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Neutron diffraction measurement of residual stresses in an ITER-like tungsten-monoblock type plasma-facing component

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Neutron diffraction measurements have been carried out for non-destructive characterization of the residual stress field in a mock-up of the ITER-like divertor target plasma-facing component made of 4 tungsten blocks joined to a CuCrZr cooling pipe via a soft copper interlayer. The mock-up was manufactured by hot radial pressing in the frame of EUROfusion task WPDIV 2.1-T001. The neutron diffraction measurements were carried out, at room temperature, at FRM II reactor in Garching. The selected gauge volumes were the following: 1x1x5 mm^3 for radial and hoop directions, 1x1x3 mm^3 for W block and 1x1x2 mm^3 for CuCrZr tube respectively in the axial direction. Stress-relieved W and CuCrZr were examined as un-strained reference state before joining. The 3D stress tensor was determined in one of the two external W-blocks and CuCrZr pipe segments, scanning the mock-up from the outer surface of the W block towards the inner wall of the CuCrZr pipe with the interval of 0.4-0.5 mm. A residual stress distribution from tension to compression through the bonding line is detected, as expected from the requirement of force balance. The results are discussed together with the comparative FEM-based numerical prediction obtained for the same mock-up geometry and fabrication history.

Keywords: divertor, hot radial pressing, stress distributions, neutron diffraction, FEM

1. Introduction

It is well known that a reliable and accurate characterization of residual stresses is of utmost relevance in the design of plasma-facing components and more specifically of the divertor [1]. *Theoretical calculations and FEM modeling of the stress field present in such components provide an essential tool in the design phase, since are based on well-assessed physical assumptions and mathematical procedures* [2-4]. *However, they need to be validated by comparison with experimental results, obtained measuring the stresses, non destructively and in the bulk, on the real components as they are after all the fabrication steps are achieved. Neutron diffraction is probably the only technique capable to provide such experimental data; it is widely utilized for stress mapping in complex samples of industrial interest and it is based on an internationally acknowledged protocol, both concerning the measurements themselves and the data treatment. The comparison between such experimental results and the numerical predictions requires to analyze carefully the fundamental assumptions of the two procedures, the experimental one and the numerical one, in order to come to meaningful conclusions. Furthermore, ideal samples are usually considered in modeling, while neutron diffraction experiments are always carried out on real samples, potentially affected by a series of undesired and uncontrolled uncertainties relating to sample fabrication, material heterogeneity, and so on. This combined numerical and experimental procedure has been applied to the characterization of residual stresses in an ITER-like tungsten monoblock; experimental and numerical results are presented here after.*

2. Material characterization

The investigated ITER-like diffusion bonded 4-tiles W-Cu-CuCrZr mock-up is shown in Fig. 1; reference is made to [5, 6] for description of mock-up fabrication by hot radial pressing and all other technical details. The bonding between W tile and CuCrZr tube is obtained by a 0.1 mm thick pure Cu interlayer; that increases the complexity of micro-structural and crystallographic characterization, particularly at the CuCrZr/Cu interface, potentially modified by inter-diffusion and precipitation phenomena during the bonding procedure. The quality of the obtained bonding was tested by ultrasounds, finding good results for all of the four tiles, except within 1 mm from the outer surfaces of each tile. In addition to the mock-up, a stress relieved un-brazed tile and an un-brazed segment of CuCrZr tube were prepared as un-strained reference samples for the neutron diffraction measurements.

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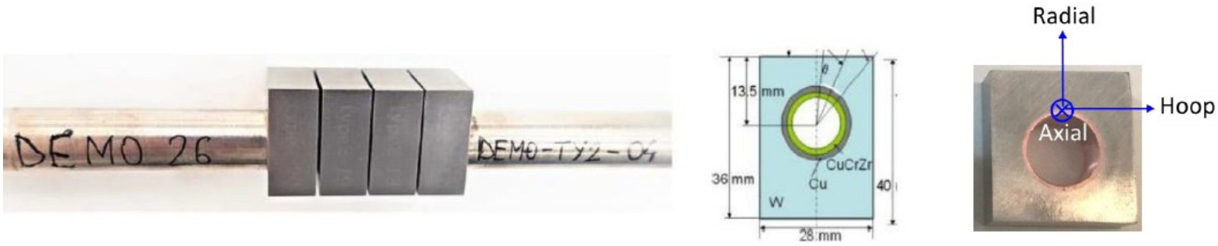


Fig. 1 - ITER-like diffusion bonded 4-tiles W-Cu-CuCrZr mock-up, with 0.1 mm Cu interlayer, and related sizes; the W tiles are 12 mm thick each one. The principal stress components are also indicated.

3. Experimental technique

Reference is made to the [7-9] for a general presentation on the use of neutron diffraction for strain and stress determination and to [10-14] for some applications to divertor components. The measurement of strains and stresses by neutron or X-ray diffraction is based on the well-known Bragg's law

$$2 d_{hkl} \sin\theta = n\lambda \tag{1}$$

relating the spacing, d_{hkl}, between crystallographic lattice planes characterized by Miller indices *hkl* with the wavelength, λ and the angle 2θ where the reflection is observed. The main advantage of utilizing neutron beams with respect to X-rays is their deeper penetration, down to a few mm in some materials. Defining the strain ε as:

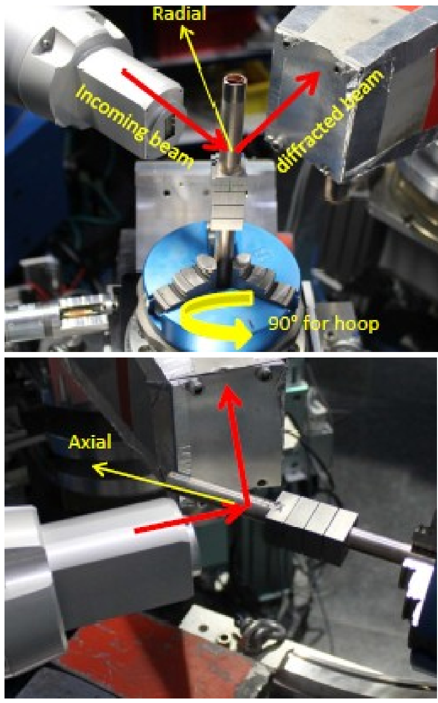
$$\varepsilon = \frac{(d-d_0)}{d_0} \tag{2}$$

where d and d_0 are strained and un-strained lattice spacing, respectively. ε is determined by the shift in the position of the Bragg peaks. A 'strain-free' sample, with lattice spacing d_0, is therefore needed to calculate the strains. Defining X, Y, Z the principal directions of deformation, the residual stresses components are given by:

$$\begin{aligned}
\sigma_X &= \frac{E}{(1+v)(1-2v)}[(1-v)\varepsilon_X + v(\varepsilon_Y + \varepsilon_Z)] \\
\sigma_Y &= \frac{E}{(1+v)(1-2v)}[(1-v)\varepsilon_Y + v(\varepsilon_X + \varepsilon_Z)] \\
\sigma_Z &= \frac{E}{(1+v)(1-2v)}[(1-v)\varepsilon_Z + v(\varepsilon_X + \varepsilon_Y)]
\end{aligned} \tag{3}$$

where E is the Young modulus of the investigated material and ν the Poisson's ratio.

The neutron diffraction measurements were carried out, at room temperature, at the STRESS-SPEC diffractometer [15], operated at the FRM-II reactor, in Garching, by the Helmholtz Zentrum Geesthacht and Technical University of Munich. The selected neutron wavelength was 1.47 Å, produced by Si (004) monochromator. One of the two external W-blocks and CuCrZr pipe segments were investigated, scanning the mock-up from the outer surface of the W block towards the inner wall of the CuCrZr pipe with the interval of 0.4-0.5 mm. The measured gauge volumes, defined by primary slit and a radial collimator (FWHM =1) at outgoing beam side, were the following: 1x5x1 mm^3 for radial and hoop directions, 1x3x1 mm^3 for W block and 1x2x1 mm^3 for CuCrZr tube respectively in the axial direction. The 2D detector was set at 90°, to cover simultaneously W (211) reflection (2θ≈74°) and Cu (311) reflection (2θ≈91°), utilized to measure the peak shift and strain calculation. The experimental layout for the mock-up is shown in Fig.s 2 a-b, where the principal stress direction are indicated. The *SteCa* fitting procedure [16] was utilized to fit the measured diffraction peaks and to obtain the 2θ value of each point, with associated errors. The correction of so called spurious strains [17], due to the instrument setup, has been applied to the points close to the interlayer. Strains were calculated by Eq. (1). Then, by Eq.(3), the stresses were calculated, assuming Young module and Poisson ratio values of 401 GPa and 0.283 for W, of 128 GPa and 0.33 for CuCrZr respectively [5,6].



a)

b)

Fig. 2. Experimental layout for measurements of stress components in ITER-like diffusion bonded 4-tiles W-CuCrZr mock-up, with 0.1 mm Cu interlayer: a) radial and hoop, b) axial component.

4. Results and discussion

Fig. 3 and Fig. 4 present the three principal components of residual strains and stresses, respectively measured by neutron diffraction, each one compared to

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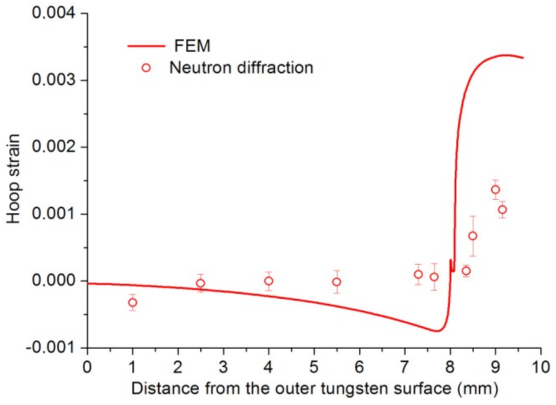
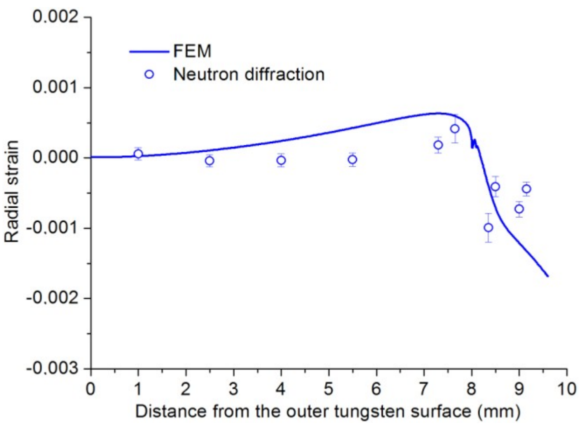
the numerically calculated residual strains and stresses from finite element analysis.



a)



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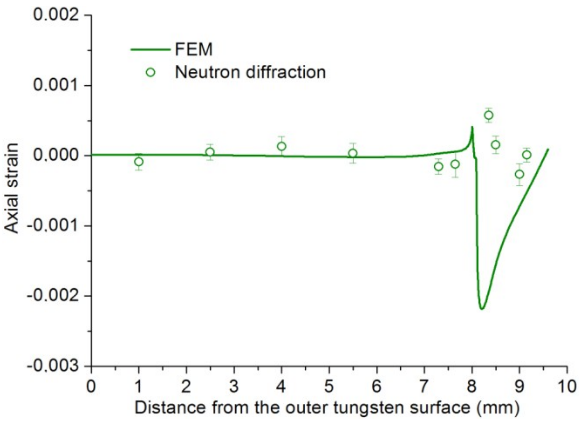
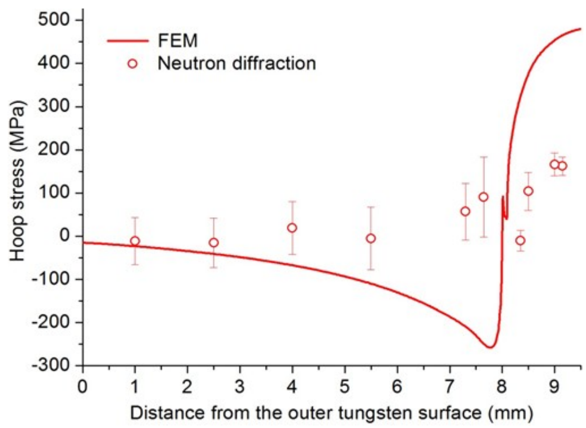


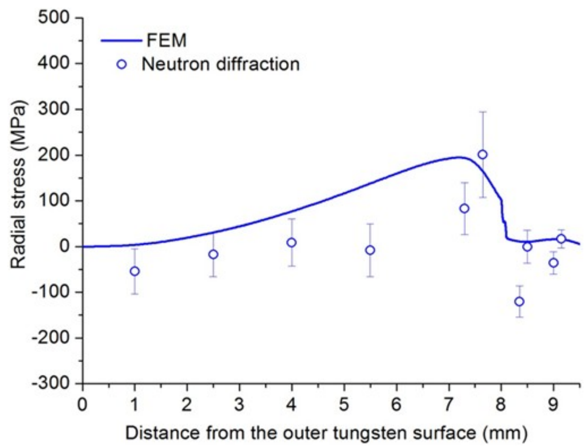
c)

Fig. 3. Experimentally measured (neutron diffraction) and numerically calculated (finite element method) residual micro-strains. Three principal components are presented in reference to the global cylindrical coordinate system illustrated in Fig. 2. The Cu interlayer is located at approximately 8 mm.

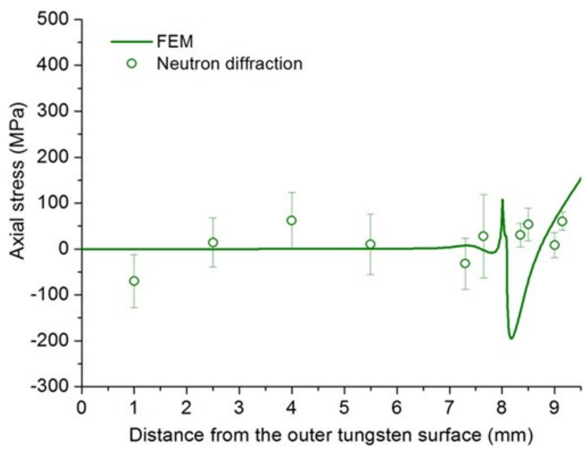
Three principal components are presented in reference to the global cylindrical coordinate system illustrated in Fig.s 1 and 2.



a)



b)



c)

Fig. 4. Experimentally measured (neutron diffraction) and numerically calculated (finite element method) residual stresses. Three principal components are presented in reference to the global cylindrical coordinate system illustrated in Fig. 2. The Cu interlayer is located at approximately 8 mm.

Generally, the experimental data show a very low strain level for all three strain components through the vertical scan profile except in the cooling pipe region. In the tungsten armor region, no significant remnant strain is measured as predicted by finite element analysis

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indicating that there is neither macroscopic residual stress due to differential thermal strain mismatch nor mesoscopic stress due to microstructural heterogeneity or any other fabrication defect. The latter confirms the good fabrication quality of the sample mock-up used. On the other hand, a quite substantial discrepancy is seen in the interfacial and the cooling pipe region for the hoop as well as the axial strain component. This disagreement between the measured and calculated strains obviously reveals a couple of technical issues which potentially might have affected the accuracy of either the experimental measurement or the numerical simulation, or probably both. One source of errors could be introduced in experimental setting. As already mentioned, the spatial resolution of the neutron beam scan was relatively coarse (W block: 0.5mm interval, CuCrZr pipe: 0.4mm interval) and moreover, the gauge volume was rather big as well (3 or 5 mm^3, depending on stress components) so that the actual strain profile, particularly in the sharp material transition region around the bond interface, is very likely to be averaged over the voxel volume yielding inaccurate intermediate values with only an insufficient density of data points for graphical visualization. For corrective action, a sharper linear spatial resolution shall be adopted in the next round measurement campaign, possibly comparable with the size of the interlayer region (0.1 mm). Another major source of errors may be attributed to the material model (particularly CuCrZr alloy) used for the finite element analysis. For the thermal strain simulation, a monotonic elasto-viscoplastic constitutive model was employed where J_2 type plasticity (i.e. von Mises yield criterion) with isotropic hardening and the secondary creep was considered using temperature dependent material parameters. However, the primary creep was not applied due to the complete lack of material data in the literature. It is deemed that the primary creep should have a much pronounced effect on stress relaxation than the secondary creep, especially for a short period thermal exposure. The numerical analysis revealed that the stress relaxation effect by the secondary creep was surprisingly negligible, though the duration of the joining process amounted to 5 hours at 500-600°C. It is still an open question that to what extent the primary creep would relax the intensity of residual stresses (currently not to be answered due to the lack of material data). This issue remains a topic for future study.

5. Conclusions

Numerical modeling and experimental investigation, by means of neutron diffraction, have been combined to characterize the stress field in an as-received 4 tiles ITER-like divertor monoblock. Experimental strain and stress value are not only in the same order of magnitude as the theoretical ones but also in several of the investigated points coincident, within the experimental errors. A sharper gauge volume and additional micro-structural information on the interlayer region will be necessary to provide a more detailed mapping at the interface of the two materials and to validate the strain and stress gradients numerically predicted in such a critical region.

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