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Neutron and X-ray Diffraction as a Tool to Study High-Temperature Materials for Fusion Applications

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For the fusion of hydrogen isotopes, plasma temperatures of around 100 million ℃ are required. Although the plasma does not come into direct contact with the reactor walls, the surrounding materials are subjected to extreme thermal loads, high neutron flux, and hydrogen implantation. Consequently, advanced structural materials must be developed to withstand these harsh conditions.
Diffraction techniques—both neutron and synchrotron-based—are well suited to investigate candidate materials in situ and non-destructively under relevant environmental conditions. Especially, the high penetration depth of neutrons allows bulk studies for industrial applications. In this study, we demonstrate how diffraction can be employed to gain insight into the behavior of high-temperature materials that may be used in fusion reactors.
Hydrogen incorporation into the crystal lattice can be tracked indirectly by monitoring changes in the lattice parameter, as interstitial hydrogen increases the spacing between metal atoms. Furthermore, irradiation-induced defects such as vacancies and dislocations influence peak shapes and broadening, and can likewise be characterized via diffraction. Also, microstrains induced by the hydrogen can be tracked by diffraction. [1]
We present results on the recently developed polycrystalline superalloy VDM® Alloy 780, studied under hydrogen exposure and elevated temperatures. In situ diffraction experiments were performed to monitor hydrogen effusion during continuous heating. The observed decrease in lattice parameters confirms hydrogen effusion, indicating reversible hydrogen uptake. [2]
Complementary tensile tests with a self-developed testing machine (up to 100 kN and 1300℃) revealed the influence of hydrogen on the mechanical properties. Hydrogen-charged specimens exhibited reduced elongation at fracture compared to uncharged reference samples. Subsequent annealing at 500 ℃ for various durations led to a partial recovery of ductility, further validating the reversibility of hydrogen embrittlement.
These findings highlight the potential of diffraction methods to support the development and qualification of structural materials for future fusion energy systems.
[1] O. Nagel, M. Fritton, A. Mutschke, R. Gilles, S. Neumeier, Scr. Mater. Volume 260, 2025.
[2] M.Fritton, A. Mutschke, O. Nagel, M. Hafez-Haghighat, B. Gehrmann, S. Neumeier, R. Gilles, J. Alloys Compd. Volume1014, 2025.

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