MAX phases: embracing fire and radiation

MAX phases for MAXimum safety: advances in materials for nuclear reactors

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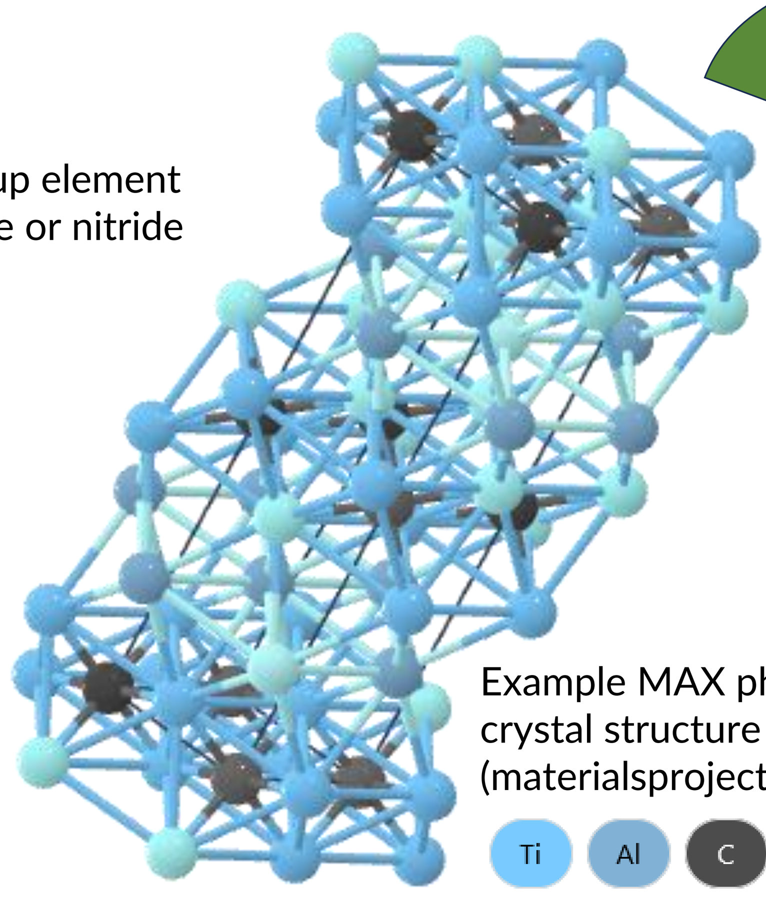
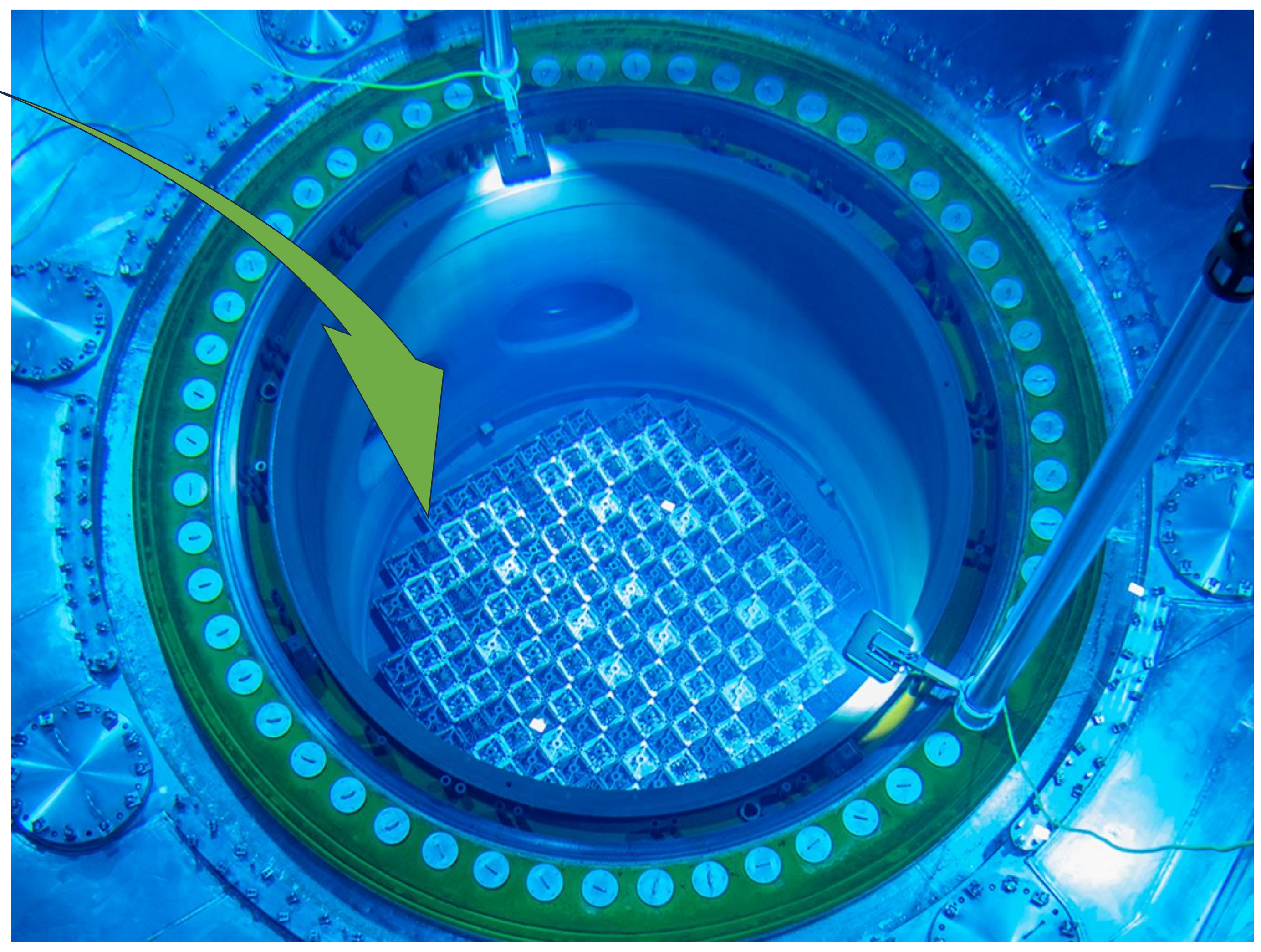
Background: **MAX phases**, a class of layered ternary ceramics, are a candidate material for **accident tolerant fuels (ATFs)**, and as structural materials in Gen IV reactors. ATFs would enable safety and efficiency upgrades in existing reactors. Gen IV designs operate in more extreme conditions for which novel material solutions are necessary. MAX phases are great candidates for these applications due to their **high temperature (HT) stability, radiation tolerance and healing, and corrosion resistance** [1].

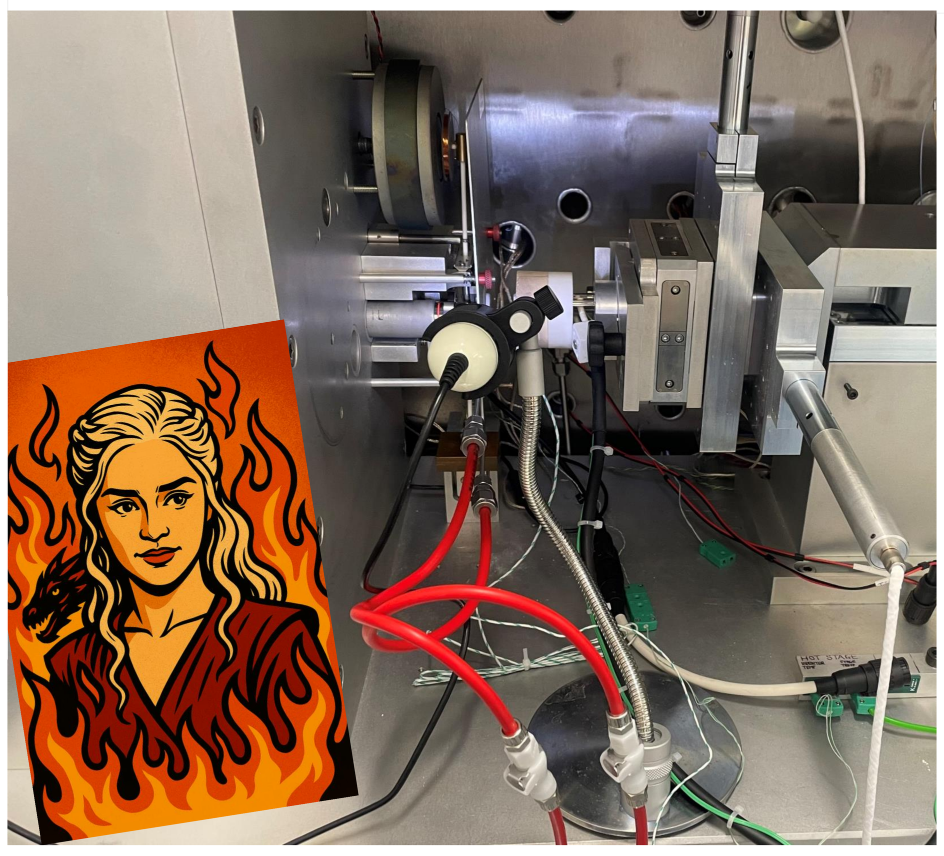


Example MAX phase crystal structure (materialsproject.org)

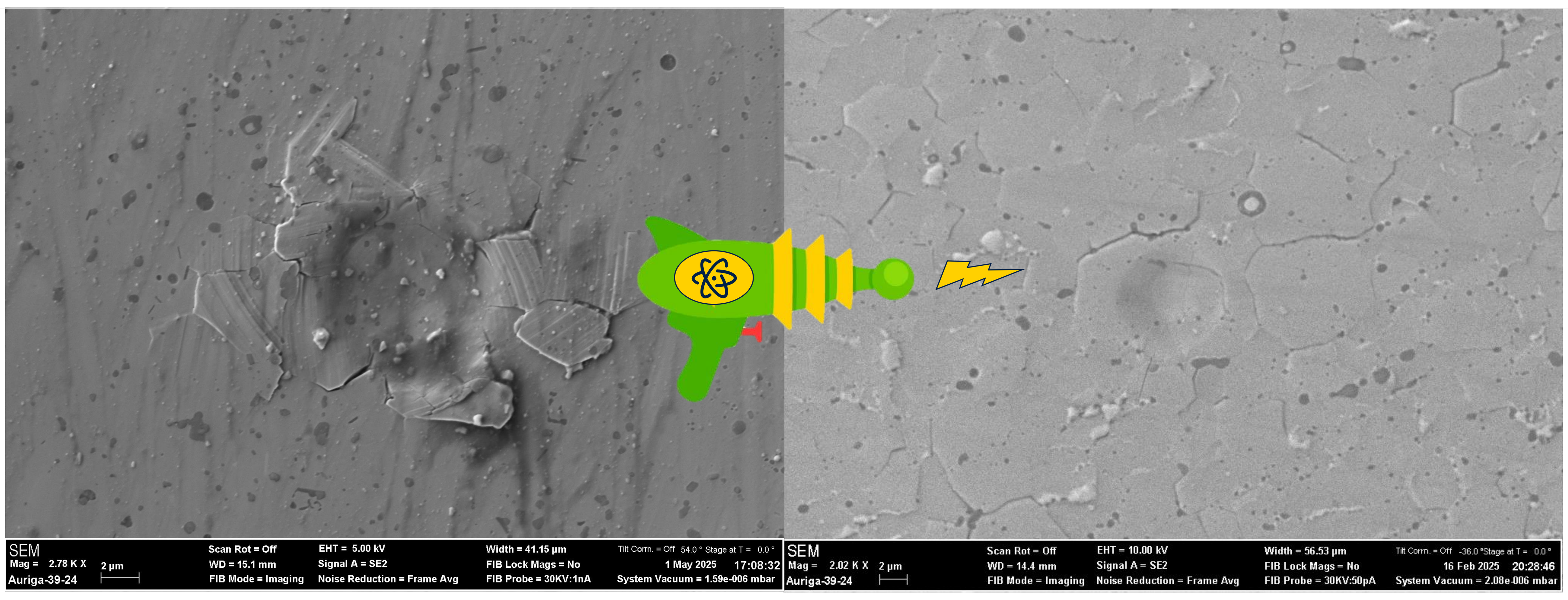


Fuel-loaded core of Vogtle Unit 2 (photo: US DOE)

Methods: **To emulate** the radiation and high temperature **conditions of a real nuclear reactor**, the **samples** were **irradiated with ions** at the Dalton Cumbrian Facility, and **nanoindented at high temperatures** with a spherical tip at Oxford. The MAX phases used in this project are Cr_2AlC, Ti_2AlC, and $Zr_3(Si, Al)C_2$.
Cr_2AlC and Ti_2AlC samples were **irradiated with 5.8 MeV Ni^+ ions**, and $Zr_3(Si, Al)C_2$ **with 2 MeV H^+ ions**. For **high temperature nanoindentation**, the samples and the tip were heated up to **700°C**.

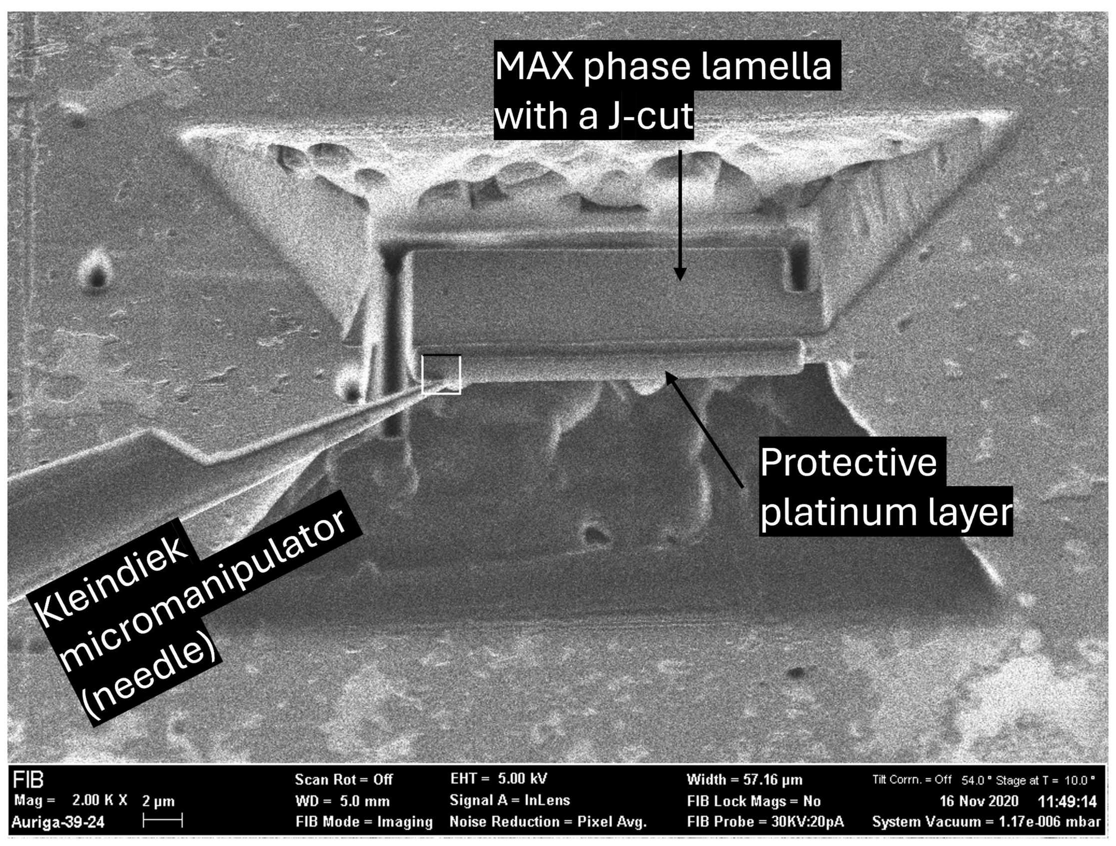


HT nanoindenter on the inside. Prototype of the MicroMaterials Xtreme

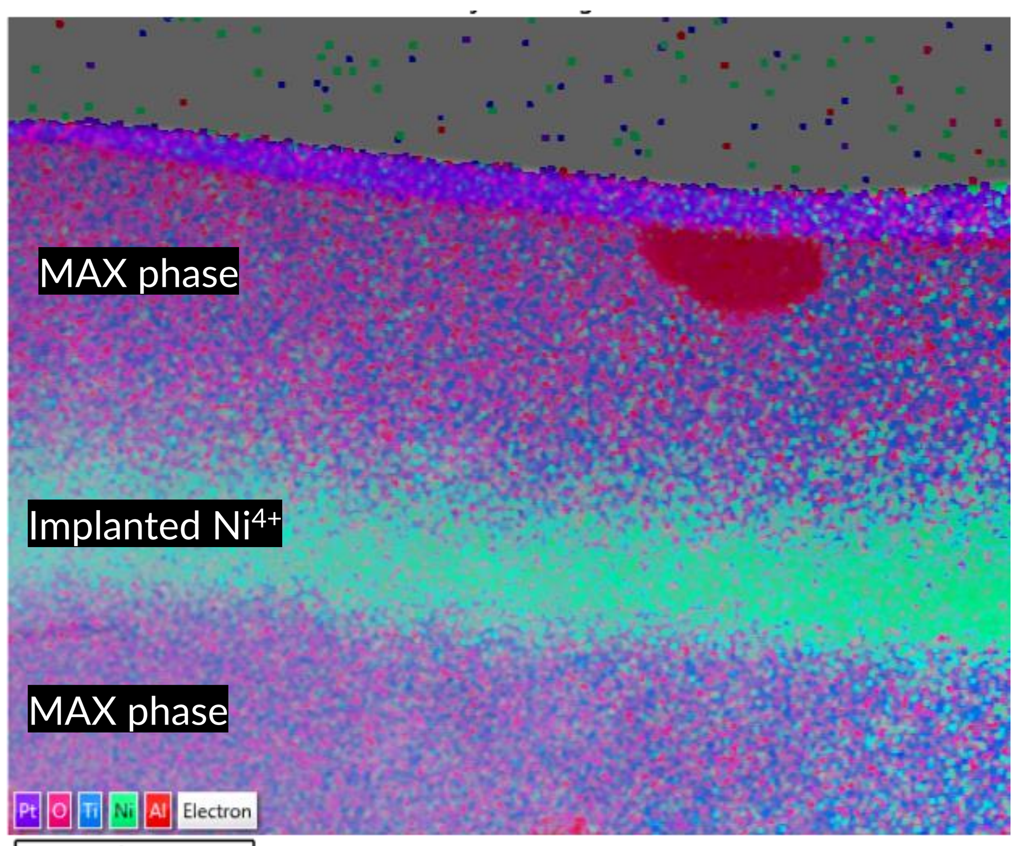


Electron micrographs of Cr_2AlC MAX phase indented in unirradiated (left) and irradiated (right) regions. Note the cracks throughout the sample surface in the irradiated region on the right.

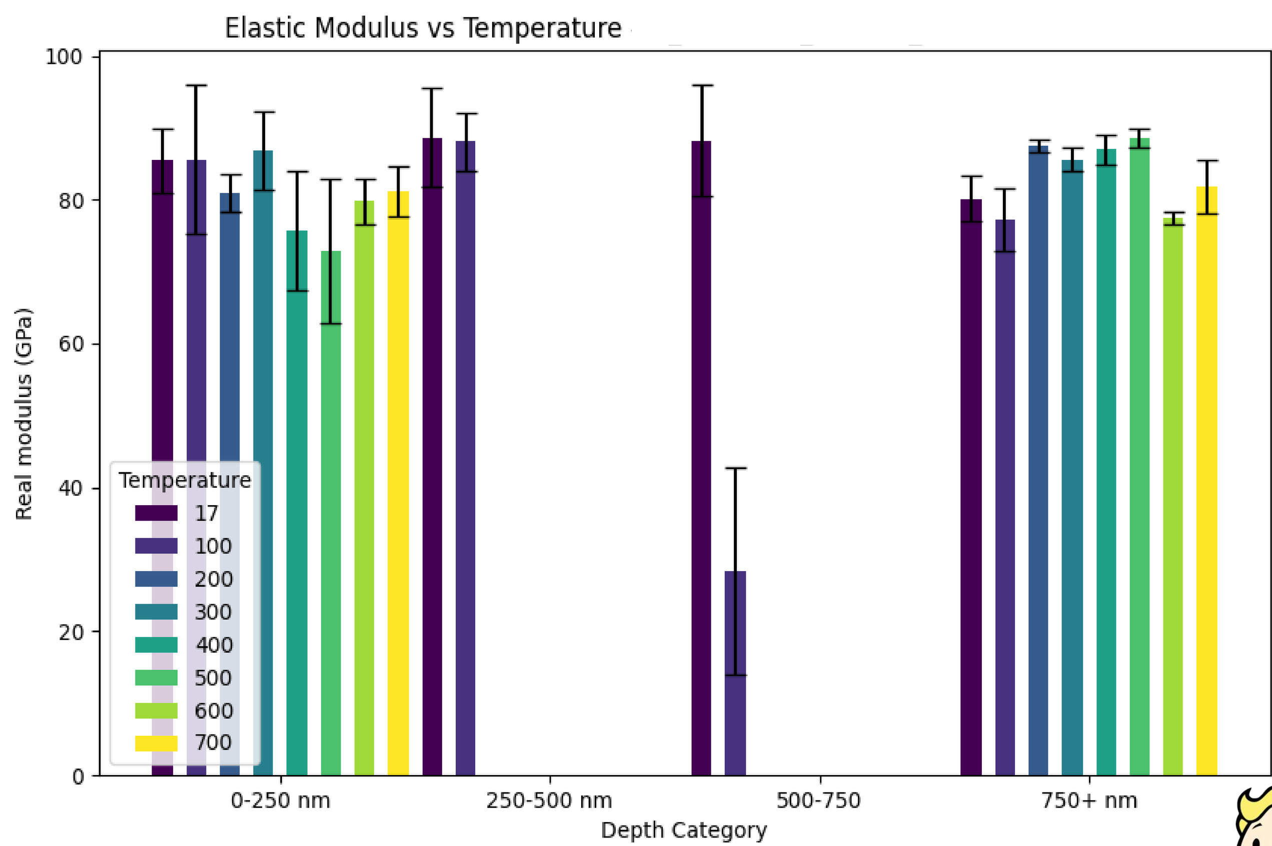
Results: Elastic moduli are stable at temperatures up to 700°C and with respect to irradiation with 5.8 MeV Ni^{4+} ions and 2.0 MeV H^+!



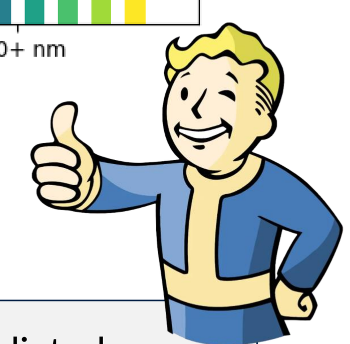
Focused ion beam sample preparation for transmission electron microscopy (TEM)



TEM of an irradiated Ti_2AlC indent. The fluorescent green streak is implanted nickel



Ti_2AlC modulus is **stable** up to **700°C**. Analysed according to [2] and [3]



Acknowledgments: Cr_2AlC and Ti_2AlC samples were made by Prof Konstantina Lambrinou's group at KU Leuven, and irradiated at the DCF under NNUF Application 22. $Zr_3(Si, Al)C_2$ irradiated samples were obtained from Prof Philipp Frankel's group at the Uni of Manchester. The EPSRC funded Marin Vukšić's studentship (Project Reference 2282513). Marin Vukšić acknowledges the support of the Frankopan Fund of the Stapleton Trust. The nanoindentation analyses codes were developed with generous help from Millie Zhou and LLMs. Graphical elements developed by Matej Korlaet.

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UKRI Engineering and Physical Sciences Research Council

NNUF National Nuclear User Facility

References

[1] M.W. Barsoum et al., *Ripplocations: A universal deformation mechanism in layered solids*. Physical Review Materials, 2019. 3(1): p. 013602.
[2] S. Pathak, S.R. Kalidindi, *Spherical nanoindentation stress–strain curves*, Materials Science and Engineering: R: Reports, 2015. **91**: pp. 1-36.
[3] A. Leitner, V. Maier-Kiener, D. Kiener, *Essential refinements of spherical nanoindentation protocols for the reliable determination of mechanical flow curves*, Materials & Design, 2018. **146**: pp 69-80