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Application of tungsten-fibre-reinforced copper matrix composites to a high-heat-flux component: A design study by dual scale finite element analysis (P2-F-69)

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According to the European Power Plant Conceptual Study, actively cooled tungsten mono-block is one of the divertor design options for fusion reactors. In this study the coolant tube acts as a heat sink and the tungsten block as plasma-facing armour. A key material issue here is how to achieve high temperature strength and high heat conductivity of the heat sink tube simultaneously. Copper matrix composite reinforced with continuous strong fibres has been considered as a candidate material for heat sink of high-heat-flux components. Refractory tungsten wire is a promising reinforcement material due to its high strength, winding flexibility and good interfacial wetting with copper.

We studied the applicability of tungsten-fibre-reinforced copper matrix composite heat sink tubes for the tungsten mono-block divertor by means of dual-scale finite element analysis. Thermo-elasto-plastic micro-mechanics homogenisation technique was applied. A heat flux of 15 MW/m² with cooling water temperature of 320 °C was considered. Effective stress-free temperature was assumed to be 500 °C. Between the tungsten block and the composite heat sink tube interlayer (1 mm thick) of soft Cu was inserted.

The finite element analysis yields the following results: The predicted maximum temperature at steady state is 1223 °C at the surface and 562 °C at the interface between tube and copper layer. On the macroscopic scale, residual stress is generated during fabrication due to differences in thermal expansion coefficients of the materials. Strong compressive stress occurs in the tungsten block around the tube while weak tensile stress is present in the interlayer. The local and global probability of brittle failure of the tungsten block was also estimated using the probabilistic failure theories.

The thermal stresses are significantly decreased upon subsequent heat flux loading. Resolving the composite stress on microscopic scale yields a maximum fibre axial stress of 3000 MPa after fabrication and 1550 MPa during heat flux loading. The matrix equivalent plastic strain reaches 5 %. The stress level in the cold state is critical, since the tensile strength of commercial tungsten wires ranges between 2800 – 3500 MPa. This implies that annealing treatment for the stress relaxation is necessary during fabrication.