Grain Boundary Characterization of Carbide Ceramics for Fusion First-Wall Applications

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Nuclear fusion offers a promising pathway towards clean and high-density energy generation; however, the difficulty of developing materials that can withstand these extreme conditions hinders its practical feasibility. Ultra-high temperature ceramics (UHTCs) appear to be promising solutions, and are being studied for potential first-wall applications because of their stability under harsh conditions. Their performance, however, depends strongly on their microstructural properties, particularly grain boundaries. These interfaces between differently oriented crystals can weaken the material and serve as preferential sites where defects can accumulate. This work investigates the properties of grain boundaries and their relationships to material properties in four carbide-based ceramics: VC–SiC, VC–SiC–CF, WC–SiC–CF, and WC–ZrC–Ta–CF, where CF denotes carbon fibers, particularly focusing on SiC particle dispersion and grain size.

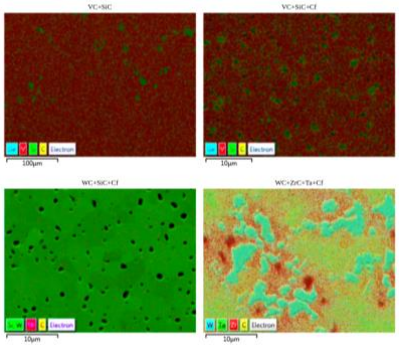


Figure 1 – Layered SEM-EDX elemental maps comparing four carbide composites.

Optical microscopy was used to survey large-scale microstructural features, helping to select regions for higher-resolution imaging with scanning electron microscopy (SEM), focusing on defects and grain boundaries potentially relevant to the materials' response to extreme thermal and radiation conditions. Energy-dispersive X-ray spectroscopy (EDS) mapped silicon-rich regions attributed to SiC, helping the identification of second-phase SiC particles near or along grain boundaries (Figs. 1–2). Binary-collision-approximation simulations using RustBCA modeled irradiation-induced damage. Atomic force microscopy provided surface-topography and lateral-force maps, helping to reveal local surface morphology and friction-related contrast (Fig. 4).

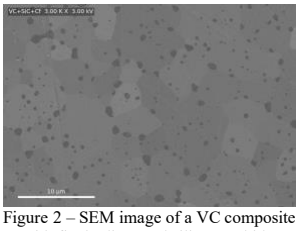


Figure 2 – SEM image of a VC composite with finely dispersed silicon carbide.

SEM measurements compared the VC–SiC–CF composite containing finely dispersed SiC with the VC–SiC composite containing agglomerated SiC (Fig. 3). The dispersed composite exhibited substantially smaller grains and finer SiC particles than the agglomerated composite, as well as a lower fraction of SiC particles located on grain boundaries.

	VC+SiC+Cf dispersed	VC+SiC agglomerated
SiC second phase		
Mean particle radius, r (μm)	0.26	2.44
Mean spacing (μm)	1.3	10.9
Particles on grain boundaries (%)	29	90
Grains		
Measured grain size, d (μm)	10.5	82.6
Boundary density (μm^{-1})	0.80	0.06

Figure 3 – Comparison of vanadium carbide with dispersed & agglomerated SiC.

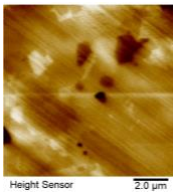


Figure 4 – AFM surface topography of WC.

Together, these observations identify finely dispersed SiC as a promising feature for developing finer-grained carbide composites. Dispersed second-phase SiC particles can help restrict the movement of grain boundaries, which limits coarsening and helps to preserve the finer microstructure during thermal exposure. Such interfaces can distribute deformation rather than allowing damage to concentrate within a small region of grains and boundaries.

Finely dispersed second-phase SiC may therefore provide a practical means of controlling grain structure for fusion first-wall applications. Future work can involve irradiating the samples to directly test whether finely dispersed SiC suppresses grain coarsening and preserves microstructural stability for fusion first-wall applications.

[1] Lin, Yan-Ru, et al. "Response of ^{11}B Enriched ZrB_2 Ultra-High Temperature Ceramic to Neutron Irradiation at Elevated Temperatures." *Acta Materialia*, vol. 276, 2024, article 120111, *https://doi.org/10.1016/j.actamat.2024.120111.*

[2] Lin, Yan-Ru, et al. "Comparative Neutron-Irradiation Effects on Thermal Conductivity Degradation and Dimensional Stability of TiC, TiB_2, and ZrB_2 at 200–1000 °C." *Journal of Nuclear Materials*, vol. 632, 2026, article 156897, https://doi.org/10.1016/j.jnucmat.2026.156897.