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X-ray and neutron diffraction for characterizing lattice defects in irradiated structural materials

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Structural materials in the nuclear industry operate within harsh environmental conditions. Cooling substances pose corrosion, irradiation produces a high density of lattice defects, and external strains cause fracture. The large density of lattice defects generated by irradiation causes embrittlement, leading to early fracture. The analysis of diffraction peak broadening, called line profile analysis (LPA), has been used successfully to characterize the quantity, nature, and size distribution of dislocation loops induced by proton or neutron irradiation in Zr alloys [1-3]. In [1] it was shown that at lower irradiation temperatures the loops created by irradiation are smaller with larger densities. This result was used to explain the discrepancy observed in the difference of dislocation densities determined either by TEM or LPA. TEM counting revealed larger dislocation densities in cladding than in channel materials, whereas LPA showed the opposite in neutron-irradiated Zircaloy-2. In [2] it was shown that while in TEM investigations the fraction of loops smaller than a critical size escapes counting, LPA is providing the total dislocation density including the smallest fraction. Using the two different dislocation density values, the size distribution of irradiation-induced loops was determined, indicating the excellent synergy between TEM and LPA investigations. In [3], a method was developed to determine the partial dislocation densities and the fractional activities of different slip modes in plastically deformed and neutron-irradiated Zr alloys. It was shown that neutron irradiation can totally eradicate the lattice dislocations produced by the fabrication procedure of Zr-based structural components. In post-irradiation tensile deformed Zr alloys, the LPA-determined dislocation densities were in good correlation with the strain-localized deformation mechanism observed by TEM or digital image correlation techniques. The experience in analyzing irradiation-induced defects in Zr alloys can readily be used in structural materials used in the fusion-based energy industry.

[1] M. Topping et al., The effect of irradiation temperature on damage structures in proton-irradiated zirconium alloys, J. Nucl. Mater. 514 (2019) 358-367.
[2] T. Ungár et al., Size-distribution of irradiation-induced dislocation-loops in materials used in the nuclear industry, J. Nucl. Mater. 550 (2021) 152945-10.
[3] T. Ungár et al., Fractional densities and character of dislocations in different slip modes from powder diffraction patterns, J. Nucl. Mater. 589 (2024) 154828-16.

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