Fusion Engineering and Design 86 (2011) 1656–1659

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Progress of He-cooled divertor development for DEMO

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ARTICLE INFO

Article history:
Available online 31 January 2011

Keywords:
Helium-cooled divertor
Impingement cooling
High heat flux tests

ABSTRACT

A He-cooled divertor concept for DEMO [1] has been developed at Karlsruhe Institute of Technology (KIT) since a couple of years with the goal of reaching a heat flux of 10 MW/m^2 anticipated for DEMO. The reference concept HEMJ (He-cooled modular divertor with multiple-jet cooling) is based on the use of small cooling fingers – each composed of a tungsten tile brazed to a tungsten alloy thimble – as well as on impingement jet cooling with helium at 10 MPa, 600 °C. The cooling fingers are connected to the main structure of ODS Eurofer steel by brazing in combination with a mechanical interlock. This paper reports progress to date of the design accompanying R&Ds, i.e. primarily the fabrication technology and HHF experiments. For the latter a combined helium loop and electron beam facility (200 kW, 40 keV) at Efremov Institute, St. Petersburg, Russia, has been used. This facility enables mock-up testing at a nominal helium inlet temperature of 600 °C, a pressure of 10 MPa, and a maximal pressure head of 0.5 MPa. HHF test results till now confirm well the divertor design performance. In the recent test series in early 2010 the first breakthrough was achieved when a mock-up has survived over 1000 cycles at 10 MW/m^2 unscathed.

1. Introduction

The development of a divertor is a challenging task because of the diverse disciplines involved such as design, materials, manufacturing and testing. To reach a heat flux of 10 MW/m^2, an anticipated value for DEMO, a modular divertor concept HEMJ (He-cooled modular divertor with multiple-jet cooling) has been proposed by Karlsruhe Institute of Technology (KIT) [1]. This modular design uses small cooling fingers favorable for stress reduction. Each of them composed of a tungsten tile and a tungsten alloy thimble (Fig. 1) joined together by brazing. The fingers are cooled by helium jet impingement at 10 MPa, 600 °C. For a proof of concept a combined test facility helium loop with electron beam (EB) was built in Efremov, St. Petersburg, Russia. Over the past four years, three series of high-heat-flux (HHF) experiments were carried out. Although the test results have already confirmed from the very first the helium cooling performance able to remove the specified heat load of 10 MW/m^2, the design has been successively improved in terms of stress reduction, reaching crack-free manufacturing quality of tungsten parts and the use of high temperature brazing fillers to avoid an overheating of the joint when performing tests at higher load level.

This paper will give an overview of the progress of development in the design supporting areas. The first test results shall be reported, which were carried out at the beginning of this year in the upgraded facility.

2. Manufacturing and joining tungsten parts

Tungsten is regarded the most suitable material for divertor application because it possesses high melting point, large thermal conductivity, and high strength. On the other hand it has both high hardness and high brittleness that make it difficult to machine the components. As shown in Fig. 1, the plasma-facing surface of tungsten tile has a hexagonal cross-sectional shape with a width across flats of 18 mm. The lower surface of the tile is a concave shape that fits exactly to the thimble head shape and forms a stable braze joint.

From the previous experiments, it was recognized that micro-cracks on the surface of tungsten parts and excessive temperature at the braze joint are the main reasons for the shortened lifetime of the divertor cooling finger. This is particularly the case when the finger is subjected to temperature cyclic loading. The micro-cracks (depth ~30 µm [2]) were found to be initiated by EDM (electro discharge machining) and/or conventional machining (turning, milling, grinding) with insufficient surface quality. They lead to crack growths in tile and thimble during thermal cyclic-loading.

Improved mock-up machining: After comprehensive study of tungsten machining [3] at the NC machine center of KIT, micro crack

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doi:10.1016/j.fusengdes.2010.12.005

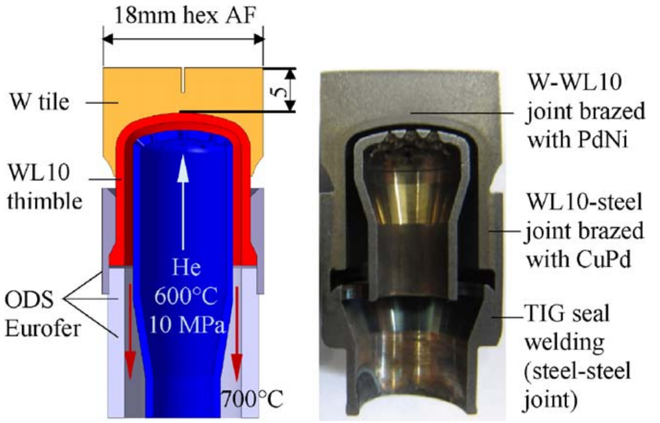


Fig. 1. Reference design HEMJ [1], left: 1-finger module, right: brazed joints of the parts.

free machining (milling W tile and turning WL10 thimble) has been successfully completed. The components of the cooling finger (tile, thimble and conic sleeve) could be manufactured with high quality. They are prepared for assembly and following HHF tests at Efremov (Fig. 2).

Innovative mass production methods: Because of the required large number of the cooling finger of about 250,000 in the entire reactor, an economical method for mass production of tungsten parts is now being sought. Two cost-saving methods for function-oriented and load-oriented production of tungsten components have been investigated at KIT: *Powder injection moulding* (*PIM*) of a tungsten tile and deep drawing of tungsten alloy thimble. For the former method key steps in injection moulding tungsten parts, i.e. feedstock formulation, injection moulding process itself, debinding, and a combined compacting process sintering/hot isostatic pressing (HIP) were comprehensively studied [4]. The first work outcomes are very promising for use as mass production of tungsten tile, which is a functional part of the divertor. For example, a compacted density of the product by almost 99% of theoretical density at a grain size of about 5 μm after sinter and HIP steps was achieved. For mass production of WL10 thimble, which is a structural part of the divertor a forming process deep drawing is being investigated. This kind of forming process provides an advantage in that the grains of the material are formed uniformly along the contour, which is favorable for the strength increase in the structure. The deep drawing investigation was started with related press-rolling method [5]. It was first tried on steel and TZM (molybdenum alloy with titanium and zirconium) sheets, which were successfully pressed to form a thimble at a temperature of about 400 °C. In a further step cupping was performed on 1 mm W sheets in a newly constructed tool with electric heater (Fig. 3left). To date, a thimble-profile depth of 5–6 mm was reached (Fig. 3right) at a deep-drawing temperature of about 600 °C. In order to deep draw the thimble completely to its end form, further improvements have to be made to the tool, e.g. (a) remedy against cracking of the work piece by larger transition radius in the tool, (b) increasing the deep-drawing temperature to enhance the ductility of tungsten work piece. These activities are running.

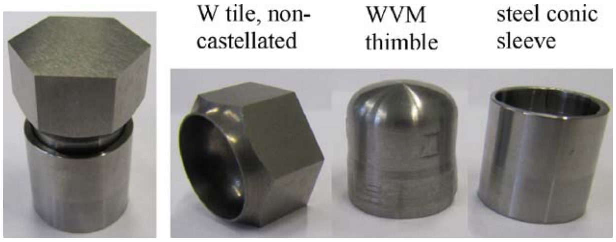


Fig. 2. 1-finger module components 2010 (W tile, WVM thimble, and steel conical sleeve) manufactured at KIT.

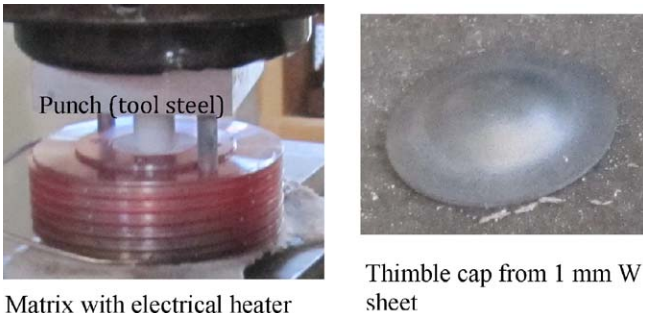
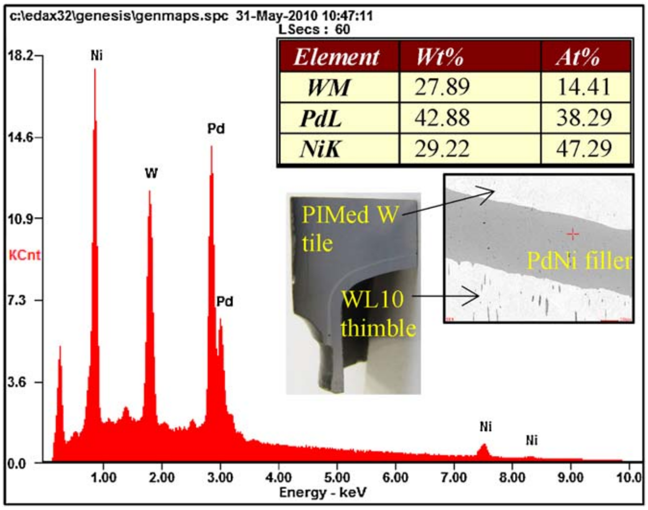


Fig. 3. First W deep draw attempt with a new developed tool.

Joining of mock-up parts: Another type of failure observed in the preceding tests was the detachment of tile and thimble due to an overheating of the brazed joint – top surface melting of the W tile as a consequence – when ramping up the incident heat flux beyond 13 MW/m^2. The reason for this kind of failure was that STEMET®1311 (amorphous Ni based alloy, T_{br} = 1050 °C) brazing filler metal was originally used for the W tile/WL10 thimble joint (working temperature ∼1200 °C) of the first mock-ups. In order to improve the braze joint a study on new brazing technology for high-temperature brazing has been launched at KIT [3]. New brazing filler 60Pd40Ni (liquidus temperature T_{lq} = 1238 °C) was chosen for the W-WL10 joint, taken into account the recrystallisation temperature of WL10 material (1300 °C). For the brazing of WL10-Steel joint (working temperature ∼700 °C) 18Pd82Cu filler (T_{lq} = 1100 °C) was found suitable. A common muffle furnace was used which allows for 10^{-5}–10^{-4} mbar vacuum and a homogeneous temperature distribution, important for successful brazing. Preparation steps are sand blasting and acetone ultrasonic bath. In both cases W-WL10 joint with PdNi and WL10-steel joint with CuPd good adhesions of brazing fillers to the basic materials were achieved. In general, no cavities were detected. The results of EDX point scan of a successful brazed joint between a PIMed W tile and a WL10 thimble with PdNi filler are shown in Fig. 4 as an example. In the EDX spectrum (Fig. 4bottom), the EDX signal intensity as a function of the photon energy is plotted according to the point scan data of elements in the table (Fig. 4top). Here a diffusion of tungsten in the brazing material is clearly seen.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Element	Wt%	At%
WM	27.89	14.41
PdL	42.88	38.29
NiK	29.22	47.29

Fig. 4. SEM and EDX scan results of a successful brazed joint PIMed W tile – WL10 thimble with PdNi40.