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High temperature residual strain measurements in a brazed sample for NET/ITER ☆

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Abstract

The strain-free temperature in a brazed divertor mock-up for NET/ITER was measured using neutron diffraction. The investigated sample was a CuCrZr alloy cooling pipe armoured by a carbon/carbon fiber composite (CFC) monoblock tile. The joining between CFC and CuCrZr alloy was obtained by an intermediate layer of copper. Neutron diffraction measurements were carried out measuring the strain evolution as a function of temperature in the CuCrZr pipe and the lattice parameter of a reference powder of the same material, in the same temperature range. Both radial and tangential strains were determined inside the pipe in two representative points at 90°, finding well-reproducible results namely: radial strain vanishes at 370°C and tangential strain at 430°C approximately. These experimental results are discussed in the light of numerical analyses and simplified finite element method (FEM) calculations.

1. Introduction

One of the main concerns in the lifetime prediction of plasma facing components is the evaluation of the stress field following the manufacturing, arising from the fabrication or joining operations. In order to evaluate the residual stresses in a brazed component many attempts have been carried out to find an analytical (numerical) solution using the finite element method (FEM). These attempts yielded relevant results in view of evaluating the temperature at which the strains and therefore the stresses vanish (stress free temperature), which is of utmost importance in engineering calculations to predict mechanical behaviour and reliability of such components. However, an experimental determination of this temperature is necessary to validate those theoretical predictions. In this regard, neutron diffraction is a very appropriate experimental tool, allowing a bulk determination of the strain field a few mm inside the sample. Furthermore, in situ experiments requiring the use of furnaces or testing machines are also possible due to the low absorption coefficients of neutron beams. Refs. [1–4] report neutron diffraction strain and stress studies in different kinds of brazed mock-up for plasma facing components such as the divertor, including high temperature studies. In this work, the evolution of the strain field in a brazed mock-up, developed in view of its possible use for the ITER divertor (Task T222), has been investigated using neutron diffraction to determine experimentally the temperature at which residual strains vanish in the cooling pipe. After describing the experimental conditions the results are presented and discussed making reference to numerical analyses and simplified FEM calculations.

2. Material characterization and experimental conditions

Fig. 1 shows a schematic drawing of the sample investigated by neutron diffraction. It was extracted from a mock-up manufactured by Metallwerke Plansee [5] obtained armouring a CuCrZr alloy (Cu–0.68%Cr–0.11%Zr) pipe with a carbon/carbon fiber composite

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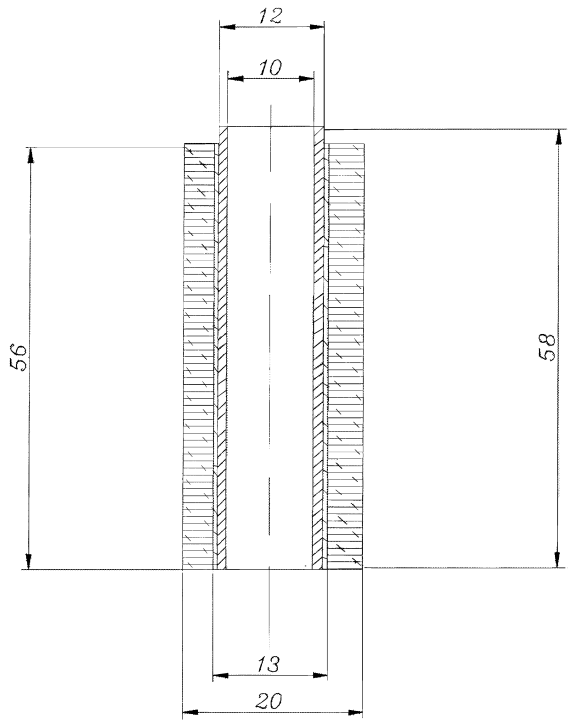

Fig. 1. Schematic picture of the investigated mock-up (figures are in mm); CFC tile is dashed.

(CFC Dunlop) monoblock tile. The joining between the CFC and the CuCrZr alloy was obtained by an intermediate layer of copper, with a thickness of about 1 mm, which connects the inner CuCrZr pipe to the CFC monoblock tile; laser substructuring technique was used to improve the coupling between Cu and CFC.

Neutron diffraction measurements were carried out using the G5.2 diffractometer at the 'Orphée' reactor (LLB, CEA–CNRS Saclay), following the experimental procedures reported in [1–3]. As it is also recalled in those works, changes in Bragg scattering angle θ are converted into lattice strains (ε) by differentiating the Bragg equation $2d\sin\theta = \lambda$ yielding

$$\varepsilon = \frac{(d - d_0)}{d_0} = -(\cot\theta_0)(\theta - \theta_0), \tag{1}$$

where λ is the neutron wavelength and d is the lattice spacing corresponding to the diffracting angle 2θ (d_0 and $2\theta_0$ are the corresponding stress free values).

The furnace used for these measurements consists in a heating resistance placed in a glass bell under He atmosphere. The temperature is measured by a thermocouple in the lower part of the sample near the free end of the CuCrZr pipe with a precision of ± 3°C. Part of the CFC armour had been removed by a diamond saw to fit the space available in this furnace; as shown in Fig. 1, the remaining thickness of the CFC was approximately 3 mm. The sample and furnace were positioned on an X–Y translation table and on ω rotation (around cylinder axis) in order to measure tangential and radial strain components (Fig. 2). The incident neutron wavelength was 2.86 Å and the diffracting volume selected by the Cd masks, placed at the exit of the neutron guide and in front of the detector was $0.5 \times 0.5 \times 20$ mm^3. Since with an instrument resolution of about 0.25°, the (1 1 1) diffraction peaks of the pure Cu surrounding ring and the CuCrZr alloy are not separable due to the fact that the crystallographic lattice cells a of these two fcc materials are very close ($a_{Cu} = 3.6151$ Å and $a_{CuCrZr} = 3.621 \pm 0.0003$ Å), the sample was positioned by recording the (1 1 1) Cu reflection peak intensity as a function of the sample position, starting from the middle of the pipe. As the CuCrZr pipe enters the diffracting volume, the neutron counting rate increases up to a maximum, then decreases. This positioning was repeated for the two points A and B reported in Fig. 2 in the two different directions.

The measurements were performed at the following temperatures: 30°C, 100°C, 200°C, 300°C, 370°C, 430°C. For each temperature, the measuring sequence was the following: point B in the tangential direction, point A in the radial direction, point A in the tangential direction and then point B in the radial direction. In order to improve counting statistics runs of approximately 9 h at each temperature were selected.

The reference lattice parameter was measured using a powder (approximately 3 cm^3) ground from a CuCrZr sample issued from the pipe used for the mock-up (and therefore submitted to the same preliminary thermal treatments), at the same sample measuring temperatures in order to get

$$\varepsilon(T) = (d(T) - d_0(T))/d_0(T). \tag{2}$$

The reference lattice parameter was also measured at the same temperatures from a small bulk sample (approximately $5 \times 5 \times 3$ mm^3 in size) cut from a CuCrZr plate.

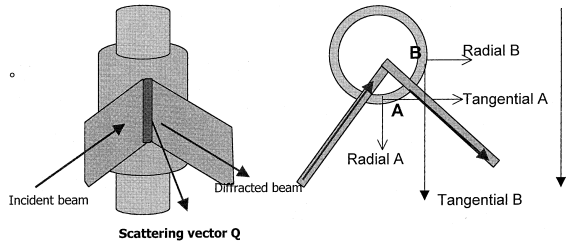

Fig. 2. Neutron diffraction experimental layout, showing at the left sample orientation with respect to neutron beam path and the resulting diffracting volume. On the right-hand side (sample as seen from the top) the two investigated points and strain components are marked.

In this case, since the thermal history of this plate was not fully characterized, it was impossible to reproduce it on the reference sample. Therefore spurious effects relating to differences in precipitation or recrystallization phenomena in this reference sample and in the mock-up cannot be taken into account. The diffraction peaks were fitted with a Gaussian function in order to locate the exact peak position. The error in the peak position is given by a fitting error. The strains were then calculated with respect to the reference parameter d_0 by using Eq. (1), and the errors were calculated by differentiating the same equation.

3. Results and discussion

Fig. 3 shows the d_{111} lattice parameters as a function of temperature for the reference powder and the CuCrZr pipe. The corresponding strains measured in the CuCrZr pipe are shown in Fig. 4. Fig. 5 reports as a function of temperature the same strains as determined using as a reference the bulk CuCrZr sample. Concerning first Fig. 4, within the experimental uncertainties, which are a few %, there is no difference between the two points in the two directions (radial and tangential) and the strains vanish at about 370°C in the radial direction and at about 430°C in the tangential direction. This equilibrium temperature is determined by fitting the data with a straight line: the determination coefficient (R^2) is 0.995 and the error on the determination of the equilibrium temperature is less than 30°C. The results show moreover a high reproducibility, also indicated by the quality of the linear fit. This is consistent with what can be expected from thermomechanical behaviour of the component, namely that both tangential and radial strains vanish at a temperature well below the brazing one (650°C). However, the results show compressive strains in the pipe, which is not in agreement with the common understanding of the problem, since tensile strains are expected after fabrication. On the other side an analysis of the results taking into account the mechanical constants of the different materials and the sample geometry showed the consistency of the neutron diffraction results and suggested that the experimentally determined strain values can be affected by strains remaining after the fabrication process [4]. Namely, assuming for the reference powder a lattice parameter $d_{(111)} = a/\sqrt{3}$ giving tensile strains in the CuCrZr pipe ($d_{(111)} = 2.0710$ Å instead of the experimental value of $d_{(111)} = 2.093$ Å) one could not get a temperature where the strains vanish, because the strains themselves would diverge with the temperature. In order to get a null strain with the calculated d_0 at 430°C and 370°C, thermal expansion coefficients should assume values fully out of the range of those typical of copper alloys. On the other side consistent instantaneous and integral thermal expansion coefficients are found using the experimentally determined values of the powder lattice parameter at the

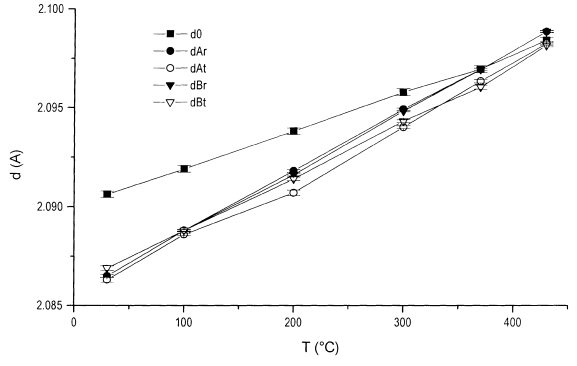

Fig. 3. Evolution of d_{111} lattice spacing with temperature in the reference powder (full squares) and in CuCrZr pipe (full circles A radial, empty circles A tangential, full triangles B radial, empty triangles B tangential).

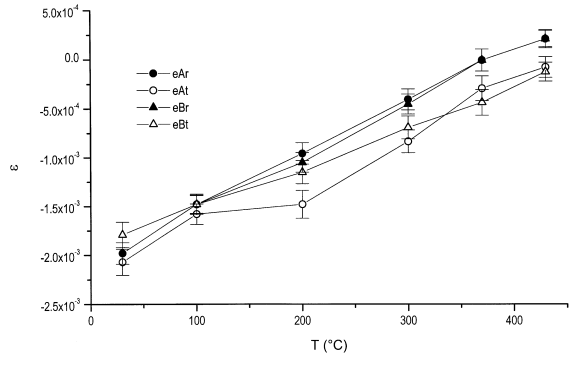

Fig. 4. Strains vs temperature in CuCrZr pipe as determined using reference powder d_0 (full circles A radial, empty circles A tangential, full triangles B radial, empty triangles B tangential).

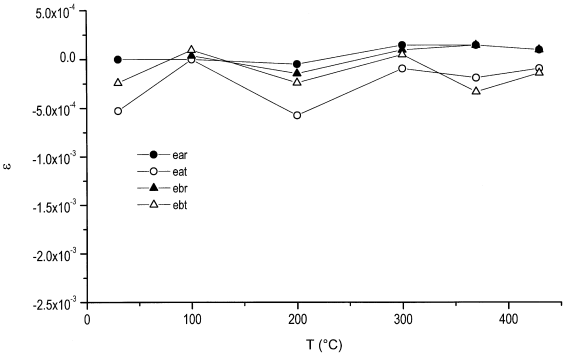

Fig. 5. Strains vs temperature in CuCrZr pipe as determined using bulk CuCrZr specimen d_0 (full circles A radial, empty circles A tangential, full triangles B radial, empty triangles B tangential).

different investigated temperatures. Therefore, as it also suggested by the fact that the strains found in the mock-up are practically indistinguishable from those found in the bulk reference sample (Fig. 5), the experimentally determined compressive strains should be related either to boundary conditions or to stresses present in the pipe before brazing and incompletely recovered during this treatment.

The occurrence of compressive strains in the investigated structure has also been checked by a simplified axisymmetric FEM model, representing the pipe and the intermediate copper layer and simulating the CFC armour with an infinitive stiffness [4,6]. The load has been imposed as a radial displacement of the external surface of the copper layer equal to 36×10^{-3} mm, obtained from the differential strain in copper and CFC from 430°C to 20°C [7]. As a matter of fact, taking from these references a value of thermal strain from 430°C to 20°C equal to 6.97×10^{-3} mm/m and to 0.84×10^{-3} mm/m for CuCrZr and CFC, respectively, the difference is about 6×10^{-3} mm/m which, with a radius of 6 mm leads to the net differential displacement reported above. The mechanical characteristics of the CuCrZr alloy have been taken from [8]. The strains in the volume where the experimental values have been obtained are reported in Fig. 6. It is evident that compressive residual stresses cannot be excluded from the circumferential direction, while the same value and the presence of compressive stresses have not been found in radial direction.

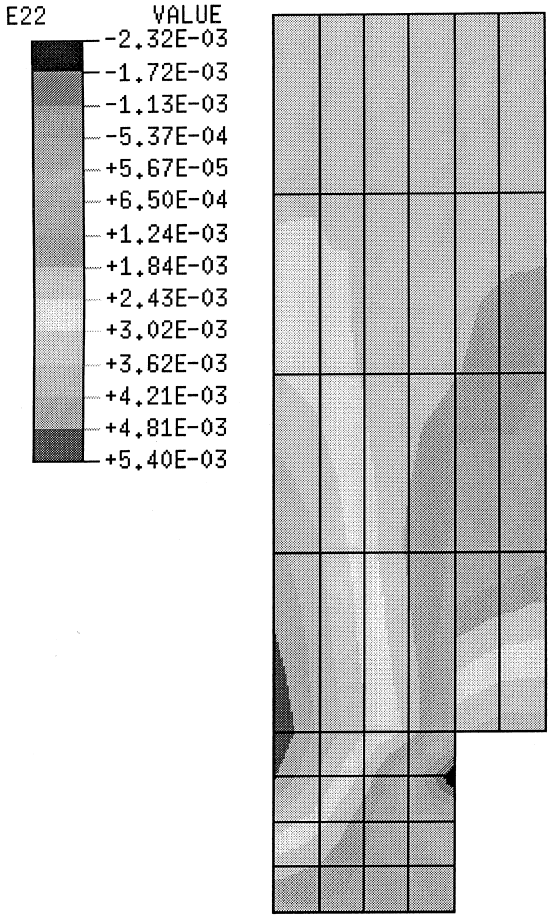

Fig. 6. FEM determined longitudinal strain distribution in the diffracting volume. The first four elements starting from left refer to the inner CuCrZr pipe, the remaining ones to the Cu pipe.

4. Conclusion

Neutron diffraction has been used to experimentally determine the zero strain temperature in the CuCrZr cooling pipe of a brazed divertor mock-up. The values of this temperature, obtained at two different points and for two different strain components, show that the measurements are fully reproducible and well consistent with what is expected from strain evolution in such structures namely that both tangential and radial strains vanish at a temperature well below the brazing one (650°C). However, compressive strains are found in the as-received sample; furthermore the lattice parameter evolution with temperature is identical in a CuCrZr bulk reference and in the pipe. This means that the strains measured in the mock-up should be largely dominated by those produced during the fabrication and prior to brazing. Future neutron diffraction measurements should therefore be carried out on mock-ups prepared using initially stress free materials in order to detect the strain field associated to the brazing and possibly to confirm the significance of the zero strain temperatures determined by the present work.

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References

[1] M. Ceretti, R. Coppola, E. Di Pietro, A. Lodini, M. Perrin, A. Piant, F. Rustichelli, J. Nucl. Mater. 212–215 (1994) 161.
[2] G. Albertini, M. Ceretti, R. Coppola, E. Di Pietro, A. Lodini, J. Nucl. Mater. 233–237 (1996) 954.
[3] M. Ceretti, R. Coppola, E. Di Pietro, C. Nardi, J. Nucl. Mater. 258–263 (1998) 1005.
[4] C. Nardi, R. Coppola, B. Riccardi, ENEA Report RTI, DEMO/WCLL/002, April 1999.

[5] The Manufacturing of Actively Cooled, Carbon Armoured Divertor Elements – to be used for Neutron Irradiation Tests within ITER Task T1, Internal Report N RP 564, 1 September 1996.
[6] ORIGIN, User's Manual Version 5, Microcal Software Inc., 1998.
[7] E. Zolti, Material Data for Predesign Analysis of In-Vessel Components, NET Internal Note N/I/3300/5/A, 14 September 1990.
[8] V. Barabash, G. Kalinin, Cu Alloy Data-base for First Wall, Blanket and Divertor Design Evaluations, ITER Report G DB TY16/17 00 94.06.05 WS1, November 1995.