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Manufacturing and joining technologies for helium cooled divertors

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HIGHLIGHTS

- The manufacturing and joining technologies developed at KIT for helium cooled divertors are reviewed and critically discussed.
- Various technologies have been pursued and further developed aiming divertor components with very high quality and sufficient reliability.
- Very promising routes have been found for which however still R&D works are necessary.
- Technologies developed are also useful for other divertor and even blanket concepts, particularly those with tungsten armor.

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ABSTRACT

In the helium cooled (HC) divertor, developed at KIT for a fusion power plant, tungsten has been selected as armor as well as structural material due to its crucial properties: high melting point, very low sputtering yield, good thermal conductivity, high temperature strength, low thermal expansion and low activation. Thereby the armor tungsten is attached to the structural tungsten by thermally conductive joint. Due to the brittleness of tungsten at low temperatures its use as structural material is limited to the high temperature part of the component and a structural joint to the reduced activation ferritic martensitic steel EUROFER97 is foreseen. Hence, to realize the selected hybrid material concept reliable tungsten–steel and tungsten–tungsten joints have been developed and will be reported in this paper.

In addition, the modular design of the HC divertor requires tungsten armor tiles and tungsten structural thimbles to be manufactured in high numbers with very high quality. Due to the high strength and low temperature brittleness of tungsten special manufacturing techniques need to be developed for the production of parts with no cavities inside and/or surface flaws. The main achievement in developing the respective manufacturing technologies will be presented and discussed.

To achieve the objectives mentioned above various manufacturing and joining technologies are pursued. Their later applicability depends on the level of development including their transferability to the component. Hence, specifying design and requirements for the components of interest will determine appropriate time and criteria for selecting most promising technologies. Although the considered technologies are mainly developed for the HC divertor it is worth to note that they are also useful for other divertor and even blanket concepts, particularly those with tungsten armor.

1. Introduction

The divertor is a key component in fusion power plants which acts as an exhaust for the fusion reaction products and their high energy. Common feature of divertor concepts developed so far is the use of target structures intensively cooled by proper coolant and mostly built from tungsten because of its high melting point, very low sputtering yield, and good thermal conductivity. For cooling pressurized sub-component is thermally joined to target and as structural component is built from suitable structural material fulfilling appropriate requirements particularly for high temperature strength and sufficient toughness in the operational temperature range. Due to the brittleness of tungsten in the low temperature range its use also as a material for the structural component is only possible for the high temperature part of it. Consequently to build a divertor at least another material beside tungsten needs to be selected and technologies for joining with tungsten need to be realized.

One of the most advanced designs for helium cooled (HC) divertor is that developed at the Karlsruhe Institute of Technology (KIT) [1]. The KIT HC divertor has a modular design, in which the divertor target plate is built from several 9-finger-modules each of them consists of 9 one-finger-modules. The one-finger-module is assembled of three parts: tile, thimble and housing (see Fig. 1). The tile is the plasma facing target built from tungsten (W). For cooling the tile it is thermally bonded to the thimble which in turn is

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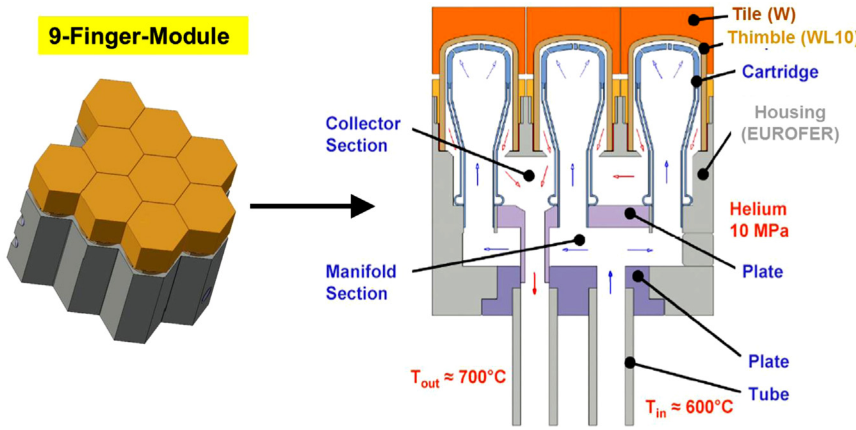

Fig. 1. Modular design of the helium cooled divertor developed at KIT [1].

joined to the housing. The thimble and the housing are flown and pressurized on their inner side by helium and hence are structural parts. Due to its high temperature strength, low thermal expansion and low activation tungsten lanthanum oxide (WL10) is selected for the thimble while the housing is built from to the reduced activation ferritic martensitic steel EUROFER97 or its oxide dispersion strengthened variant, EUROFER-ODS. With thermal load of 10 MW/m^2 and impingement helium cooling the temperatures expected in the tile are in the range between 1200 °C (thimble side) and 2200 °C (plasma side). Hence, the operation temperature of the joint between the tile and the thimble is around 1200 °C which is at the same time the upper operation temperature of the thimble mainly limited by the creep strength and the recrystallization temperature of WL10. The lower operation temperature of the thimble, 650 °C is determined by the ductile to brittle transition temperature (DBTT) of WL10 and proper margin considering its shift due to neutron irradiation. Consequently the joint between thimble and housing is designed at the position where the temperature ranges around 650 °C which is at the same time the upper operation temperature of the steel housing.

To realize the KIT HC divertor described above technologies are required for joining the tile with the thimble, tungsten–tungsten joints, and the thimble with the steel housing, tungsten–steel joints. In addition and in view to the large number of one-finger-modules required (250,000 for one fusion power plant) special manufacturing technologies are necessary for mass producing tiles and thimbles with very high quality from tungsten and WL10, respectively, which however are hard to machine particularly at room temperature. In the following the recent developments in the mentioned joining and manufacturing technologies are presented and discussed.

2. Tungsten–steel joints

The main challenges in realizing reliable tungsten–steel joints range from mismatch in thermal expansion between tungsten and steel over metallurgical reactions with brittle phase formation to crack stopping ability and in case of brazing excellent surface wetting. These requirements were only met partly and insufficiently in the past, e.g., by casting Cu between tungsten and steel. To fulfil them three types of joints, namely brazed, diffusion bonded and functionally graded tungsten–steel joints have been investigated and further developed.

2.1. Brazed tungsten–steel joints

In the first approach pursued for compensating stresses caused by the mismatch in thermal expansion brazed joints have been investigated. The investigations started brazing parts of finger-module mock-ups for High Heat Flux (HHF) experiments. The first filler material used for this purpose is copper and thereafter a Co-based filler metal. As the creep strength of the filler material at the joint operation temperature is quite low for structural application a special joint design is proposed with which the filler material is mainly loaded by compressive stresses. In that design the thimble at the joint area is conically shaped and is brazed with the counter conical side of a steel ring whose other side is welded to the steel housing by electron beam welding (see Fig. 2). Initial experimental HHF test results showed that the joint filled with copper often leads to helium leak, because copper and tungsten are not mutually miscible and consequently have not a good adhesion. The cobalt filler proved to be too brittle braze material and is a highly activation material what is not desired for fusion application. To improve this brazed joint a study on new brazing technology for the brazing of WL10–steel joints (working temperature ~700 °C) has been conducted. Thereby and based on a literature review a filler metal, Pd18Cu72 (T_{liq} = 1100 °C) is found suitable for achieving sufficient strength of the joining interface. The successful brazing tests with this filler material [2] reveal good adhesion of PdCu to tungsten and steel (see Fig. 3).

As mentioned above due to the immiscibility of Cu and W, copper cannot be directly used for brazing of tungsten to steel. Therefore, intermediate activation layers have to be selected which exhibit affinity to both tungsten and the filler metal Cu. For the first test series Ni is chosen as reference and provisional metal to study e.g., deposition, adherence and alloying behavior due to the vast knowledge in Ni deposition technology and the possibility to handle Ni in aqueous solvents. Fig. 4 shows the excellent coating

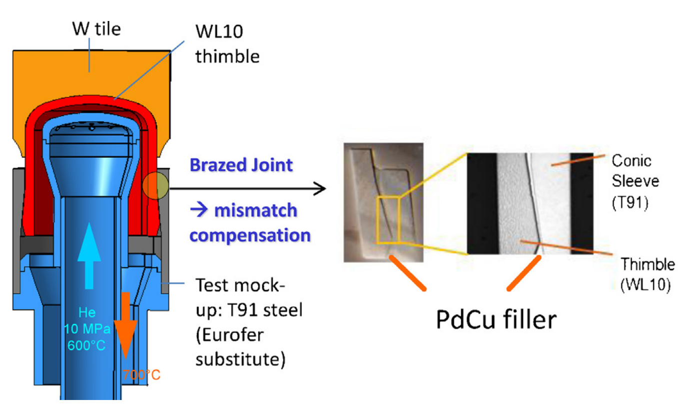

Fig. 2. Design of brazed tungsten–steel joint developed for the KIT helium cooled divertor.