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Materials and Components for the DEMO Divertor

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In view of the severe operating conditions for plasma facing components (PFCs) in future power producing fusion devices, the development of advanced materials is mandatory {1}. The materials not only have to withstand high steady state power loads but also high number of thermal cycles and shocks. Moreover, the change of thermo-mechanical properties by damage, activation and transmutation through fusion neutrons has to be taken into account when designing PFCs and selecting the adequate armour and structural materials. Within the research along the European Fusion Roadmap, water cooled PFCs are foreseen in a first DEMO design in order to provide reliable heat removal capacity and to only moderately extrapolate the technology developed and tested for ITER.

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In order to make best use of the water cooling concept, copper (Cu) based alloys (as for example CuCrZr) are foreseen as heat sink whereas tungsten (W) based materials will be used as armour. Combining both materials in a high heat flux component bears the difficulty that their optimum operating temperatures do not overlap: W should be operated above 800 ℃ in order to be in a ductile state even under neutron irradiation to avoid brittle cracking under cyclic load, whereas CuCrZr should be operated below 300 ℃ to provide enough mechanical strength. A remedy for both issues –brittleness of W and degrading strength of CuCrZr –could be the use of W fibres in W and Cu based composites. The W fibres consist of drawn potassium doped tungsten wires as used in the lighting industry. They are characterized by very high strength (>2500 MPa), ductility already at room temperature and embrittlement by recrystallization and grain growth only above 1900 ℃.

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Industrial textile techniques have been successfully established to prepare the W fibre preform for the production of flat tungsten fibre reinforced tungsten (W_f/W) samples {2} and tungsten fibre reinforced copper (W_f/Cu) pipes {3}. By introducing W fibres, the toughness of W could be increased significantly through several toughening mechanisms attributed to plastic fibre deformation, fibre pull-out and crack bridging. A further improvement in workability and strength is achieved by the use of W yarns instead of single fibres, consisting of up to 20 thin individual W fibres with a diameter of 20 µm. In recent experiments with ion-irradiated W fibres only a very moderate reduction of strength and no loss of ductility even at 10 dpa are observed {4}. This provides good confidence that the strengthening and toughening by fibre reinforcement is preserved. Although W_f/W composites are not yet at hand in the required dimensions, W monoblock PFC mock-ups were fabricated using W_f/Cu composite pipes. Figure 1(b) shows such a pipe together with the tubular W braid (Fig. 1(a)), a cross section of the infiltrated pipe (Fig. 1(c)) and a complete W/W_f-Cu PFC mock-up after testing (Fig. 1(d)). The mock-ups were subjected to high heat flux (HHF) tests in IPP's ion beam facility GLADIS. Figure 2 shows infrared and visible images of the mock-up taken during the first and the last pulse (1000th) pulse under DEMO relevant power load (20 MW/m²) and cooling conditions (T_f=130 ℃). During the cycling the W surface reached well above 2000 ℃. Although a plastic deformation of the W armour is noticeable (see also Fig. 1(d)), no cracking or degradation of the thermal properties is found, demonstrating the very high performance of the mock-up with W_f/Cu composite pipes {3}.

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Combining the concept of composite materials with the prospects of additive manufacturing (AM) opens up the possibility to produce W-Cu composite structures with tailored material distribution, minimizing thermally induced stresses. For this purpose a numerical scheme based on the finite-element method was set-up to optimize computationally the W-Cu material distributions in a PFC. As a result, the von Mises stresses could be reduced in the simulations by a factor of 6 compared to the conventional W monoblock design at a heat load of 10 MW/m² {5}. In parallel, the Laser Powder Bed Fusion process was optimized for pure tungsten allowing manufacturing W parts with a mass density in the range of 98% {6}. Fig. 3(a) shows the CAD drawing of a cross section of an optimized tungsten structure consisting of a bcc lattice and in Fig. 3(b) the AM counterpart ready for infiltration of Cu is presented. The rolled W build plate will serve as plasma facing side (corresponding to the top of Fig. 3(a)). As for the infiltration of the W-fibre braids a perfect filling of the AM W-skeletons with Cu could be achieved and in 2020, tests will be performed in GLADIS applying cyclic loads above 20 MW/m² in order qualify AM mock-ups for the use in fusion devices.

{1} J.W. Coenen et al., Nucl. Mater. Energy 12 (2017) 307
{2} J. Riesch et al., Nucl. Mater. Energy 9 (2016) 75
{3} A.v. Müller et al., to appear in Phys. Scr. 2020
{4} J. Riesch et al., to appear in Nucl. Mater. Energy 2020
{5} B. Curzadd et al., Nucl. Fusion 59 (2019) 086003
{6} A.v. Müller et al., Nucl. Mater. Energy 19 (2019) 184

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