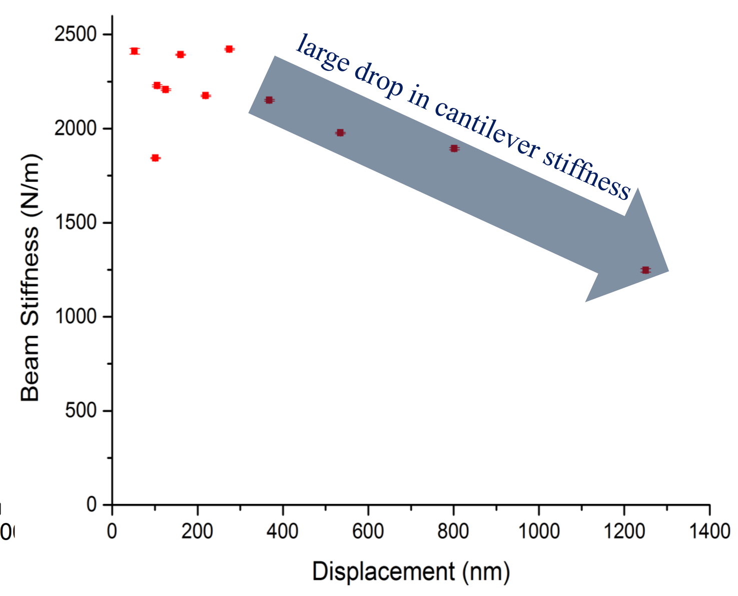


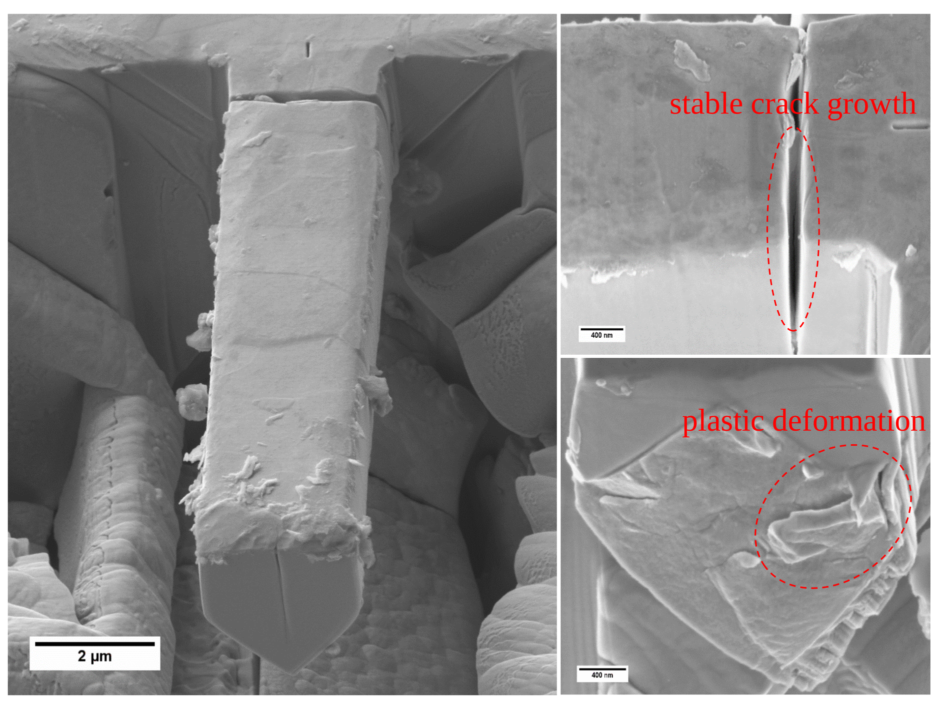




560 °C





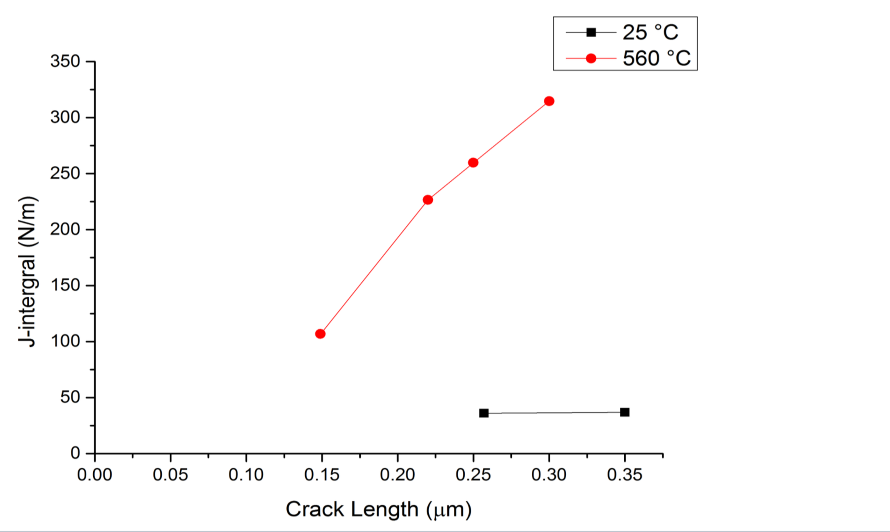


Conclusions

- Chevron notch microcantilever promotes stable crack growth
- Crack length is measured via partial load/unload method
- EPFM analysis reveal the crack resistance curve of tungsten at 25 °C is flat, but a clear rising trend at 560 °C

$$J_i = J^{el}_{(i)} + J^{pl}_{(i)} = \frac{K^2_{IQ}(1-\nu^2)}{E} + \frac{\eta\left(A^{pl}_{(i)} - A^{pl}_{(i-1)}\right)}{C_{(i)} - C_{(i-1)}}$$

η: constant 2, **$C_{(i)}$**: crack open area at i-th loading, **A_{pl}**: area under the load-displacement curve



Acknowledgements

The authors would like to thank the EPSRC grant *"Materials for Fusion & Fission Power"* and Dr. James Gibson for the help on the hot-nanoindentation.