Fracture behavior of tungsten-based composites exposed to steady-state/transient hydrogen plasma

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The fracture behavior of plasma-facing components (PFCs) under extreme plasma-material interaction conditions is of great concern to ITER and future fusion reactors[1-3]. Despite numerous studies, the physical picture of the fracture of tungsten-based PFCs exposed to steady-state/transient hydrogen plasma is still incomplete.

Hot-rolled pure tungsten, and W-1%TiC and W-2%Y₂O₃ composites fabricated by powder injection molding were exposed to a combined steady-state/transient hydrogen plasma up to a base surface temperature of ~2200 K (one steady-state cycle), and up to 5000 transient pulses (5000 transient cycles) for 1000 seconds using the linear plasma generator Magnum-PSI. The applied heat loads were characterized by combining sheath physics, infrared thermography and finite element analyses. This was then used to evaluate the thermal stress/strain in the samples caused by the transient heat load. The steady-state hydrogen plasma has a peak ion energy of ~ 5-10 eV, a peak flux of ~ 0.8-2.93 ×10²⁴ m⁻² s⁻¹, and a peak fluence of ~ 0.8-2.93 ×10²⁷ m⁻². The transient hydrogen plasma has a peak ion energy of ~ 50 eV, a duration of ~ 1 ms, and a peak heat flux of 460-600 MW/m².

Combining microstructural investigation and thermo-mechanical numerical analyses, the failure phenomena are rationalized as follows: the transient heat loads drive surface crack initiation, whose depth can be estimated by a simple analytical model for pure tungsten. The cooling period following the steady-state heat load induces tensile stresses, opening existing surface cracks deeper. The fracture process is mediated by the microstructure whereby the ceramic particles stabilize the microstructure but promote surface crack initiation due to suppressed plasticity at the grain boundaries. The surface cracks relieve the subsequent cycles of transient thermal stress but intensify the steady-state thermal stress, therefore, promoting deep crack propagation. These results help to understand failure mechanisms in PFCs under extreme operation conditions which are valuable for developing advanced PFCs.