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High Entropy Alloys In Advanced Nuclear Fusion Applications

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The safety and reliability of tokamak fusion reactors rely on the successful design and fabrication of advanced structural materials resilient to the incident flux of helium and neutron particles at both low and high temperatures (>700°C). While some traditional refractory materials, such as tungsten (W), have been considered for application in the first wall and divertor region of tokamaks due to their suitable properties—such as a high melting point, low tritium (T) retention, and favorable mechanical response—they experience intergranular brittle failure due to the accumulation of helium bubbles and susceptibility to neutron-induced swelling and embrittlement. The new quest in fusion reactor material search focuses on overcoming these limitations by developing a new class of engineering materials that can withstand the extreme conditions within the tokamak environment while maintaining optimal structural integrity and mechanical response to irradiation and high heat loads.

In this work, we address the above limitations by developing a non-conventional class of alloys, high entropy alloys (HEA), based on several principal elements W, Ta, Mo, Ni, Cr and Mo, Co, Cr, Fe, Ni in the near-equiatomic composition. The W-based HEA was grown as thin film (100 nm) showing a homogeneous chemical distribution of W, Ta, Mo, Ni and Cr across the depth of the film. The analysis of the cross-sectional TEM shows the columnar structure in the as-deposited W-based high entropy alloy with the columnar size about 5nm. To test the irradiation resilience the HEA samples were exposed to He ions with the fluence of 1.2×10^{25}m^{-2} in the magnetized plasma interaction experiment (MAGPIE) [1]. No phase separation or elemental segregation was observed in the irradiated samples as evidenced by the EDS analysis (Figure 1(c)). The W-based HEA thin film show perseverance of the uniform elemental distribution and structural integrity without any distinct sign of He irradiation damage in the form of observable microcracks, blistering, or compositional shifts.

The nanomechanical testing shows large hardness in the as-deposited HEA films of 20.74 GPa with the near-negligible irradiation hardening of ~1GPa and ~5GPa in the irradiated at 500°C and 700°C W-based HEA thin films, respectively. The nanoindentation analysis confirms exceptional radiation tolerance to the He irradiation damage in W-Ta-Mo-Ni-Cr high entropy alloy showing promise for applications demanding robust materials under extreme conditions.

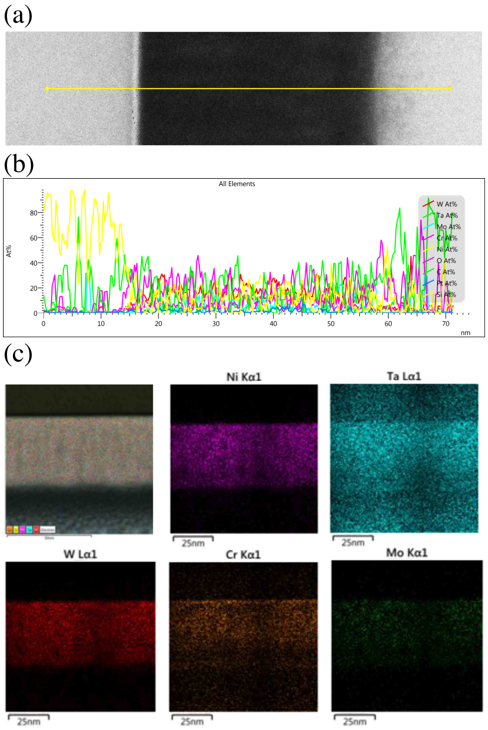

Figure 1 - Cross-sectional TEM micrograph of (a) as-deposited and (c) He irradiated at 700°C W-Ta-Mo-Ni-Cr based HEA, (b) elemental distribution of principal elements across the as-deposited W-Ta-Mo-Ni-Cr thin film

Treatment	Hardness, H_v, GPa	Elastic modulus, E, GPa
As-deposited	20.74	209.28
500°C He irradiation	21.34	217.29
700°C He irradiation	25.47	219.15

Table 1 - Results for mechanical properties of W-Ta-Mo-Ni-Cr HEA after He irradiation (Elastic modulus, E, and Vickers hardness, H_V)

References

[1] Blackwell, Boyd D., et al. "Design and characterization of the Magnetized Plasma Interaction Experiment (MAGPIE): a new source for plasma–material interaction studies." Plasma Sources Science and Technology 21.5 (2012): 055033.