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HIGH HEAT FLUX PERFORMANCE OF W-EUROFER BRAZED JOINTS

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Keywords

Tungsten, Eurofer, brazing, fusion reactor, high heat flux, plasma facing component

Abstract

The qualification process of the materials and components for the next generation of fusion reactors makes it necessary to expose them to similar service conditions as expected during the service life of the reactor. In the present work, W-Eurofer brazed joints (tungsten block: 8 × 8 × 4 mm; steel 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 and mechanical integrity. Three different W surface temperatures were tested (400, 500 and 600 ºC) varying the number of applied cycles (100 and 1000). The results allowed identifying 400 ºC as threshold condition under which the brazed joints could be used without deterioration. The increase of the surface temperature deteriorated the mechanical integrity of the joints in comparison to those analyzed after the brazing process and accordingly reduced the refrigeration capabilities.

1. Introduction

The components and materials used in the First Wall (FW) of the DEMOnstration fusion reactor (DEMO) will be exposed to high thermal loads, among other relevant phenomena which will take place inside the vacuum vessel (i.e. neutron irradiation, particles exposure, etc.). For the materials and components selection, it is necessary to characterize and finally qualify them by exposure them to similar conditions that are expected during the service life of the reactor, which in the case of the first wall of the DEMO reactor could vary from 2-4 MW/m^2 depending on the location inside the vessel [1]. The FW design includes a tungsten layer, which will face the plasma and protect the other materials from the most adverse conditions. The layer will be supported by a reduced activation steel (Eurofer) structure. Therefore, it is necessary to develop bonding procedures to join both components and ensure its stability during service life [2-4]. The joint, has to withstand the mechanical stresses, as well as to meet also other requirements such as thermal stability up to certain temperature and restrictions in the filler compositions [5].

In the present paper, 80Cu-20Ti alloy is used as filler material for W-Eurofer brazed joints, for which its suitability has been demonstrated in previous works [6]. The characterization showed the viability of the brazing process, which gave rise to high strength joints with a low distortion of the base material properties [7]. In addition, the composition of the filler material fulfilled the compositional restrictions to be used in the DEMO reactor.

High heat flux (HHF) tests have been widely used to simulate the most relevant conditions (thermal loads) expected inside the reactor during its service life [8, 9]. Therefore, it is a valuable tool to validate and qualify Plasma Facing Materials (PFMs) and Components (PFCs) for fusion reactor applications in sample or mock-up forms.

However, there are not many specific experiments about the qualification of joints under steady state loads despite the investigation of mock-ups and components. Norajitra et al. proposed and examined two different concepts of the DEMO divertor component based on W-W joints under HHF [10, 11]. Later, several papers have been published on the impact of the HHF tests in W-CuCrZr, Be-CuCrZr and CFC-CuCrZr joints for their application in the FW and tungsten concept of the ITER divertor [12-14].

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. Thus, the joints were monitored with IR and pyrometers during the tests to detect possible surface overheating. After the tests, the joints were subjected to microstructural and mechanical analysis (shear test) to determine possible changes, diffusion phenomena or phase formation, which could degrade the mechanical integrity of the joints.

2. Joint design and HHF test

The base materials used for the joint were tungsten (>99.97 %, P*lansee*) and Eurofer with the standard composition and microstructure. The fabrication procedure of the filler consisted of laminating a mixture of 80Cu-20Ti powders with polypropylene carbonate as organic binder (powder/binder ratio: 95/5) to obtain flexible tapes of 250 μm thickness [6, 15]. The solidus temperature of the filler measured in previous studies is 885 ºC [7]. Brazing tests were carried out in a high vacuum furnace to avoid oxidation with a residual pressure of 10^{-6} mbar. The brazing cycle consisted of heating up to 960 ºC during 10 min and the heating and cooling rates were 5 ºC /min [6].

The W-Eurofer joints were also brazed to an actively cooled copper cooling structure (heat sink) to ensure the metallic continuity necessary for the refrigeration of the samples (figure 1 (a)). The filler material used in this case was a tape shape filler supplied by *STELLA WELDINGS ALLOYS* with the following composition (wt. %): 56Ag-22Cu-17Zn-5Sn. The brazing treatment applied was: heating from room temperature up to 775 °C (5 °C/min), holding the temperature for 10 min and cooling down to room temperature (5 °C/min). Figure 1 (b) shows a schematic representation and dimensions of the sample and cooling component used for HHF tests.

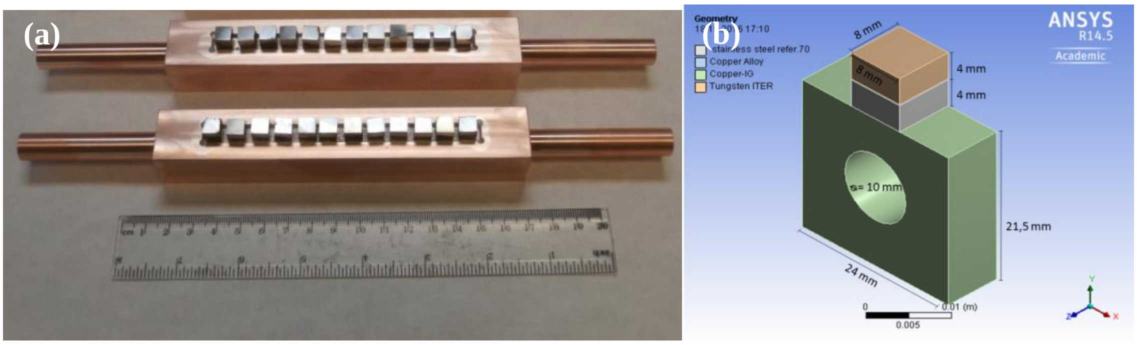

Figure 1. (a) General view of cooling structures with the brazed samples used for HHF tests. (b) Schematic representation and dimensions of the sample and cooling component.

The HHF tests were carried out at the electron beam facility JUDITH 1 at Forschungszentrum Jülich (FZJ). The samples were exposed to the electron beam, of approximately 1 mm diameter, with a scanning frequency of 40 × 31 KHz. Water coolant with an inlet pressure of 0.5 bar at 21 ºC and a velocity of 14.6 m/s was used for the refrigeration of the samples. The tests were monitored with IR camera and pyrometers to determine the surface temperature, adjust the applied power density, and analyze possible surface overheating caused by a deficient refrigeration of the samples. The cycles of heating and cooling (12/10 s, respectively) were chosen to reach the thermal equilibrium. The vacuum conditions in JUDITH 1 reached an oxygen partial pressure of about 1×10^{-5} mbar.

Samples were tested under different conditions varying the surface temperature (400 ºC, 500 ºC and 600 ºC) and the number of cycles applied (100 and 1000). In the case of 600 ºC surface temperature only 100 cycles were planned due to the failure of the joints observed in the early stages of the test. For each condition, a batch of four samples was exposed to the electron beam, three of them to study the mechanical behavior after the test (shear test) and one for microstructural examination.

The distribution of temperature across the joint and in the braze was calculated by FEM simulation with ANSYS software using the material data described at the beginning of section 2.

After HHF tests, samples were cut perpendicularly to the joint for microstructural analysis by Scanning Electron Microscopy (SEM). The samples were prepared with the standard polishing technique.

The shear strength values of the joints were obtained by shear tests of three samples. The fixture was placed between compress plates in a Universal Testing Machine (*Zwick Z100)* and the tests were carried out at a speed of 1 mm/min.

3. Results and discussion

Figure 2 shows an infrared image of the four samples batch exposed to a tungsten surface temperature of 400 ºC. The image indicated higher temperatures obtained in the outermost part of the joints and this effect is associated to the reflection of the IR radiation caused by the adjacent joints. Therefore, the pyrometer used for the monitoring of the surface temperature was always set at the center of the joint. Under this condition, FEM simulation (figure 2 (b)) indicated that tungsten did not experience a significant temperature drop through its thickness while there was a strong temperature gradient in Eurofer. This effect was caused by the considerable difference of the thermal conductivity of the two materials, which constituted the joint. The thermal conductivity of tungsten and Eurofer at 400 ºC is 130 $W\cdot m^{-1}\cdot K^{-1}$ [16] and 30 $W\cdot m^{-1}\cdot K^{-1}$ [17], respectively. The temperature of the braze obtained by the simulation under these conditions was 359 ºC, which was 40 °C lower than the surface temperature but low enough to keep the braze in solid state.

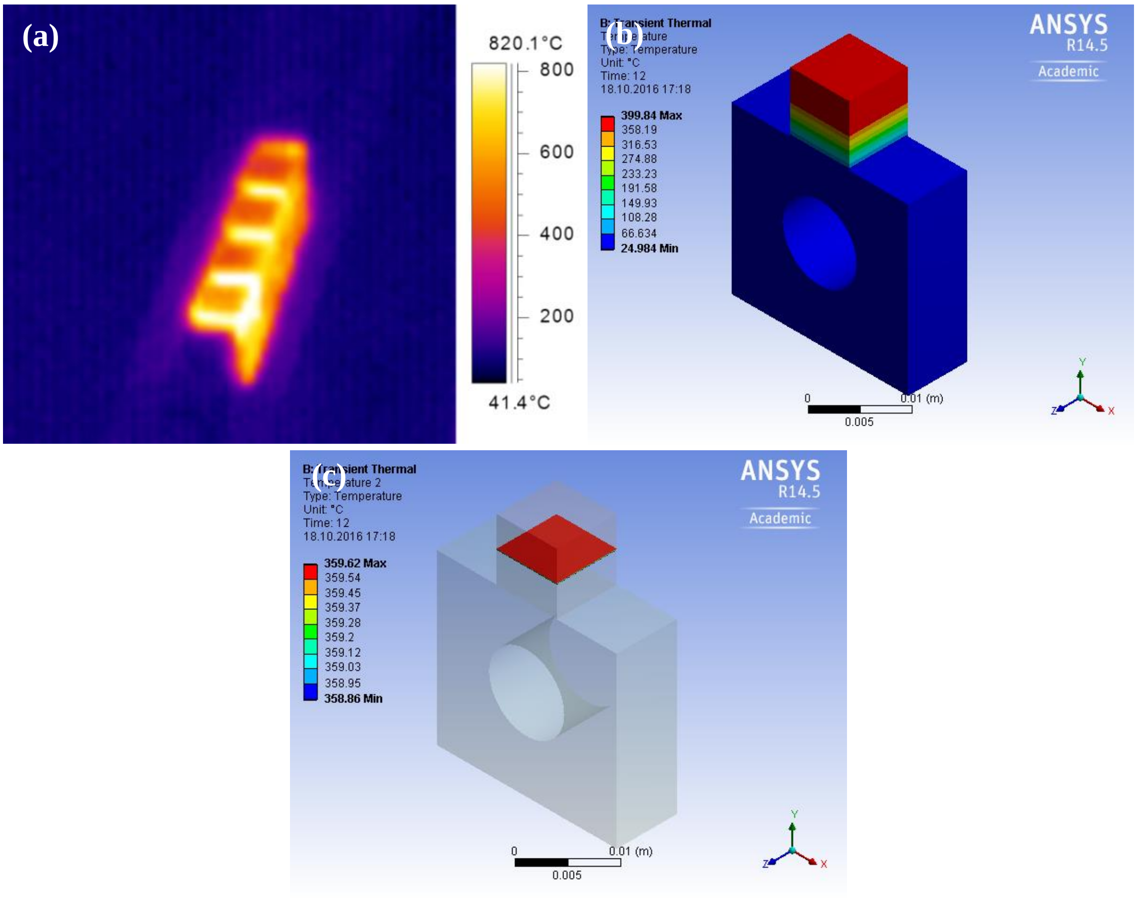

Figure 2. (a) IR-image of the samples during the test at 400 ºC surface temperature. (b and c) Simulation of the temperature distribution across the joint and in the braze, respectively.

At this thermal loading condition, 100 and 1000 cycles were applied without any incident reported during the performance of the tests. This behavior demonstrated the absence of defects at the Eurofer/heat sink interface, which could impair the heat transfer capability.

The metallographic examination images of the joint after the tests are shown in figure 3. The general analysis of the brazed joint did not show any effect of the thermal loads on the microstructure of the braze after 100 and 1000 cycles (figure 3 (a) and (b), respectively) compared to the one obtained after brazing process [6]. Neither a sign of diffusion nor of secondary phase formation were detected. Besides, the continuity of the joints was not affected and there was no evidence of delamination or failure at the joint interfaces, which could result in a sudden increase of the surface temperature. However, a detailed analysis of the W-braze interface revealed the formation of incipient cracks along the interface after 1000 cycles (arrowed in figure 3 (d)). This effect was not observed in the 100 cycles sample (figure 3 (c)). The formation of these cracks after a large number of cycles is associated to the thermomechanical stress caused by the mismatch of the coefficient of thermal expansion (CTE) of tungsten and Eurofer base materials. Furthermore, in previous mechanical tests it was observed that W-braze interface was weak due to the lack of an extensive interaction between the filler and W base material [6]. Therefore, the stresses induced by the continuous heating/cooling processes affected mainly this interface.

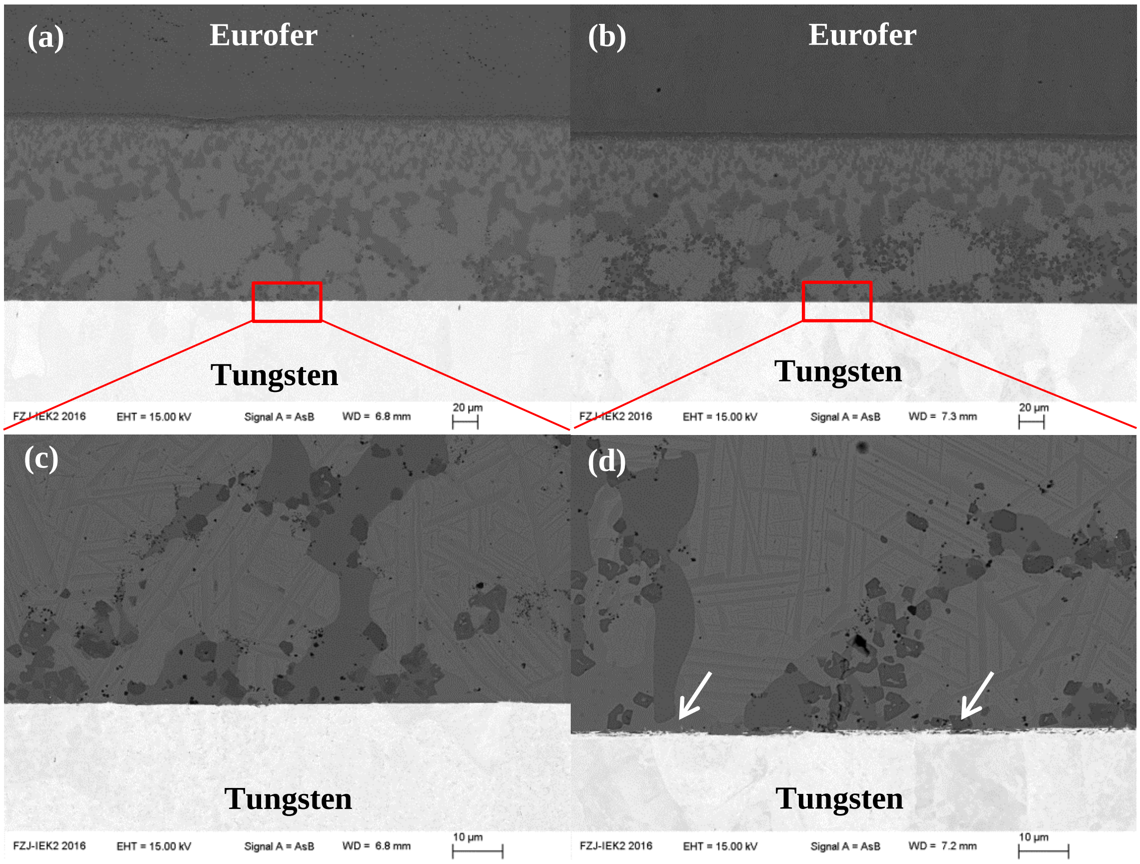

Figure 3. SEM micrographs of the joint after (a) 100 and (b) 1000 cycles. Detail of the W-braze interface after (c) 100 and (d) 1000 cycles.

The analysis of the cooling curve, obtained by monitoring the surface temperature with an IR video, allowed studying the refrigeration capability of the joint under three conditions after the stop of the heating source: before the test and after 100 and 1000 cycles. The results indicated that the refrigeration capability of the joint has not been modified for any tested conditions. Therefore, the formation of the incipient cracks described in the metallographic analysis did not affect the refrigeration capabilities of the joint as the metallic continuity along the interface was good enough to ensure the heat transfer through the joint.

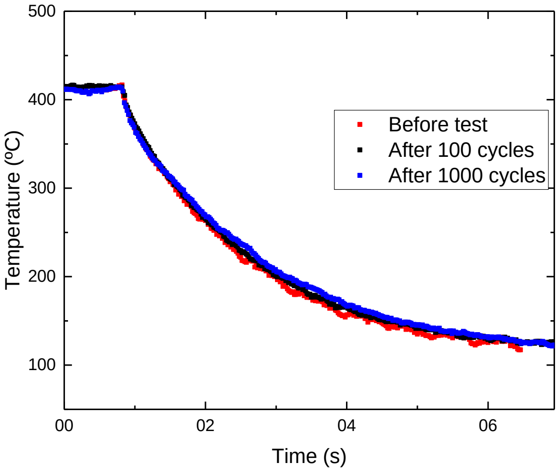

Figure 4. Cooling curves obtained after the stop of the heating source for a tungsten surface temperature of 400 ºC.

The heating of the tungsten surface up to 500 ºC resulted in a similar temperature distribution through the joint to that obtained for 400 ºC, according to the simulation carried out (figure 5 (a)). Under this condition, the temperature of the braze was 445 ºC at the equilibrium stage (figure 5(b)).

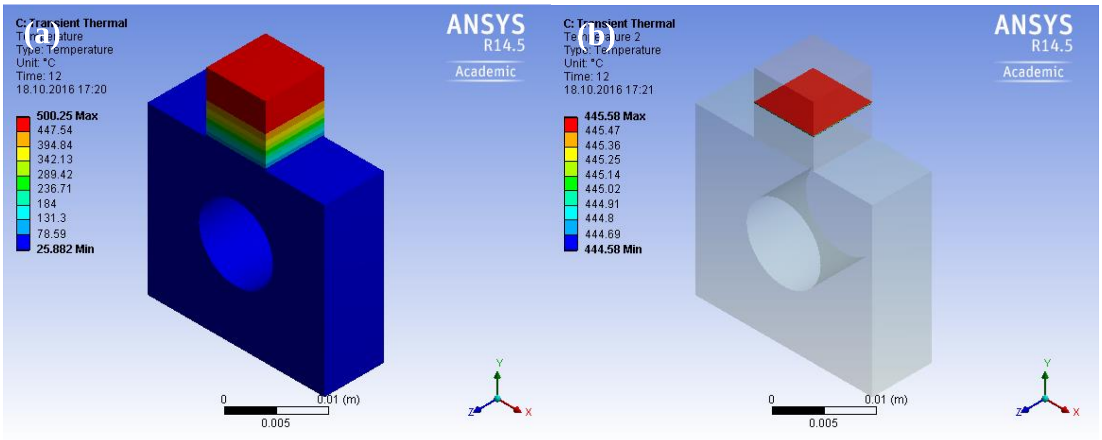

Figure 5. Simulation of the temperature distribution (a) across the joint and (b) in the braze for a surface temperature of 500 ºC.

The IR and pyrometer monitoring system did not report any significant event during the test of 100 cycles as the temperature measured at the W surface kept constant during the experiment. However, during applying 1000 cycles the samples underwent a slight increase of the surface temperature, of approximately 25 ºC after 675 cycles (figure 6 (a) and (b)).

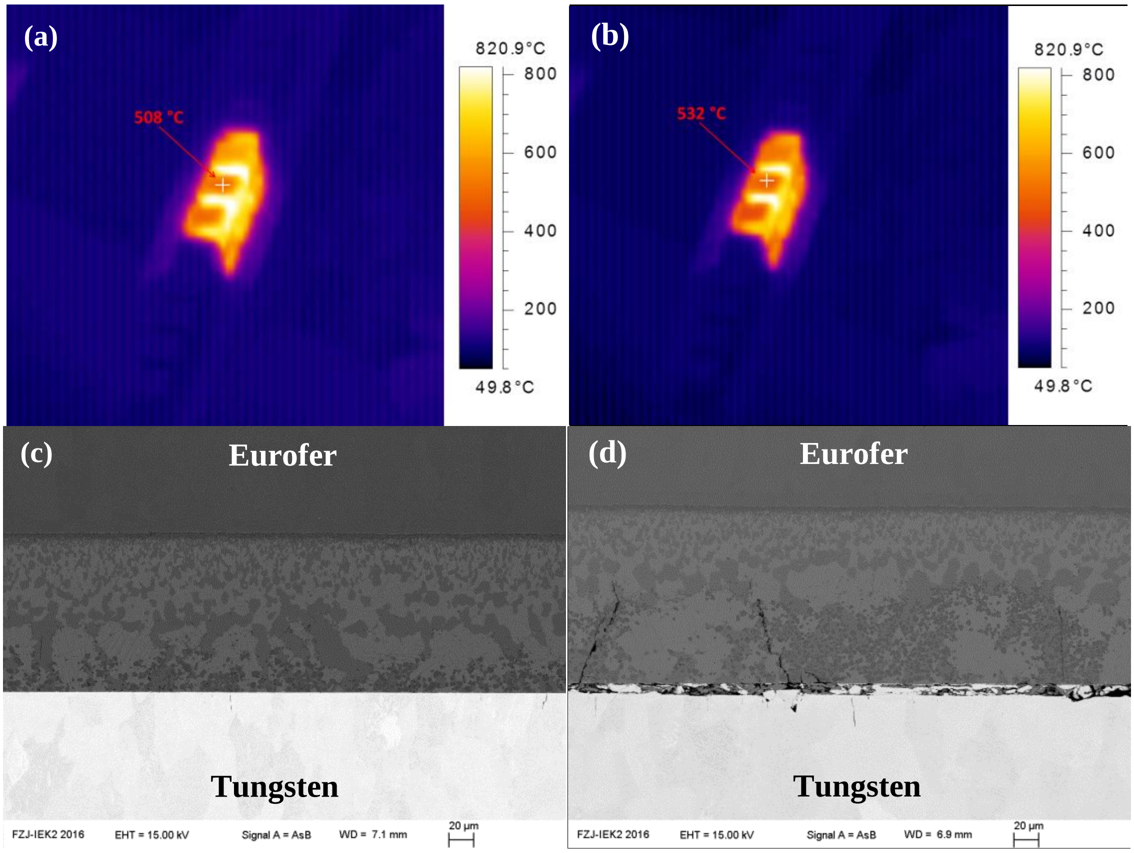

Figure 6. IR-images of the samples subjected to 500 ºC surface temperature (a) before and (b) after 675 cycles. SEM micrographs of the joint after (c) 100 and (d) 1000 cycles.

The microstructural analysis of the joints after 100 cycles did not show any evidence of cracks or discontinuities (figure 6 (c)). However, samples subjected to 1000 cycles showed the presence of several cracks and discontinuities located at the W-braze interface, which were caused by the stress induced by the thermal fatigue assisted by the mismatch in the CTE (figure 6 (d)). The increase of the surface temperature mentioned before was probably caused by the formation of these defects parallel to the joint, which hinder the refrigeration mechanism. Besides, cracks penetrated up to the half of the braze but did not pose an obstacle for the refrigeration of the joint because they were situated parallel to the heat flux.

The last condition was 600 ºC surface temperature (figure 7 (a)) and it involved that the braze had to withstand temperatures of approximately 528-538 ºC (figure 7 (b)). Although these temperatures maintained the braze temperature far from the solidus one, Eurofer was close to the upper limit of its operational window temperature. Temperatures above 550 ºC produce softening of Eurofer [18].

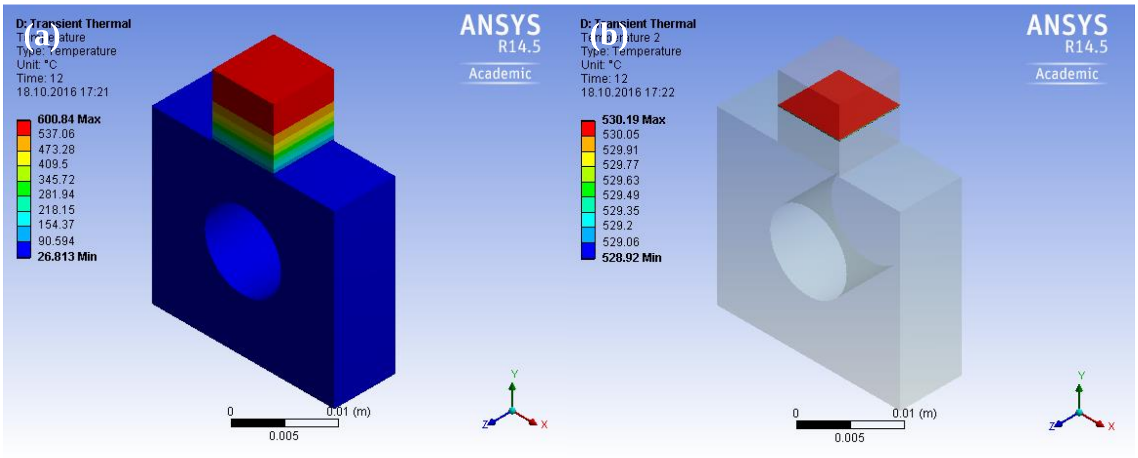

Figure 7. Simulation of the temperature distribution (a) across the joint and (b) in the braze for a surface temperature of 600 ºC.

During the test, the monitoring system registered a sudden overheating of the surface temperature of two samples after 45 cycles and the other two specimens reported a similar event after 79 cycles (figure 8 (a)). At that point, the test was stopped and the joints were examined. The metallographic analysis of the cross section revealed the presence of cracks at the W-braze interface (Figure 8 (b)), formed due to the mismatch in the CTE as it has been explained before, which sometimes propagated into the braze. Cracks formed at the interface caused a detriment in the refrigeration capability of the joint giving rise to overheating of the surface. The sudden failure of the samples under these conditions could be associated to the greater stresses caused by the high heating and cooling rate of each cycle (~ 60 °C/s). However, the failure in the refrigeration capability did not result in the failure of the joint and both parts continued to be joined.

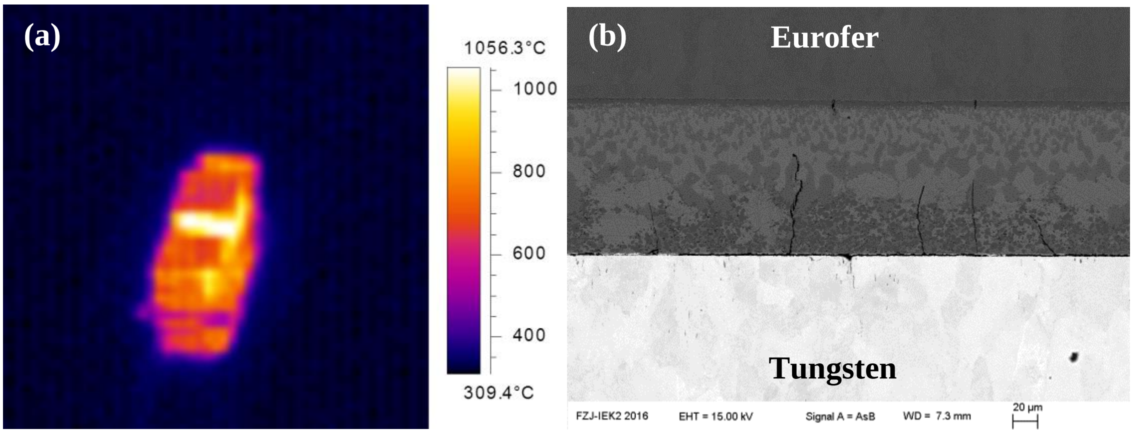

Figure 8. (a) IR-image of the sample subjected to a surface temperature of 600 ºC. (b) SEM micrograph of the joint after 79 cycles.

Figure 9 summarizes the main registered events and microstructural observations associated to the absorbed power density and the surface and braze temperatures. As expected, the absorbed power density increased the temperature of surface as well as of the braze. Besides, the gap between both temperatures increased with the power density, due to the augment in the temperature gradient between the heat source and sink. According to the simulation, the gap calculated for a surface temperature of 400 ºC was 41 ºC, while for the most energetic condition it was 62 ºC.

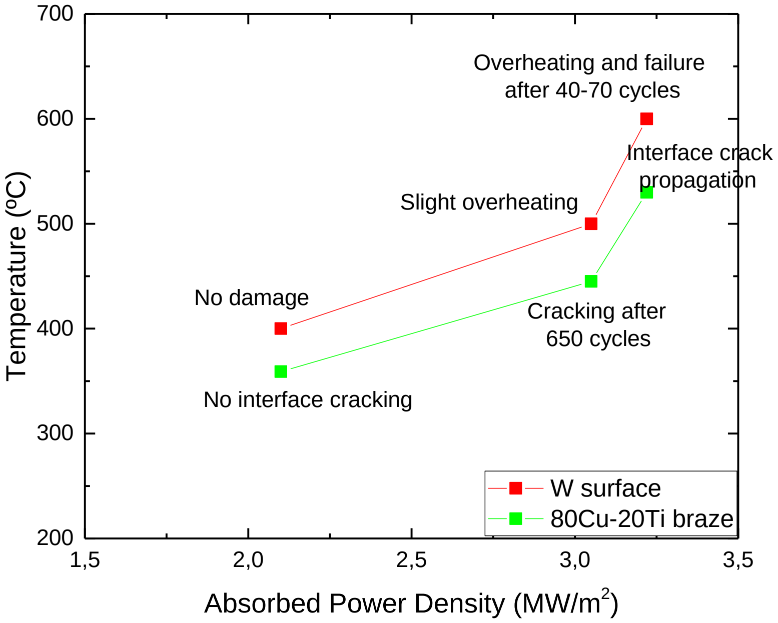

Figure 9. Relationship between surface and braze temperature versus the absorbed power density and the main event associated to each condition.

Mechanical properties

The mechanical properties of the joints after the test were evaluated by means of shear tests to study the effect of the thermal fatigue on the strength. The shear strength values are shown in Figure 10. The joints exposed to a surface temperature of 400 ºC reported values above 100 MPa that were similar to the reference strength of the joint after the brazing process (104 MPa). On the other hand, samples exposed to 1000 cycles showed an increase in the joint strength. This could be explained as the temperatures reached were not high enough to cause a detriment in the mechanical properties, but to promote a stronger interaction between tungsten and braze associated to diffusion processes. In previous studies, it has been observed that samples fractured following the W-braze interface during the shear tests. Therefore, the incipient crack process observed in the microstructural study of the 1000 cycles samples did not have any effect on the refrigeration capability and the mechanical properties of the joint.

The shear strength values of the joints tested under 500 ºC surface temperature were 87 and 77 MPa after 100 and 1000 cycles, respectively. This indicated that the cracks and discontinuities observed at the W-braze interface and in the braze after 1000 cycles affected the mechanical integrity of the joints. Although the mean values corresponded to considerable strength, the high variability of the values could be an inconvenience for the mechanical design of these joints.

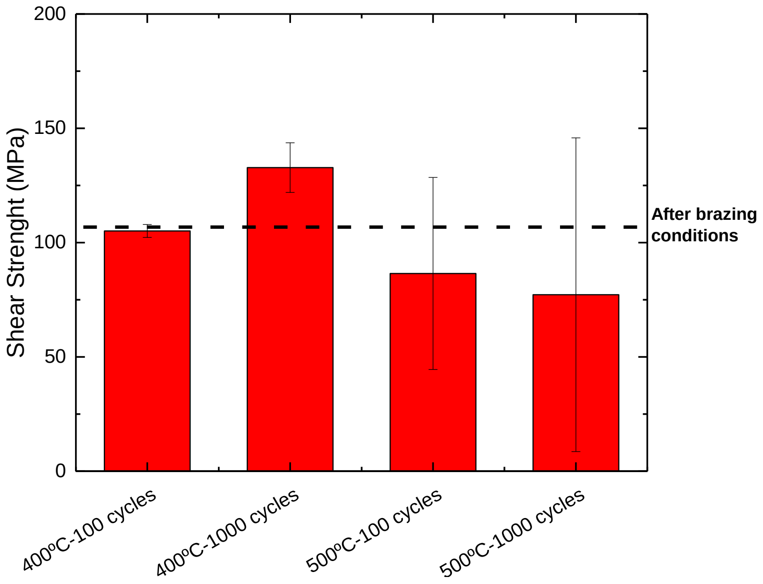

Figure 10. Shear strength of the joints.

4. Conclusions

W-Eurofer brazed joints fabricated using 80Cu-20Ti filler alloy were exposed to different conditions under steady state loads. HHF tests allowed identifying threshold conditions under which the joints could be used without degradation. The surface temperature threshold was 400 ºC that corresponded to a heat load of 2 MW/m^2, taking into account the used sample geometry. At this temperature no impact on the heat load removing capability was found. The microstructural examination revealed the formation of incipient cracks on the W-braze interface in 1000 cycles samples. However, they did not have influence on the mechanical properties of the joints because the shear strength values were similar or higher than the strength reported after brazing process.

The increase of the surface temperature up to 500 ºC produced the deterioration of the joint in a short period of time. After 675 cycles, an overheating of the tungsten surface temperature caused by the formation of cracks was detected, which hinder the refrigeration mechanism. At this surface temperature, a detriment in the mechanical properties of the joints occurred which was more accused as the number of cycles increased.

Finally, at 600 ºC the thermomechanical stress caused by the mismatch in the CTE involved the failure of the joints after 45-79 cycles.

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