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Fabrication of a He-cooled divertor module for DEMO reactor

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Abstract

One current design of the divertor for a fusion reactor like DEMO uses He-cooled thimble-like tungsten, which is covered by sacrificial tungsten tile. Each thimble has to be connected with a supporting unit made from ferritic steel. This paper describes the development of joining techniques between tungsten thimbles and steel supporting units. Paper also provides an evaluation of simple geometries up to more complex conical interlocks filled with cast copper. Four candidates tungsten alloys (WL10, W-single crystal, W–Cu composite and chemical vapour deposited (CVD) tungsten) were experimentally checked by 'non-isothermal' heating to characterize the thermal gradient in the range 600 °C (for joint) and more than 1000 °C (for thimble top) using a special testing procedure. Basing on the test results, several mock-ups were manufactured for future high heat flux testing in a helium loop.

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1. Introduction

Previous study of helium-cooled refractories [1,2] showed a helium-cooled divertor concept as one of the most promising lines towards a DEMO reactor. Further development of a helium-cooled divertor depends strongly on progress in selection of suitable materials and technologies of their manufacturing and joining. Divertor design requires surviving at cyclic heat load of 10–15 MW/m^2. During operation, the temperature on the top of the thimble-like divertor element is raised to 1000 °C, while it remains 600–700 °C at thimble/steel joining area [3]. The main goal of this work was to select suitable materials, develop a joining method and manufacture the experimental sample that meets these requirements.

2. Evolution of tungsten-alloy/ferritic steel joining technique

The W thimble design consists of an outer diameter about 15 mm and wall thickness about 1 mm that is joined to coaxial steel tube made from ferritic steel. The main problem of such a joint is a significant mismatch of thermal expansion coefficients that causes large thermal stresses during cyclical heating. Several attempts to join thimble to steel were made using simple mechanical locking by means of pins filled with copper. Two W thimbles were joined to steel tube by tungsten. The first sample withstood 15 MPa of internal He pressure at

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room temperature (RT) but during the isothermal heating up to 600 °C, a number of vertical cracks appeared in the W thimble. The second sample also passed 10 MPa He pressure test at RT but leaked during the non-isothermal heating. Metallography of such joints showed poor uniformity and vacuum tightness. Other attempts to join a W thimble to a steel tube using bayonet locks were stopped (because of thimble cracking) either during the stage of W thimble manufacturing or during the final machining after filling the bayonet lock with cast copper. In addition, manufacturing of such type of lock is too expensive and complicated. Finally, a combined method using a conical mechanical lock filled with cast copper was found as the most suitable and a number of such samples were manufactured for further investigation. The scheme of joining via a conical lock filled with cast copper and a general view of the sample joined by this means (without sacrificial tile) are shown in Fig. 1.

3. Experimental selection of thimble material

3.1. Tungsten grades for experimental selection

Several tungsten grades were considered as a material for the strength thimble. Among them are WL10 (W–1La$_2$O$_3$), W-single crystal (SC), W–Cu (W–15Cu) composite material, and CVD-tungsten. The advantages or disadvantages of some of these materials in comparison with conventional PM pure tungsten are discussed and listed in Table 1. To experimentally select the best candidate, a number of identical thimble/steel samples was manufactured from WL10, W-single crystal, W–Cu composite material and CVD-tungsten. A conical lock filled with cast copper was used to manufacture the samples. As an alternative to cast copper, one sample from WL10 having a conical lock was brazed at 1100 °C using high temperature brazing with cobalt-based (Co-base, 5.8Fe, 12.4Ni, 6.7Si, 3.8B,

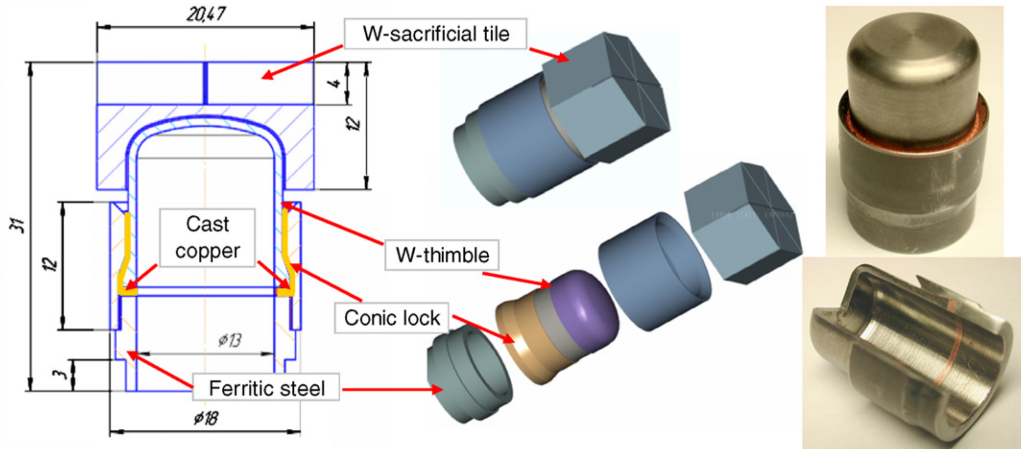

Fig. 1. Schematic of manufacturing of 'one-finger' divertor element.

Table 1
Tungsten grades for experimental selection of thimble material

Grade	Advantages	Drawbacks
WL10 (W–1La$_2$O$_3$)	Easy machining (lower DBTT) and higher recrystallization temperature	No data on radiation resistance and doping additives (La, O) are not plasma compatible
W–Cu (W–15Cu)	Easy machining (lowest DBTT), less CTE (8.1×10^{-6} estimated) mismatch with steel and highest thermal conductivity (223 estimated)	Limited data base, no data on radiation resistance, less resistance to accidents (lower melting temperature) and higher activation
SC W–1Ta (doped single crystal)	Lower DBTT and higher thermal conductivity (high purity)	Lower strength at elevated temperature, limited data base, no data on radiation resistance, difficult to machine and expensive
CVD W	Higher thermal conductivity (high purity) and easy shaping and joining (TBD)	Limited data base, no data on radiation resistance and expensive

0.1Mn, $P \leqslant 0.015$, $S \leqslant 0.015$, $C \leqslant 0.08$) brazing alloy. During the manufacturing WL10 and W–Cu were easier to machine than conventional tungsten, which requires additional measures (polishing and electrochemical etching to remove surface damage). Single crystal tungsten behaved similarly to conventional tungsten during machining (e.g. showed tendency to crack especially at the sharp corners). Other techniques instead of machining (EDM, laser) are required to make the thimble shape.

3.2. Experimental procedure

To initially investigate their high heat flux performance a number of identical samples made from different tungsten grades were manufactured so that comparative thermo-mechanical and hermetical testing of candidates could be done. Aiming to simulate DEMO relevant temperature conditions, so-called 'non-isothermal' heating was carried out at the TSEFEY-M electron beam facility, Efremov Institute, Russia [4]. A thermal gradient on the sample was provided by the following procedure. The top of the thimble was heated by an electron beam; surface temperature was monitored by IR-camera. The pulse duration of the electron beam was experimentally optimized in order to get the required level 1000 °C on the top of the thimble and a level 600 °C in the thimble/steel joint area. It should be noted that the samples were not actively cooled by helium (no helium was flowing). Each sample was loaded by 10 MPa of static He on the inside during the testing. All manufactured samples were tested as described. A schematic of the experiment is presented in Fig. 2.

3.3. Results of testing

The following testing results were obtained:

- The sample of the WL10 (conical lock filled with cast copper) thimble successfully withstood 10 non-isothermal heating cycles. Brief analysis of sample cross-section cut by EDM revealed good filling of the conical lock with cast copper.
- The sample of the WL10 (conical lock, brazed with cobalt-based brazing alloy) thimble successfully withstood 20 non-isothermal heating cycles. Brief analysis of sample cross-section revealed no pores or other defects in brazed area. An attempt to cut the sample by EDM caused cracking in the thimble, probably due to residual stresses in the sample after brazing.
- The sample of the W–Cu thimble mock-up successfully survived several thermal cycles of non-isothermal heating (from RT to 600 °C for joint – 900 °C for thimble top), but a He-leak from the thimble top (probably due to loss of copper from the thimble surface) was detected when the temperature was increased up to 950 °C (no cracks was found in cross-section).
- The first sample of the W-single crystal (SC) thimble was broken during the machining of its inner surface (a number of cracks appeared). The second sample of the SC thimble was broken into pieces just after loading by inner He pressure.
- The sample of the CVD W thimble was also broken into pieces after loading by inner He pressure.

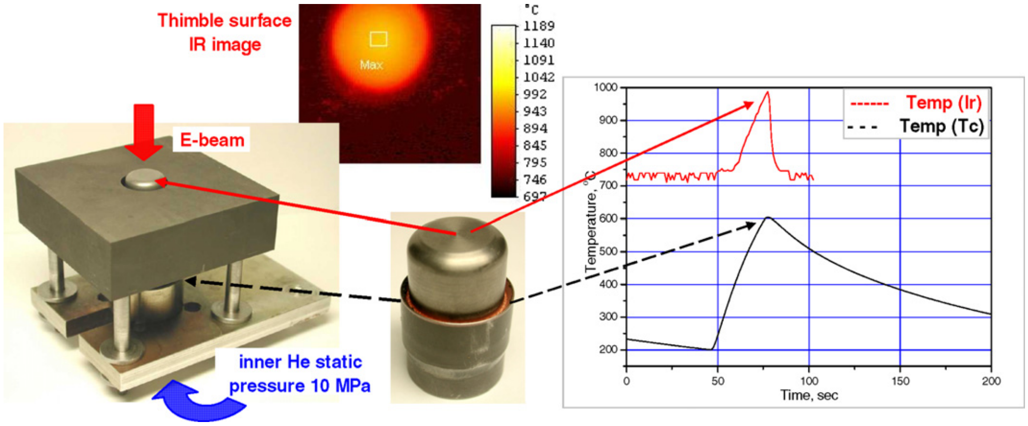

Fig. 2. Comparative testing of different tungsten grades.

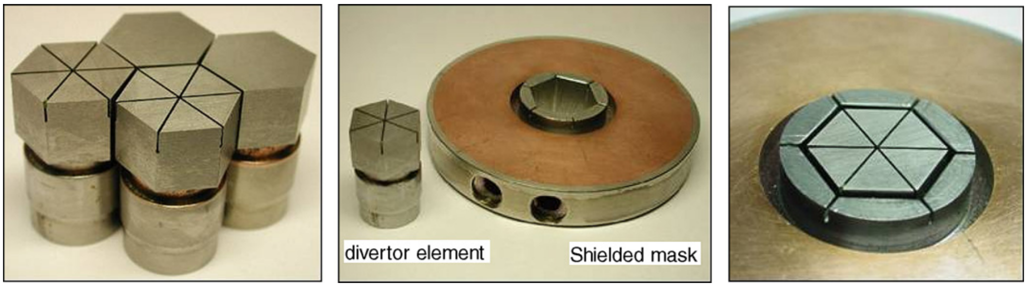

Fig. 3. Schematic of manufacturing of 'one-finger' mock-ups for the HHF test.

Comparative testing of different tungsten grades has shown that:

- WL10 is the most suitable grade for the thimble.
- Thimble/steel joining via conical lock filled with cast copper is the most reliable method of manufacturing for further mock-ups.
- Thimble/steel joining produced by brazing needs additional study with respect to residual stresses.

4. Manufacturing of mock-ups for the high heat flux testing

Bringing together optimized technology of thimble/steel joining and the results of comparative testing of different tungsten grades, a number of He-cooled thimble-like divertor modules having hexagonal protective tungsten tile was manufactured with the purpose of high heat flux testing in a DEMO-like environment. In accordance with current design a 'one-finger' divertor element (that can be assembled into nine-finger module) is shown in Fig. 1. Protective (sacrificial) tile was made from conventional PM tungsten and joined to the thimble by brazing (see details in [5]). The thimble was made from WL10 and joined to ferritic steel (Eurofer) by means of a conical lock filled with cast copper. A total of four mock-ups were manufactured. All revealed good vacuum tightness. To reduce thermal stresses, upper tiles of two of the mock-ups were additionally castellated (see Fig. 3). Each mock-up will be integrated into a cooled He-loop and will be subjected to high heat flux in the TSEFEY-M facility. With that aim a new water-cooled shielded mask has been manufactured. This mask has hexagon-shape frame made from molybdenum that enables uniform electron beam heating on the edges of the W tile during high heat flux testing.

5. Conclusions and outlook

- An intensive study of joining a tungsten thimble to a steel supporting unit was conducted. As a result, a promising joining method via a conical lock filled with a cast copper was identified.
- Thimble/steel joining using a conical lock and brazing needs additional study with respect to residual stresses.
- To optimize the material for the thimble, several tungsten grades were comparatively tested. Among the four tested, the WL10 grade was found to be the most suitable.
- As result of these investigations, several 'one-finger' divertor modules were manufactured in accordance with design.
- High heat flux testing of manufactured modules in helium loop is planned for the near future.

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