COMPUTED TOMOGRAPHY AND PULSED THERMOGRAPHY OF CARBON REINFORCED CARBON/COPPER COMPONENTS FOR THERMONUCLEAR FUSION

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Abstract

Thermonuclear fusion seems to be one possibility to overcome the lack of energy in the future. One of the key components of a nuclear fusion reactor is the so called divertor, the component facing the high temperature plasma and bearing the highest heat load. For the ITER (International Thermonuclear Experimental Reactor) in France a maximum loading of 25 MW/m^2 is planned. This task can be solved by using coolable cooper-alloys, which are bonded to carbon fibre reinforced carbon (CfC) or wolfram as plasma facing material. The extreme heat loading during operation requires stable processes for the production of such components and a comprehensive concept for quality assurance. Special attention is given to the material joint between fibre reinforced carbon and CuCrZr as material for the cooling system. Various non destructive testing methods like X-ray computed tomography and thermography testing have been adopted for different inspection tasks of CfC and the whole divertor. CT enables the precise size measurement of defects and structures in the CFC and at the CFC-CuCrZr interface. Pulsed Thermography can be also used at any stage of production and leads to very useful information. For the interpretation of the thermographic testing results finite element modelling was performed and the effect of different defect shapes at the interface could be studied.

1. Introduction

The efforts of developing nuclear fusion as energy source focus now on the so called ITER project (International thermonuclear experimental reactor), which is situated in the south of France. This fusion reactor with an actual power output of 200 MW will starts its operation in 2016. The component facing the plasma and therefore bearing the highest heat load is called divertor. The extreme heat and also neutron loading during operation requires detailed and reliable methods for quality assurance of these components. Various non destructive testing methods (NDT) like ultrasonic inspection, thermographic testing (TT), X-ray radioscopy and X-ray computed tomography were used for different inspection tasks [1,2]. Since it is most critical, these methods were especially used for the characterisation of the material joint between fibre reinforced carbon (CFC) as plasma facing material and CuCrZr as material for the cooling system [1,2].

Within this paper we apply cone beam X-ray computed tomography for non-destructive testing and quantitative characterisation of nuclear fusion reactor components. Computed tomography is a radiographic NDT method of locating and obtaining the size and volumetric details in three dimensions [3,4]. Using CT, a specimen is placed on a rotary plate between the X-ray source and the detector. The specimen is rotated step by step, taking a projection image at each angular position. A computer cluster reconstructs the radiographic images to a volume dataset. At each position of the resulting dataset a grey-value is calculated, which corresponds mainly to the spatial X-ray attenuation coefficient. By X-ray computed tomography characteristic data of the laser machined blind holes in the CfC like hole diameter, hole depth, flank angle as well average distances were determined. In addition, CT was used to characterise the CFC-CuCrZr interface both in flat tile design (left picture) and in a monoblock design. The CT-data are compared with the results of the TT-investigations.

2. Experimental

Samples

The fusion plasma is facing to the so called divertor element, where a high thermal and neutron flux has to be absorbed. The extreme high load and requirement reduced the possible materials for the divertor components to CfC (carbon fibre reinforced carbon) and tungsten. Both materials are used in flat tile design and in a monoblock design. A flat tile is joined to a Cu-alloy, which acts as a heat sink, whereas a monoblock covers the tube for active cooling (See Fig. 1). The bonding of the CFC monoblocks to the CuCrZr tube consists of two production steps. Initially a Cu layer is attached to the CFC monoblock by active metal casting followed by a joint between the active metal casting layer of the monoblock and the CuCrZr tube which is established by hot isostatic pressing.

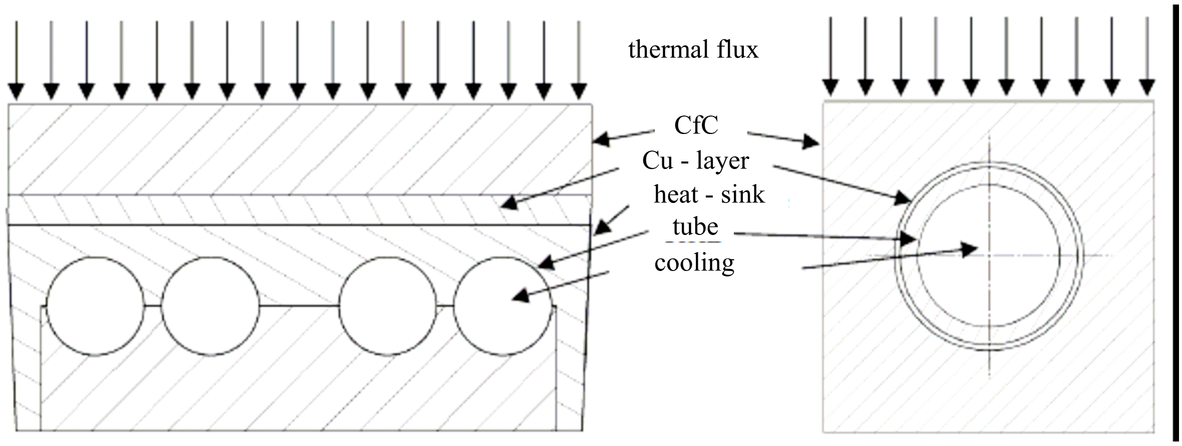


Fig. 1: Drawing of a divertor component in a flat tile design (left picture) and in a monoblock design (right picture). The arrows at the top show the direction of the heat and neutron flux.

Computed Tomography (CT)

The X-ray tomograms were scanned at a Rayscan 250E cone beam CT-system constructed by RayScan GmbH with a 225 kV Viscom micro focus tube. The target material was tungsten. The spatial resolution of the method is limited by the size of the focus on the X-ray target to approx. 5 µm. The detector of the CT-device is a 1024x1024 a-Si flat panel matrix-detector Perkin Elmer RID 1640 AL1 ES with a Gadox scintillator. The cone beam CT-data were reconstructed by means of a filtered back projection Feldkamp-algorithm [3]; no beam hardening or scattering correction was applied.

Thermographic testing (TT)

For thermographic testing a cooled infrared camera (Type Jade I) produced by Cedip Infrared Systems was used. The power supply of the heat source used released an electrical energy of 12 kJ within 50 ms. A pair of flash bulbs transformed the electrical power to a flash of light which was directed towards the surface of the part under inspection. The cool down of the component after the flash was recorded by the infrared camera. Via fast Fourier transformation the time dependent cooling behaviour of each pixel was transformed in the frequency domain; amplitude and the phase images were recorded. The phase image of the first harmonic frequency was chosen for non-destructive testing of the CfC/Cu interface. The finite element modelling analyses were done by using ABAQUS/Standard V6.4. The results of the phase distribution were compared with the experimental results.

3. Results and Discussion

The left picture in Fig. 2 shows a scanning electron microscope picture of the CFC-surface structured by laser machining. A periodic structure of blind holes within the CfC can be seen. The structured CfC was also analysed by computed tomography. A CT-slice is shown in the right picture of Fig. 2, where a CT cross-section perpendicular to the structured surface is shown. The structure and the geometry of the blind holes as well the inner structure of the CfC can be seen, clearly.

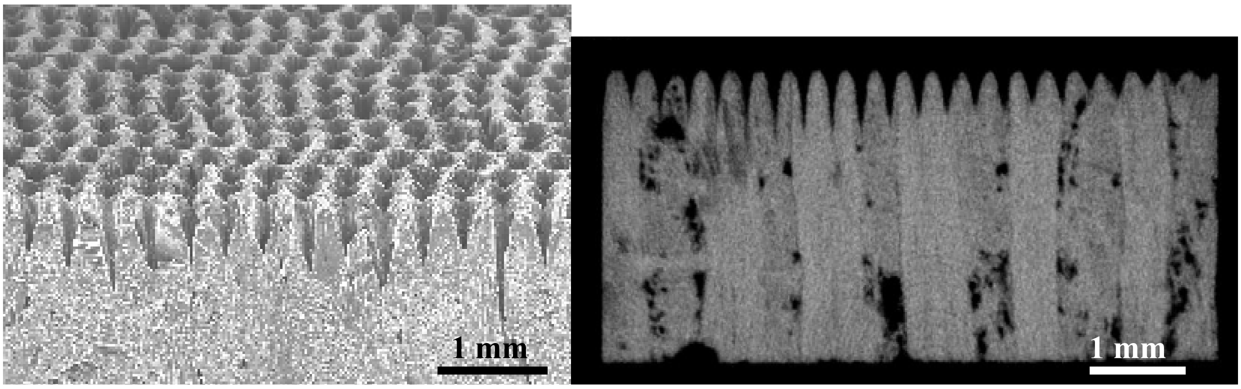


Fig. 2: Scanning electron microscope picture of CfC surface structured by laser machining (left picture) and cross-sectional CT-picture of the structured CfC surface showing the geometry of the blind holes and the inner structure of the CfC (right picture).

The CT-data of the laser structured CfC-samples were used to characterise the blind holes qualitatively as well as quantitatively. For this purpose the software "Analyse This" was developed. Fig. 3 shows how the CT-data were analysed by this software. As a first step grid lines were used to determine the positions of the blind holes. Along these lines grey-value profiles and the first derivatives of them were calculated, so that the centre points of the blind holes could be determined. Starting at these centre points a region growing algorithm with a global threshold was applied so that the blind holes could be segmented. The result of this processing step is shown in Fig. 3c, where the segmented area of every individual hole is presented in white. In addition, it can be seen that only a few blind holes are connected together.

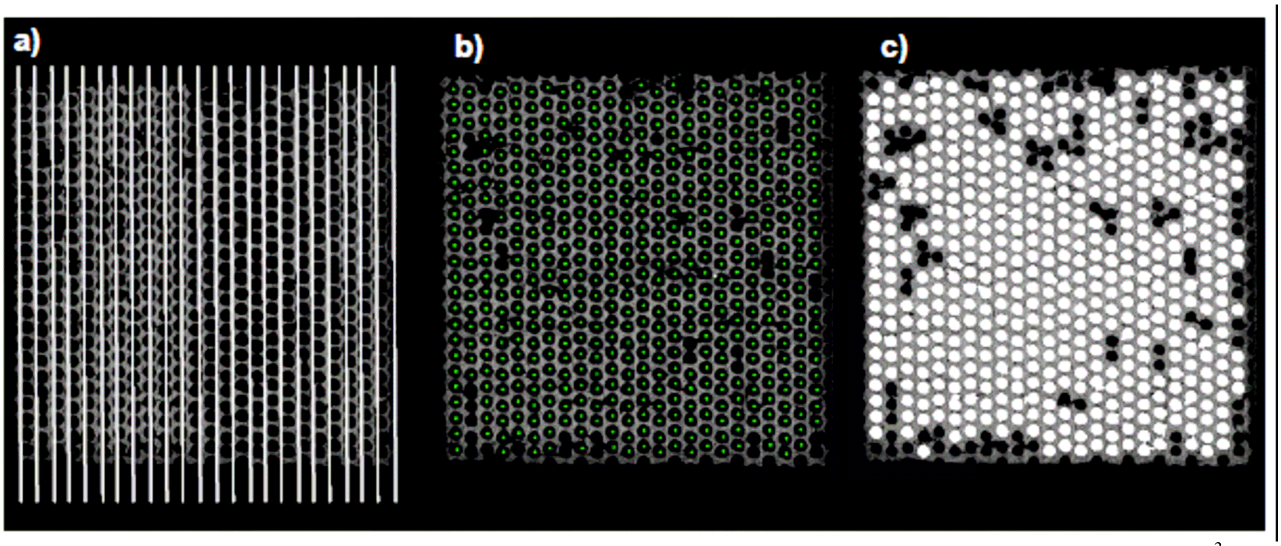


Fig. 3: Cross-sectional CT-pictures of a structured CfC-sample with a volume of $10.2 \times 10.1 \times 4.0$ mm^3 and the application of image processing algorithms for the characterisation and quantification of the blind holes.: a) grid lines for the determination of the positions of the blind holes, b) centre points of the detected holes, c) result of a region growing algorithm at a depth of 0.1 mm showing the segmented holes.

Every CT-slice was evaluated by the algorithms described above. In this way the complete geometry of all blind holes could be deduced and characteristic values like hole diameters at the surface, depth, flank angle and average distances between the individual blind holes were determined. In this way a statistically ensured evaluation of the structuring process for the CFC was performed.

In a next step the quality of the bonding between the CfC and the CuCrZr was analysed. The left picture of Fig. 4 shows an optical cross section of the bonding between the CfC and the CuCrZr-tube. The bonding of the CfC monoblocks to the CuCrZr tube consists of two production steps. At first a Cu layer is attached to the CfC monoblock by active metal casting, which is processed by hot isostatic pressing afterwards. The right picture in Fig. 4 shows a cross-sectional CT-picture along the bonding interface of CfC and CuCrZr (=parallel to the surface). There are clearly regions visible, where the Cu has fully penetrated into the CfC-needles (bright spots) but there are also pores with almost no Cu (dark spots) revealing a bad connection. These results clearly demonstrate the usefulness of computed tomography. CT reveals complete and detailed information of the quality of the bonding interface.

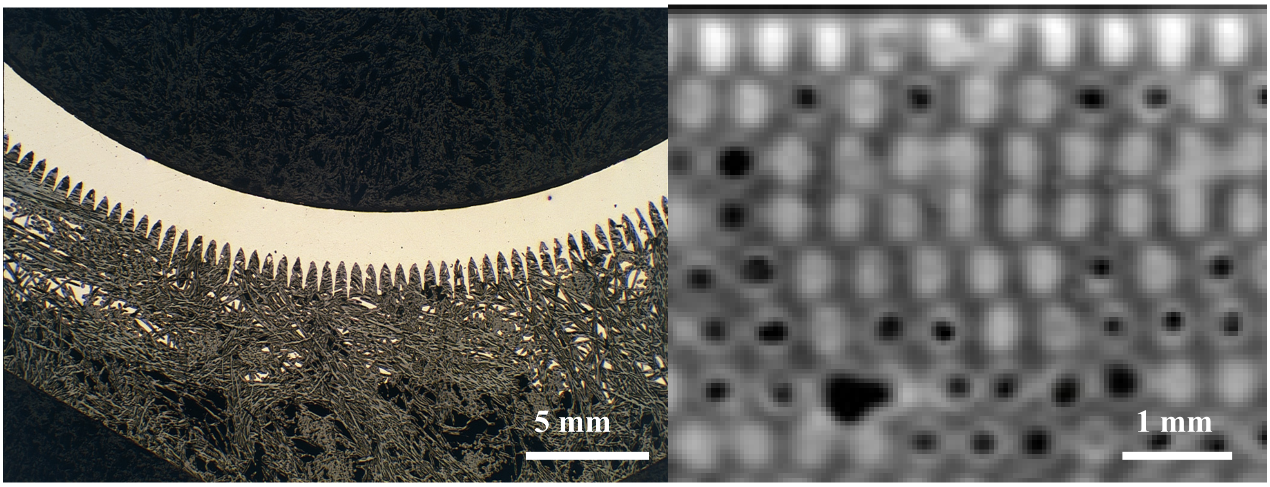
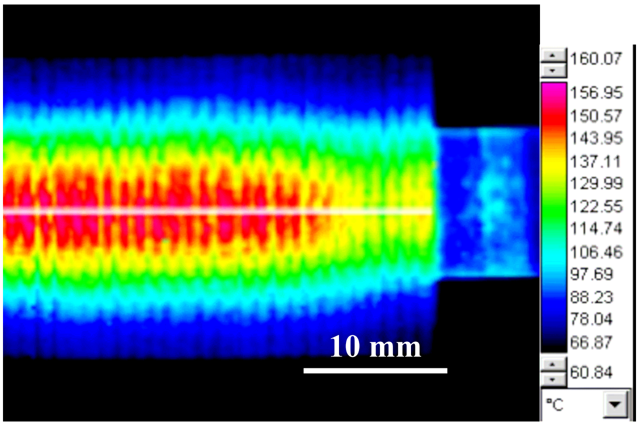


Fig. 4: Optical cross sectional picture of CFC-CuCrZr interface clearly showing the Cu-needles (left picture). Cross sectional CT-picture along the Cu-CfC-interface showing the copper needles and pores (right picture).

Fig. 5 shows a thermogram of the surface of a monoblock component. The thermographic testing-picture shows temperature gradients originating from the design of the component and from defects. Therefore, the interpretation should be supported by modelling and/or by comparative investigations. In Fig. 5 the fibre structure of CFC leads to vertical stripes in the picture. The gradient along the white line indicates a bonding defect. This was verified by computed tomography. Fig. 6 shows a CT-cross-sectional picture of the same part as in Fig. 5. The position and the length of the crack, which gave a special feature in the TT signal, can be determined by computed tomography quite well. A good correspondence between the two NDT-methods – computed tomography and thermographic testing - can be stated.



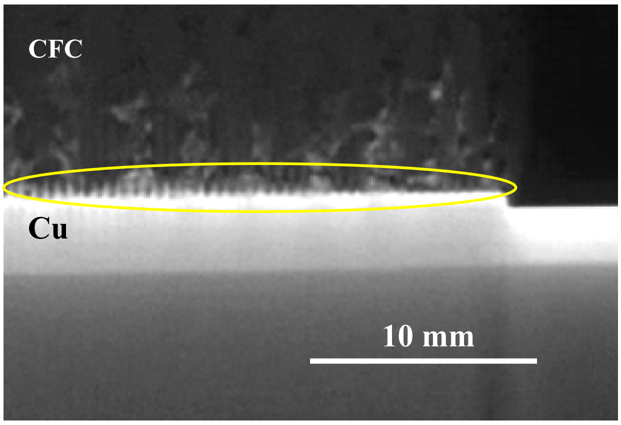


Fig. 5: Thermogram of the surface of a monoblock component.

Fig. 6: CT-slice of the same monoblock component as depicted in Fig. 2.

In addition, finite element analyses were done by using ABAQUS. The FEM results were used for interpretation of the TT-results. Via FEM the effect of the relevant defect sizes according to the acceptance criterion on the results of TT was investigated. The simulation results enable the estimation of the defect size from the TT phase image. Further details can be found in [2].

Monoblock divertors can be even analysed by CT, when the active cooling is connected. This is not the case for flat tile divertors. An example for monoblock characterisation is the scanning of a vertical target prototype for the ITER divertor. The experimental setup with the CT-device and the fixed vertical target is shown in the left picture of Fig. 7. The region, where this vertical target is engineered in monoblock design, was analysed by means of 10 overlapping CT-scans. A CT-cross-sectional picture of a typical void is shown in the right picture of Fig. 7. Pores within the CuCrZr are clearly noticeable in some regions. The positions and sizes of these pores can be analysed accurately.

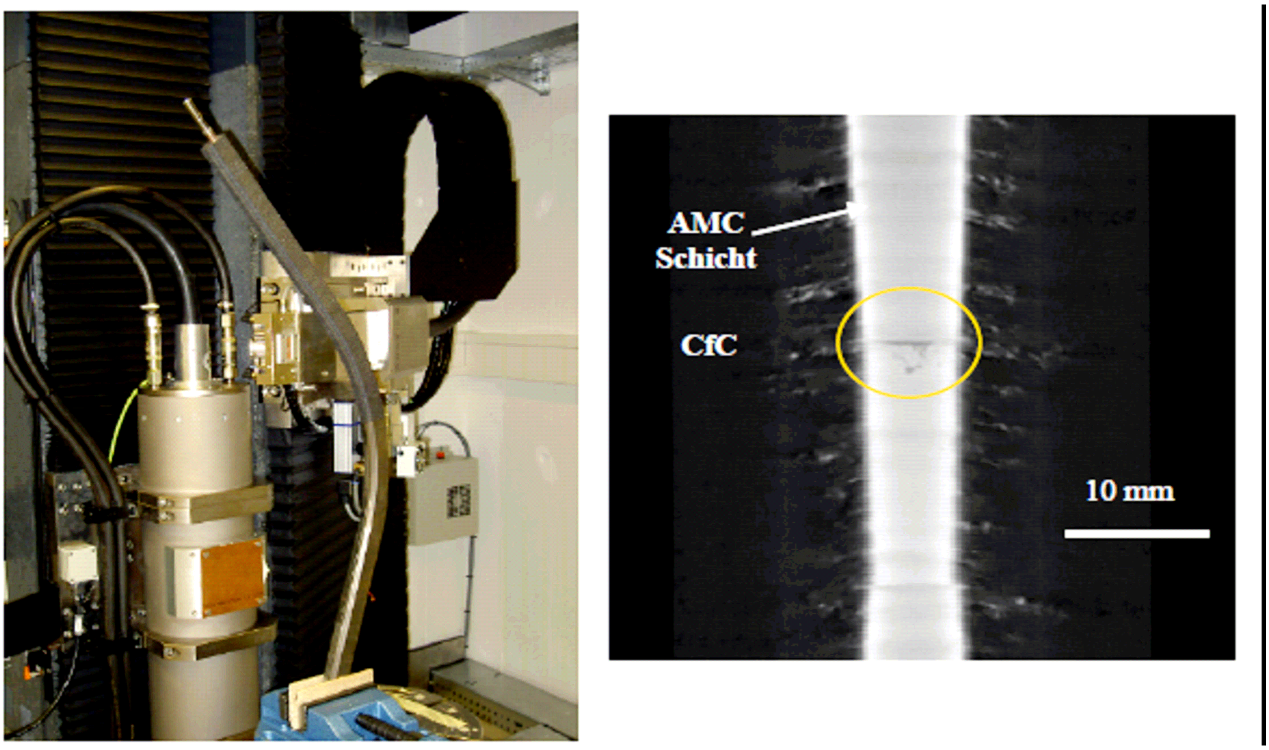


Fig. 7: Setup at the CT-device to scan vertical target of the ITER prototype (left picture). Cross-sectional CT-picture of the vertical target showing the CfC, the active metal casting layer and the CuCrZr (right picture).

4. Summary

- We applied computed tomography and pulsed thermography for the characterisation of carbon reinforced carbon/CuCrZr components which are used as divertor in nuclear fusion reactors.
- CT is very useful to get high resolution 3-dimensional information about the structure, the geometry, the interfaces and the defects of the various components. Blind hole diameters, hole depths, flank angles as well average distances for laser machined CfC were determined by CT. Especial attention was drawn to the CfC/CuCrZr, where bonding defects, pores, cracks could be identified.
- Pulsed thermography can be applied to the components in any stage of production. For the performance of the test no reference element is needed which enables a simple data treatment for defect analysis. By finite element analysis the defects sizes can be derived from the TT phase image. A good correspondence between CT, TT and finite element analysis was found.
- The results shown here are the base for the definition of the acceptance criterion for the ITER prototypes by means of thermography testing.

Acknowledgement

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