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Research paper

Impact of thermal fatigue on W–W brazed joints for divertor components

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A B S T R A C T

W–W brazed joints (tungsten block: 8 × 8 × 4 mm joined to an actively cooled copper heat sink) were exposed to steady state heat loads to study the effect of the thermal fatigue on their microstructure, mechanical integrity and heat transfer capability. Two different surface temperatures were tested (1000 °C and 1250 °C) varying the number of applied cycles (100 and 1000). The results indicated that a surface temperature of 1000 °C represents the limit condition for the joints to be used in the DEMO fusion reactor, which corresponds to a braze temperature in the range of 562–599 °C according to thermal simulation results. The use of that temperature caused a limited effect on the microstructure and heat transfer capability for both 100 and 1000 applied cycles. The increase of the surface temperature to 1250 °C caused degradation of the joint and a reduction of sustained cycles and accordingly lifetime.

1. Introduction

The divertor component of the DEMOstration fusion reactor (DEMO) will be exposed the most severe conditions among all plasma facing components of the vacuum vessel. High thermal loads, neutron irradiation and particles exposure will be the most relevant phenomena which the materials have to withstand. In order to select the materials and the joining technologies necessary for the design of the reactor, it is necessary to expose them to similar conditions than those expected during the service life of the reactor. The divertor design proposed by Norajitra et al. (2011) included one tile made of tungsten, which will face the plasma joined to a thimble structure made of a tungsten alloy. The joint is thought to be fabricated using an intermediate filler alloy to stop the propagation of the crack formed in the tile during its service life. The selected filler has to meet some requirements, compiled and discuss by Aubert et al. (2011), such as thermal stability, up to certain temperature, and restrictions in the filler compositions.

The present paper proposed 86Fe-14Ti alloy as filler material for W–W brazed joints, whose suitability has been demonstrated in previous works. The filler allows providing high strength joints with a low distortion of the base material properties reported by de Prado et al. (2016b) in previous works. In addition, the composition of the filler material fulfills the compositional restrictions to be used in the DEMO reactor.

The simulation of the expected service conditions has been carried out by several author including Kim et al. (2016) and Van Renterghem et al. (2016) by means of high heat flux (HHF) tests, which is commonly used to reproduce the thermal loads conditions inside the vessel. Norajitra et al. (2009) also examined the DEMO divertor finger unit under HHF tests but the results were not completely satisfactory. Later, several papers have been published regarding the impact of the HHF tests on W-CuCrZr joints by Gavila et al. (2015), Be-CuCrZr joints by Pintsuk et al. (2012) and CFC−CuCrZr joints by Pintsuk et al. (2016) for their application in the first wall and in the tungsten concept of the ITER divertor obtaining different results.

The present work aims to evaluate the effect of steady state loads on the quality of the joints by exposing them to different thermal loads. The joints were IR monitored during the tests to detect possible surface overheating and microstructural and mechanical analysis after the tests (shear tests) were made to determine possible changes, diffusion phenomena or phase formation that could degrade the mechanical integrity of the joints.

2. Joint design and HHF tests

The base material used in brazing experiments was tungsten (> 99.97%, *Plansee AG*). The fabrication procedure of the filler described by de Prado et al. (2016b) consisted in the lamination of a mixture of 86Fe-14Ti powders with an organic binder (powder/binder ratio: 95/5) obtaining flexible tapes of 250 μm width. Brazing tests were carried out in a high vacuum furnace ($\sim 10^{-6}$ mbar) to avoid oxidation. The brazing conditions were optimized in previous works by Prado et al. (2016), the temperature was 1350 °C which was kept for 10 min and the heating and cooling rates were 5 °C/min.

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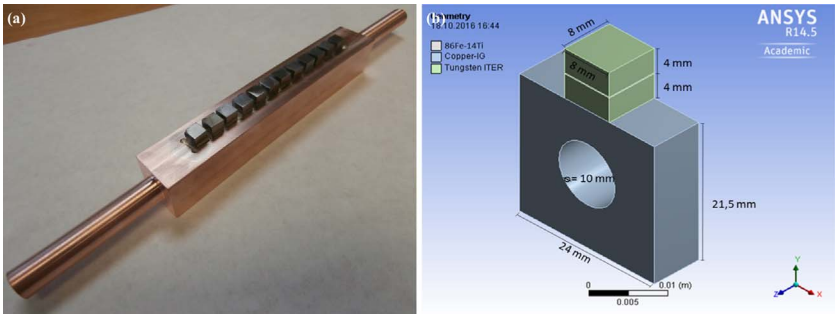

Fig. 1. (a) General view of cooling structures with the brazed samples used for the tests. (b) Schematic representation and dimensions of the samples and cooling component used for the tests.

Afterwards, W–W joints were brazed to a copper cooling structure (heat sink) to ensure the correct refrigeration of the samples during HHF test (Fig. 1a). W-W/Cu joints were carried out using a silver base filler tape with a composition Ag-28Cu-2Ge-0.2Ni (wt.%) supplied by Forschungszentrum Jülich (FZJ), applying the following cycle: heating up to 350 °C (5 °C/min); holding the temperature for 30 min; heating up to 750 °C (5 °C/min); holding the temperature for 15 min; heating up to 815 °C (3 °C/min); holding the temperature for 10 min; cooling down to 550 °C at 5 °C/min; and, finally, cooling down to room temperature at 1.5 °C/min. Fig. 1b shows a schematic representation and dimensions of the sample and cooling component used for HHF tests.

HHF tests were carried out at the electron beam facility JUDITH 1 at FZJ. The samples were individually exposed to the scanning electron beam of approximately 1 mm diameter at full width half maximum and water was used as coolant. The chosen frequencies and all other parameters are shown in Table 1. During the tests the samples were monitored with an IR camera and pyrometers in order to detect surface overheating events caused by a deficient refrigeration or failure of the samples. The heating and cooling times of each cycle were chosen to reach steady state conditions. The vacuum conditions in JUDITH 1 reached an oxygen partial pressure of about 1×10^{-5} mbar.

Samples were exposed to normal operation conditions (steady state loads) because the main interest of the present paper is to analyze the interaction and behavior of the joint interfaces during the normal operation of the reactor. The use of high transient thermal loads corresponding to off-normal operation conditions could lead to partial melting of the material and formation of crack networks along the top surface. However, the influence on the joint interfaces is limited according to the studies carried out by De Temmerman et al. (2015) and Loewenhoff et al. (2016), where the only zone affected by the transient thermal loads was the surface of the plasma facing material.

Samples were tested under different conditions varying the surface temperature (1000 °C and 1250 °C) and the number of cycles applied (100 and 1000). For each condition, four joints were exposed to the electron beam, one for microstructural examination and three to study their mechanical behavior after the test.

The temperature distribution across the joint was studied via FEM simulation with ANSYS software.

Thermal diffusivity tests were carried out at FZJ to analyze the heat transmission properties across the joint using a laser-flash equipment. Thermal diffusivity of three samples with approximately 2–3 mm thickness was measured from room temperature to 1000 °C.

After HHF tests, the microstructure of the joints was analysed by scanning electron microscopy (SEM). The samples were prepared with the standard polishing technique. Some joints were etched by immersion before microscopic observation to develop the tungsten grains and determine the effect of the thermal loads on the grain size of parent material. For it, an etchant solution of 30 ml H_2O, 10 ml H_2O_2 and 20 ml NH_3 was used. In order to obtain the mechanical properties of brazed joints, shear tests were carried out using a Universal Testing Machine (*Zwick Z100*). The specimens were tested at room temperature with a speed of 1 mm/min. For each HHF condition, three samples were sheared and the average shear strength was calculated.

Table 1
HHF testing parameters in JUDITH 1.

$A_{loading}$	64 mm^2
Scanning frequency	40 × 31 kHz
Water velocity	14.6 m/s
Water P in	0.5 bar
Water T in	21 °C
Power (on/off)	10/10 s

3. Results and discussion

The first test was carried out with a W surface temperature of 1000 °C and it was monitored using an IR pyrometer (Fig. 2(a)). The temperature gradient inside the joint from the top surface (heat source) to the heat sink (copper cooling structure) was uniform (Fig. 2(b)).

At this surface temperature, 100 and 1000 cycles were applied and no surface overheating event was detected during the performance of the test. The micrographs of two specimens after a different number of cycles are shown in Figs. 2(c) and (d), respectively. Both joints showed similar microstructural characteristics, which corresponds to the previous description made of the samples after brazing conditions described by de Prado et al. (2016a). The braze was constituted by α-Fe (dark grey) and Fe_2Ti (light grey) phases and an interdiffusion layer formed at both interfaces. Therefore, the thermal heat cycles did not produce changes in the microstructure of the joints. Cracks originated at the interface were also observed across the braze. These cracks had been detected after the brazing cycle and showed a moderate growth caused by the exposure of the joints to thermal fatigue during the cycles. As it was previously reported (de Prado et al., 2016b), the cracks stopped when a more ductile phase was reached. These cracks did not cause a drop of the refrigeration capability of the joint because they were parallel to the heat flux direction.

Under these conditions, the braze was in the range of temperatures of 562–599 °C (Fig. 3), which is approximately 700 °C lower than the solidus temperature of the filler alloy (T_{sol} = 1293 °C measured by de Prado et al. (2016b)), and melting of braze will not occur during the service life of the component. (Norajitra et al., 2009) carried out HHF in thimble-tile mock ups with similar thermal loads (10–12 MW/m^2) than those applied in the present work, but using He gas at 600 °C as a coolant fluid. The mock ups were tested for a maximum number of 100 cycles using a commercial filler with a solidus temperature of 995 °C. During the test, the temperatures reached by the braze resulted in its melting and subsequently overheating of the top part of the joint (tile). Later, an improved design tested by Norajitra et al. (2010) withstood 1000 cycles under 10 MW/m^2. However, the filler used for brazing the thimble to the tile contained Ni, and the use of this element in the DEMO reactor is not allowed because it induces swelling when is exposed to a neutron flux according to Porollo et al. (2013).

In order to analyze if the selected conditions could lead to recrystallization of tungsten, the specimen subjected to more severe conditions (1000 cycles) was metallographically etched. The general