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Mechanical characterization and modeling of brazed EUROFER-tungsten-joints

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Abstract

Within the scope of the European fusion power plant study for development of a He-cooled divertor, a tungsten–steel joint has been considered. A preferable joining technique is high temperature brazing. Brazed joints of dissimilar materials suffer from a mismatch in coefficients of thermal expansion. The components of the joint are exposed to mechanical and cyclic thermal loads which give rise to development of high stresses and could lead to failure. Brazed joints of tungsten alloy and ferritic–martensitic steel using different brazing filler materials were studied both experimentally and theoretically. Finite element computations have been performed to calculate the stress distribution and to investigate their evolution within the course of the operational thermal load. Sample joint specimen have been brazed, investigated with respect to their microstructure, and mechanically characterized by performing bend and notched bar impact testing at different temperatures. Some plastic deformation and relatively low impact energies were measured.

1. Introduction

In the course of the European power plant study, a concept for a He-cooled divertor for demonstration reactor (DEMO) has been investigated [1,2]. Main function of the divertor is to collect waste particles and impurities from the plasma and to remove part of the reactor heat. The thermal load on divertor first wall components is about 10–15 MW/m^2. This corresponds to about 15% of the total thermal power of the reactor. He-cooling system is proposed to purge the heat from the first wall components and to allow continuous operation. The neutron flux and the combination of high thermal and mechanical loads require the usage of high temperature resistant and low-activation materials for the divertor components. Favorable materials are tungsten and tungsten alloys and ferritic–martensitic steels (EUROFER 97). A leak-free material joint separates and protects the cooling system from possible penetration of plasma impurities and particle wastes and forms the divertor transition zone. Matter of interest of this work is the investigation and evaluation the brazing with high temperature materials as potential joining technology in view of the transition zone of the divertor application.

Both tungsten and EUROFER 97 have dissimilar material properties such as the Young's moduli and

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the thermal expansion coefficient. In the term of changing thermal loads due to operation, the material mismatch leads to development of high stresses on the boundary of the joint interfaces. In addition, changing cyclic loads lead to accumulation of residual stresses in the joint region which results in fatigue and creep processes. Therefore an investigation of the material behavior under different types of loading and characterization of the joint strength is needed to predict possible component failure.

2. Brazing process and micro structural analysis of the joints

Different methods of brazing [3] are introduced to join specimens of W–1%La_2O_3 (WL10) and ferritic–martensitic steel EUROFER 97. Based on the guidelines given, an enhanced brazing process for direct joining of the tungsten alloy to the EUROFER steel was applied. Two high temperature filler metals – amorphous foil ribbons STEMET 1309 (Ni, Cr 15.0; Si 7.5; Fe 4.0; Mo 4.0; B 1.5), developed at the Moscow State Engineering Physics Institute, and a commercial brazing paste BrazeTec 1135 of BrazeTec, Hanau (Ni; Cr 19.0; Si 10.1; B 0.003; C 0.06; P 0.02) – are used to braze WL10 pins to EUROFER 97 steel blocks. The specimens are heated in vacuum with constant heating rate; 600 s at a constant 400 °C allows the filler material to degas and prevent reduction of the braze strength due to gas bubbles in the joint layer. The actual brazing takes place at 1180 °C for the paste and at 1150 °C for the foil ribbons for 720 s and after that the system is slowly cooled down to room temperature. At temperatures higher than 1000 °C grain growth in steel takes place and leads to larger grain size and changed mechanical properties. Therefore an annealing procedure is applied to recover the material structure close to the initial state. The specimen are heated again to 980 °C for 30 min and annealed by 730 °C for 240 min. The process takes place under vacuum again to guarantee slow cooling rates and stress relaxation.

The mismatch in the coefficient of thermal expansion leads to a stress accumulation between the join surfaces, and cracks initiation is possible. A detailed micro structural study has been performed to determine joint characteristics at the micro-scale. Fig. 1 shows a joint of WL10 and EUROFER 97 steel with the brazing paste BrazeTec 1135 as a filler metal. The material composition in the brazing zone remains almost the same as before the brazing process. The joint is inhomogeneous and builds three basic layers. Micro structural analyses show that diffusion takes place between the brazing metal and the parent materials and two interior diffusion zones are formed. Their composition varies and includes the basic elements from the parent materials, mainly tungsten from WL10 and chromium from EUROFER steel, as confirmed by energy dispersive X-ray analysis. Through a comparison of the element consistency at different regions in the brazed joint can be measured the thickness of each of the diffusion zones. Comparisons of specimens with different brazing history show, that the diffusion process plays a key role for the strength of the joint. Extended diffusion zones provide better mechanical strength and on the opposite small diffusion zones often include defects and break easily.

3. Finite element simulation of a model

The brazed joint in the divertor transition zone has a rather complicated structure. To study the

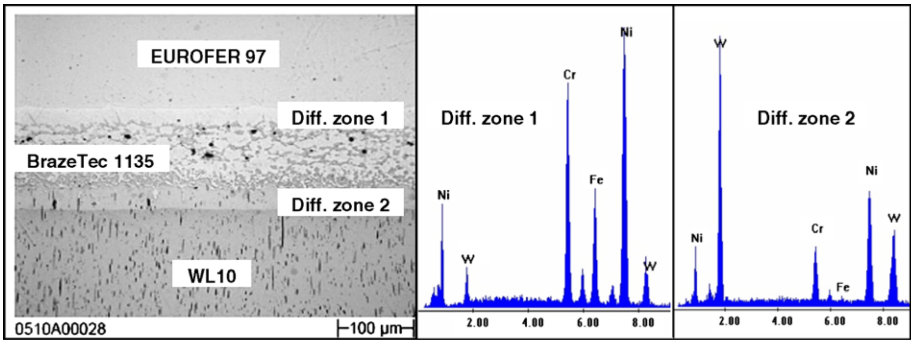

Fig. 1. SEM micrograph of the diffusion zones between the braze material and EUROFER (bottom) and the tungsten alloy (top). EDX results for the diffusion zones.

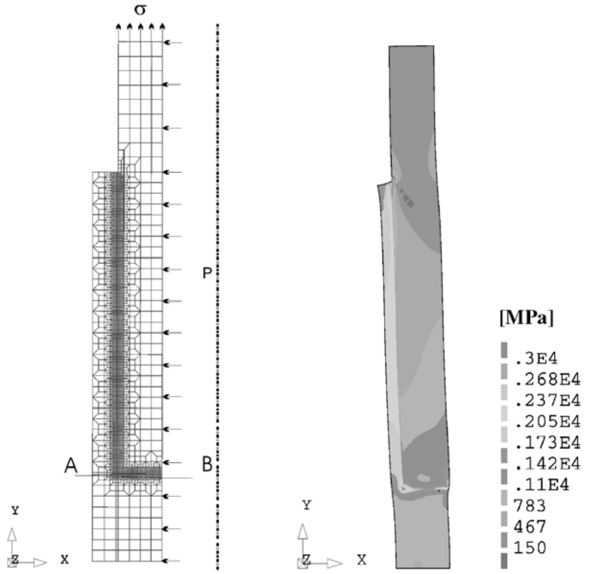

Fig. 2. FE model and von Mises stress distribution in the divertor transition zone.

evolution of stresses and deformations in the actual geometry a discrete finite element model shown in Fig. 2 was used. The model consists of a 1 mm thick tube made of W–1%La_2O_3 joined to a body of EUROFER 97 steel. Because of the axial symmetry with respect to the y-direction of the divertor modules, a symmetrical stress distribution is considered, which allows reduction to a 2D model for reducing the computational time. The bottom nodes are fixed in y-direction and an inner hydrostatic pressure of $P = 10$ MPa is applied in radial direction as a distributed load to all nodes of the inner side of the tubes. This inner pressure induces an equivalent stress of $\sigma = 28$ MPa in the wall of the upper part of the structure, which is assumed as a hemisphere. The relatively small size of the actual part allows applying a uniform temperature distribution throughout the joint region. The displacement and rotation effects are considered using the small displacement theory.

Table 1
Material properties of EUROFER 97, braze material BrazeTec 1135 and WL10

Density (kg/m^3)	Elastic modulus (GPa)	Thermal expansion (K^{-1})	Yield stress (MPa)	Reference temperature (K)
EUROFER 97				
7730	206	1.04×10^{-5}	483	293
7710	201	1.08×10^{-5}		373
7680	194	1.12×10^{-5}		473
7650	188	1.16×10^{-5}	428	573
7610	182	1.19×10^{-5}		673
7580	175	1.22×10^{-5}	376	773
7540	151	1.25×10^{-5}	194	873
7540	151	1.27×10^{-5}	41	1073
7540	140	1.29×10^{-5}		1273
	139	1.30×10^{-5}		1473
BrazeTec 1135				
7650	398		584	293
			492	473
	388	4.86×10^{-6}	429	673
	383		400	873
	379	5.14×10^{-6}	371	1073
			351	1123
			287	1223
			200	1473
W–1%La_2O_3				
18850	398	4.65×10^{-6}	1360.5	293
		4.71×10^{-6}		473
		4.79×10^{-6}		573
		4.86×10^{-6}		673
		4.93×10^{-6}	853.5	773
	390	5.07×10^{-6}	681.7	973
	383	5.14×10^{-6}	604.1	1073
	379	5.28×10^{-6}	464.8	1273
		5.41×10^{-6}	345.9	1473

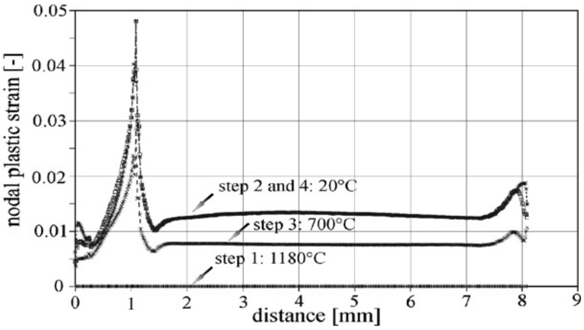

Fig. 3. Plastic strain distribution along the selected path AB in Fig. 2. The curves represent temperatures between RT and 700 °C.

The combined thermal and mechanical loadings due to operation lead to plastic deformation. The calculated stress distribution in the joint shows the most loaded places and allows assessment, giving output for further design optimization and life prediction. Previously, it was shown that pure mechanical loading does not lead to plastic deformation [2]. The stress analyses was extended in several steps considering the temperature variation while heating to 1120 °C brazing temperature, cooling down to RT and annealing at 700 °C Elastic–plastic behavior without hardening, using temperature dependent material properties, including thermal expansion coefficient, elastic moduli and yield strength (see Table 1), are assumed for the tungsten alloy, EUROFER 97, and the braze. As an initial stress free condition, a uniform nodal brazing temperature field of 1120 °C was applied. Fig. 3 shows the plastic strain along the AB path indicated in Fig. 2. Each single curve represents a certain joint temperature.

The highest stresses are concentrated mainly in the braze region. The plasticity of the braze material partly reduces the high stresses. This indicates that, in particular, under cyclic loading conditions, the brazed joints may be subject to fatigue and ratcheting. Therefore, the finite element analysis will be extended by simulating the material behavior under cyclic thermal loading with a number of cycles in the temperature range of interest in order to understand the role of ratcheting.

4. Experimental results and discussion

In order to determine the joint strength under mechanical, thermal and combined type of loading, a set of mechanical characterization experiments was performed. Results of four-point-bending test and Charpy-impact test on specimens of brazed EUROFER 97 – WL10 joints are shown in Figs. 4 and 5. The brazed samples have standard geometry of 3 × 3 × 27 mm for the four-point-bending test and 3 × 4 × 27 mm with notched bar of 60° for the Charpy samples [4]. For both geometries the braze layer is exactly in the middle of the specimen. Fig. 5 shows very low strength at 450 °C; however it increases with rising temperature. This behavior can be related to the brittleness of the braze material at low temperatures as well as the large residual stresses in the braze zone, which are reduced with increasing temperature. Charpy-impact testing showed that the highest values of the absorbed energy are achieved at temperatures of 550–600 °C. This is most likely related to the reduced mechanical toughness of the materials in the zone near the brazed joint [5,6]. More detailed investigation of fractured samples will clarify the exact crack

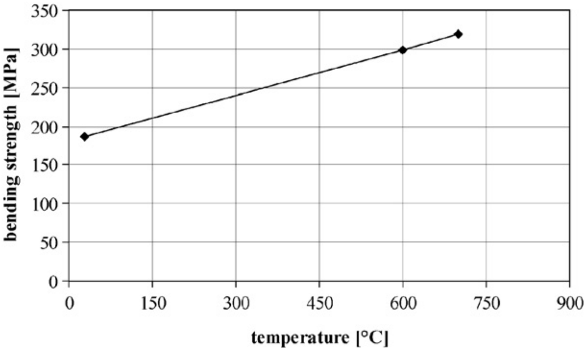

Fig. 4. Bending strength as a function of the test temperature on a specimen brazed with BrazeTec. Sample dimensions were $3 \times 3 \times 27\ \mathrm{mm}^3$.

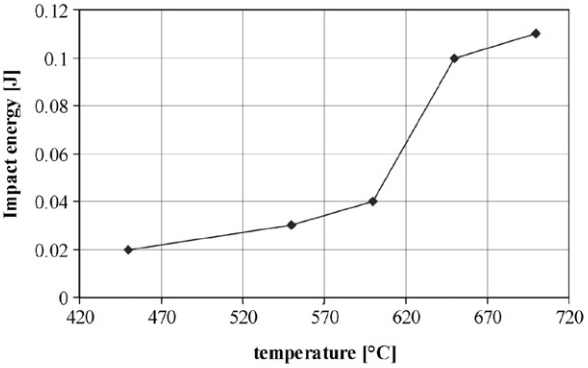

Fig. 5. Charpy-impact energy as a function of the test temperature on brazed specimen with BrazeTec. Sample dimensions were $3 \times 3 \times 27\ \mathrm{mm}^3$.

path in order to identify the weakest link in the joint. By comparing the measured bending strength with the stresses calculated in the FE simulation, it is obvious that spontaneous joint fracture is a possible issue since the calculated stresses are much higher than the measured strength.

The quality of the joints can be improved by further optimization of the brazing parameters. This will include a variation in the brazing pressure, and brazing and annealing time in order to achieve an optimized diffusion zone. Furthermore, tensile test and thermal fatigue test experiments are in progress for a more complete assessment of joint reliability.

5. Summary

Brazing as a possible technique of joining W-alloy to EUROFER was investigated with respect to a divertor application. A set of finite element computations has been performed in order to characterize the mechanical loading on the joints at different temperatures. Some plastic deformation and low impact energies below 650 °C were observed. Mechanical characterization experiments, including four-point-bending test and Charpy test were carried out to investigate the joint behavior in the temperature range RT – 700/800 °C. Those experiments help understanding of the failure mechanisms and quantitative the data, needed for a lifetime assessment of brazed divertor component.

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