नाभिकीय पदार्थों में सूक्ष्म संरचना एवं बनावट की भूमिका

Role of Microstructure and Texture in Nuclear Materials

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Microstructure and texture together form the underlying architecture that governs the performance of structural materials. While microstructure encompasses grain morphology, phase distribution, second-phase particles and defect configurations, texture describes the collective orientation of these grains and the anisotropy that arises from it. In metals with hexagonal close-packed crystal structures, such as zirconium and titanium, this anisotropy exerts a particularly strong influence on deformation pathways, irradiation response and dimensional stability. Thus, in any engineered component intended to operate reliably for decades, microstructure sets the intrinsic framework of strength and stability, and texture determines how this framework interacts with stress, temperature, hydrogen, radiation damage and time.

These considerations become central in nuclear materials, where zirconium alloys serve as the backbone of water-cooled nuclear reactor technology. Their low neutron absorption enables their use in fuel cladding and pressure tubes, but their performance is inseparably linked to their microstructure–texture state. This microstructure and texture evolves through complex series of thermo mechanical processing steps involved in the manufacturing of nuclear components and continues to evolve during the service period of these in-core components.

Over the course of thermomechanical processing—processing steps like β-quenching, extrusion, cold pilgering and carefully controlled annealing-Zircaloy-4 evolves from a Widmanstätten α morphology to a refined, partially recrystallized structure with a strong preferred orientation. Early steps such as β-quenching provide a fine basket-weave template; hot extrusion elongates α grains, strengthens prism-plane alignment and introduces the first major texture components; pilgering heavily fragments grains and sharpens the orientation distribution; and annealing restores selected orientations while stabilizing those which provide resistance to irradiation creep and growth. In pressure-tube alloys such as Zr-2.5Nb, the coexistence of metastable β-phase adds an additional layer of complexity. Depending on processing temperature and strain path, β may persist as continuous films, lamellae or globular regions, each influencing deformation behaviour and hydride nucleation sites. The α grains inherit part of their orientation from the $\beta \rightarrow \alpha$ transformation, meaning that texture is simultaneously shaped by deformation, variant selection and recrystallization.

Such engineered textures have concrete consequences in service. The distribution of basal poles strongly influences axial and circumferential irradiation growth, the ease of cross-slip or twinning, and the propensity for hydride reorientation under applied stress. A high radial Kearns factor in Zircaloy-4 cladding suppresses radial hydrides that can compromise integrity, while specific prism-plane alignments in Zr-2.5Nb pressure tubes are associated with improved creep performance and dimensional stability. Microstructural details including second-phase particles, their stability under irradiation, and the redistribution of alloying elements further shape long-term behaviour. Irradiation-induced amorphization of precipitates in Zircaloy-4 or the spheroidization of β-Nb in Zr-2.5Nb alters defect sink strengths, influences corrosion behaviour and modifies hydride precipitation patterns. Thus, what appears as a static structure is in fact a dynamic system continually evolving under neutron flux, temperature gradients and hydrogen ingress.

Looking ahead, several emerging developments promise to further refine our understanding and control of these alloys. Nanoscale tools such as atom probe tomography, precession electron diffraction, high-angular-resolution EBSD and Transmission Kikuchi Diffraction, Electron channelling contrast imaging etc are enabling unprecedented resolution in characterising dislocation loops, near boundary gradient zones, precipitate grain boundary interactions in these complex systems. Computational methods from crystal plasticity to phase-field simulations are beginning to predict texture evolution, irradiation-induced damage and hydride behaviour with high fidelity. Future progress will depend on integrating these advanced characterization and modelling approaches into processing design, allowing microstructure and texture to be deliberately engineered for next-generation reactors, accident-tolerant fuel systems and high-temperature zirconium alloys for emerging reactor concepts.

In closing, it is appropriate to acknowledge that much of the progress in this field has been shaped by decades of

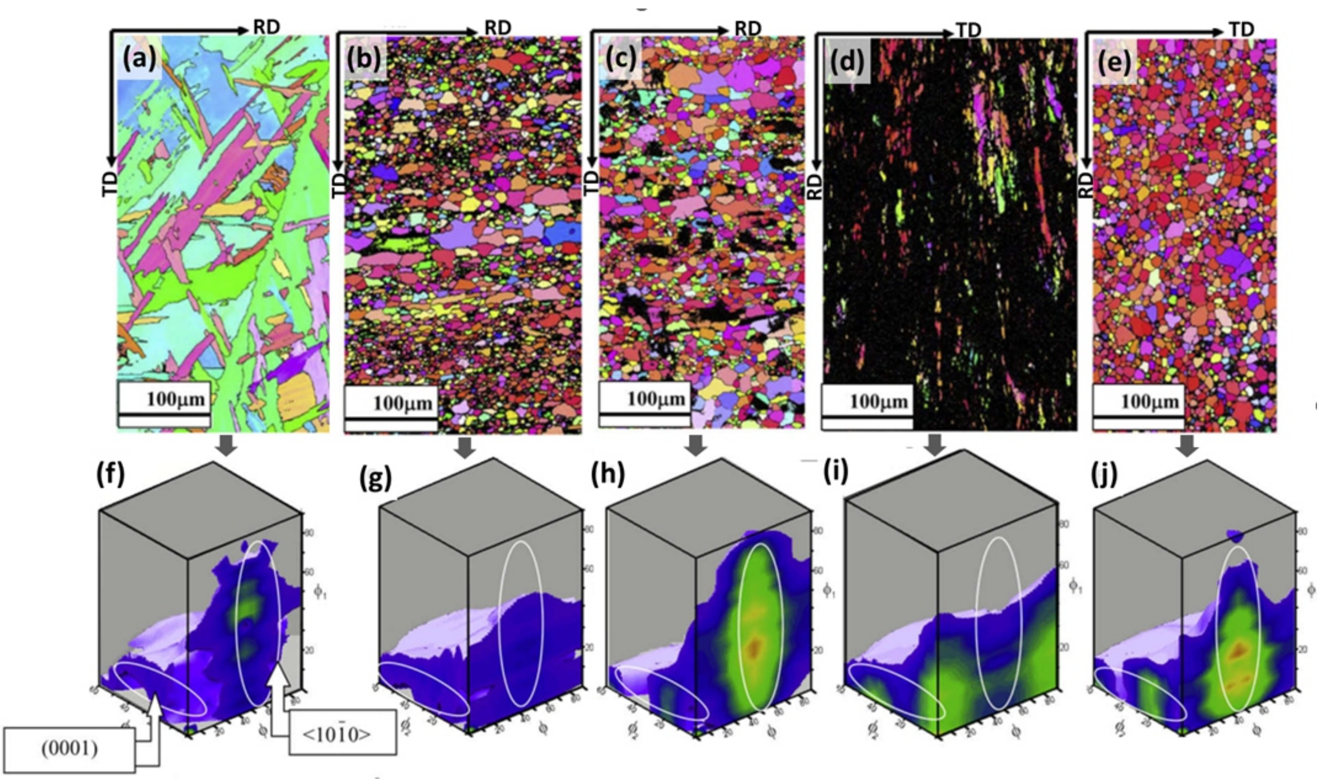

Fig.1: Evolution of microstructure (a–e) and texture (f–j) in Zircaloy-4 during TMP, illustrating refinement, deformation effects and strengthening of major orientation components.

scientific collaboration between BARC and our research group at IIT Bombay. The understanding of microstructure–texture interdependence in zirconium alloy owes greatly to these collective efforts. Among them, the contributions of Dr. R. Tewari, in whose honour this volume is assembled, stand out for their depth, clarity and enduring influence. His work in phase transformations, microscopy and zirconium metallurgy has been instrumental in shaping up of some of the outstanding results presented here.