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New Developments in the Design and Manufacturing of a He-Cooled Divertor for European DEMO

New Developments in the Design and Manufacturing of a He-Cooled Divertor for European DEMO, B.-E. Ghidersa, J. Reiser, S. Antusch, Y. Chen, Karlsruhe Institute of Technology, Germany

Particle exhaust in modern tokamaks and stellarators is associated with high loads on the divertor regions and requires substantial power exhaust capabilities, way superior to that of the first wall components. This makes the development of the divertor targets one of most challenging tasks in the designing of ITER and future power plants, including DEMO. As part of the sustained efforts in providing solutions that could be integrated into a fusion power plant like DEMO, Karlsruhe Institute of Technology (KIT) has developed a helium-cooled divertor, the HElium cooled Modular divertor with Jet cooling (HEMJ). While it has been demonstrated experimentally that this divertor concept could remove up to 10 MW/m² of surface heat flux (see [1]), using tungsten both as armor and as structural material, the licensing of such a concept requires the development of new design rules for brittle materials, rules that are not currently available in the pressure vessels codes and standards. Until such design rules are made available, as an alternative, KIT has started the development of new structural materials that would allow the operation at low coolant temperatures, while remaining ductile under fusion devices specific neutron flux. The present aim is to extend the lower temperature limit of the divertor operating window below 500°C while still having a ductile behavior of the structural material. One of the possible solutions to achieve these goals is the development of tungsten laminates. However, since it is difficult to apply such materials to the HEMJ concept, a new helium-cooled divertor has been proposed [2]. This concept combines the jet-impingement cooling with an ITER-like target arrangement where the armor is made of tungsten slabs installed on a helium-cooled tungsten laminate pipe. For the armor the preferred solution is the one of fine grain tungsten obtained by powder injection molding [3]. The present paper gives a brief overview of the current activities concerning the development of these novel materials with focus on W-Cu laminates developed at KIT, as well as new progresses achieved in developing improved armor materials via tungsten powder injection molding (W-PIM). In addition to that, the thermal-hydraulic performances of a new helium-cooled divertor concept will be discussed.

Structural material development

One major drawback of using monolithic coarse-grained tungsten as structural material is its high tendency to brittle, low energy fracture at low temperatures. Recently published studies confirm a rise in fracture toughness, K_{IQ}, and a clearly decrease of the brittle-to-ductile transition temperature (BDTT) through cold rolling [4, 5]. In our search for ductile materials for divertor applications, we make use of these facts by taking severely cold-rolled ultrafine-grained tungsten sheets to build tungsten laminated composites. The idea of the laminated composites is to produce a bulk material that retains the ductility and toughness of the heavily cold-rolled tungsten sheets. Tungsten laminates allow the assembly of three-dimensional shapes and geometries such as caps and pipes. Figure 1A shows several W-Cu laminated pipes produced at KIT: four pipes with a length of 500 mm and, one pipe with a length of 1000 mm. All pipes have an outer diameter of 16 mm and a wall thickness of 0.9 mm. These pipes can be directly used for the manufacturing of high heat flux components as it can be seen in Figure 1B where the manufacturing of a divertor mock-up has been demonstrated. Thus, the armor is made of tungsten blocks installed on a W laminate pipe that contains the coolant, in this case helium at 10 MPa. The cooling of the loaded surface is done through impingement jets that are generated through a cartridge inside the pipe that acts also as inlet manifold.

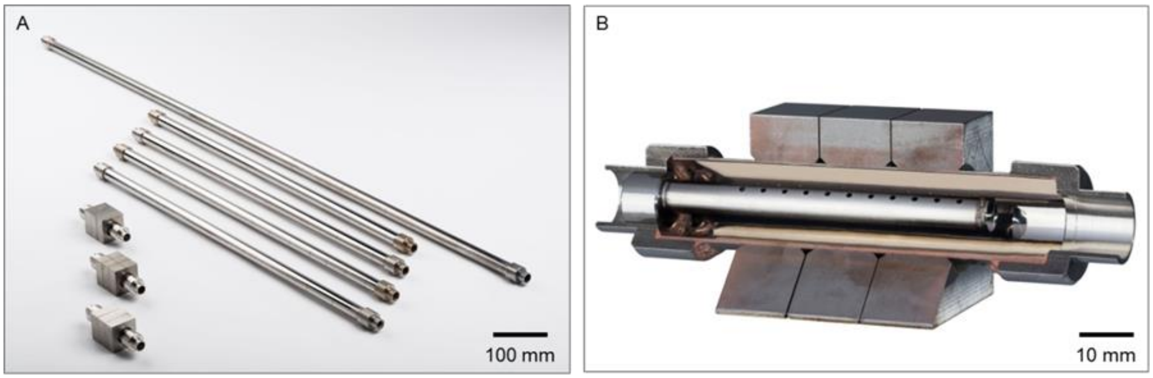

Figure 1. A: W-Cu laminated pipes with a length of 1000 mm can be produced. B: Manufacturing mockup for a high-temperature helium cooled divertor.

Divertor armor material development

KIT research on armour material is mainly focused on the development of new tungsten grade materials via Powder Injection Molding (PIM), as well as on the manufacturing of small or full divertor armor parts (medium size monoblocks). With its high near-net-shape precision, the method offers particularly the advantage of reduced costs compared to conventional machining [6]. The combination of an inorganic metal or ceramic powder with a small quantity of a polymer, a so-called feedstock, can be molded. The average particle size distribution of the used tungsten powder is in the range of 1.0 to 2.0 µm Fisher Sub-Sieve Size (FSSS). Depending on the size and shape of the parts, for simple geometries, only 20 seconds are needed to produce a green part [7]. After shaping the green part (consisting of powder and binder), the polymeric binder must be extracted and the powder sintered at 2400 °C to the near-theoretical density. Isotropic materials, equiaxed grain orientation, good thermal shock resistance, shape complexity and high final density (>98% theoretical density) are typical properties of powder injection molded tungsten [8]. Such manufactured pure tungsten parts have an achieved grain size in the range of 50 to 100 µm. This process is very effective and the easy up-and down-scaling in size and shape of the parts, from a micro gearwheel 3 millimeters in diameter and a weight of 0.050 grams, up to a 1.4 kilo plate with the dimensions 60 x 60 x 20 mm, as it is shown in Figure 2 [9].
One of the possibilities for manufacturing fusion relevant parts via W-PIM has been already demonstrated by the latest produced series of Langmuir samples for diagnostics for the French tokamak WEST (Tungsten (W) Environment in Steady-state Tokamak) [10]. WEST is intended to become one of EUROfusion's test benches for tungsten components under ITER-like conditions. Figure 2 (left) shows two of the 70 produced probes, each 25 mm long, 17 mm tall and only 2 mm thick. The feedback from using these Langmuir probes in WEST will provide a valuable input into the ITER design process [11].

Figure 2. Range of dimension of the produced W-PIM parts (left side) [9]; W-PIM Langmuir probes for WEST (right side) [10]

Fracture mechanics and high heat flux tests already performed on W-PIM manufactured samples indicate a better transition temperatures and higher crack resistance than for tungsten materials produced by common manufacturing routes. These results indicate that tungsten produced by PIM is a viable option for armor applications [11]. Furthermore, the W-PIM process enables the further development and assessment of new custom-made tungsten materials, as well as allowing for further scientific investigations on prototype materials for use in general R&D, and for developing industrial products for a wide range of applications.

Divertor concept and thermal-hydraulic performance evaluation

To evaluate the heat transfer performances, CFD simulations were done with Ansys-CFX V15 using the k-ω-SST turbulence model. The geometry used for the investigations was the same as the one for the manufacturing mock-up shown in Figure 1. The only difference was that, to reduce the computational time, only one tungsten slab was considered. For this mock-up, besides the 16mm laminate pipe, the distribution manifold was done out of a 6 mm steel pipe and the jet holes are 1mm in diameter. The tungsten blocks had a plasma facing side that was 32 x 13 mm large. The thickness of the tungsten block towards the plasma facing side is 8 mm. A helium flow rate of 20 g/s and an inlet pressure of 10 MPa have been considered, while the inlet temperature was adjusted to meet the operating limits of tungsten laminate pipe, namely 500 °C. This temperature was chosen by extrapolating the results of the first irradiation campaign performed for the W-laminates [12] assuming that, during the divertor lifetime, the pipes material will be subject to 3 dpa.

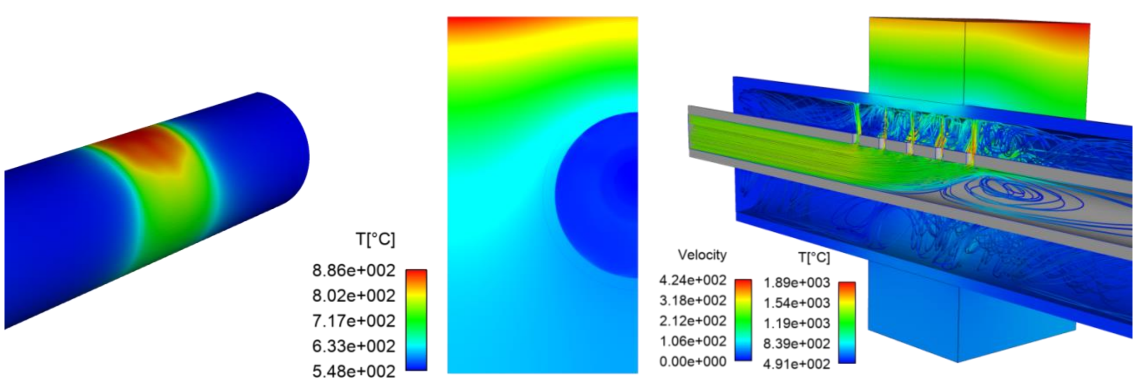

Figure 3. Pipe-multi jet concept: temperature field for 10 MW/m² heat flux

The results show that, for the W-Cu laminate pipe the proposed concept could operate at fluxes up to 10 MW/m², the pipe wall temperature approaching 900 °C at the outer surface which is within operating window defined for these materials.
Further simulations are currently focusing on optimizing the cooling pattern in order to reduce the required flow rates. Thus, parametric studies concerning the holes pattern as well as the distance between the inner manifold to the pipe heated surface are currently under way. In addition to that, the integration of such a cooling concept into a DEMO divertor target with a length of about 650 mm is also investigated.

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