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Are tungsten-based nuclear fusion components truly invisible to x-ray inspection?

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Abstract. The ability to detect undesired volumetric defects in reactor components could affect the safety and reliability of a fusion power plant and change the expected lifetime and performance of the reactor. This is even more true for critical reactor parts like plasma-facing components which have to withstand challenging in-vessel conditions due to a combination of plasma bombardment, radiation, and nuclear heating. The structural integrity of these components prior to their installation in a nuclear fusion reactor need to be assessed non-destructively. Until now, industrial x-ray radiography and tomography have not been used to non-destructively inspect fusion components due to their lack of penetration power into dense material such as tungsten which is often used to manufacture plasma-facing components. However, aiming to revert this consolidated belief, we have demonstrated for the first time the feasibility of assessing volumetric defects non-destructively on DEMO divertor mock-up by means of MeV energy range x-ray tomography. The authors believe that the application of this technology could be easily extended for inspecting large fusion components and positively impact procedures to be followed in the qualification of fusion components for current and future nuclear reactors.

Keywords:Divertor target, Tungsten, Thermal break, CuCrZr, X-ray tomography, Non-destructive evaluation, Qualification. Submitted to: *Nucl. Fusion*

1. Introduction

In a magnetic confinement nuclear fusion reactor plasma-facing components (PFCs) are the most exposed elements to high heat flux (HHF) loads due to a combination of plasma bombardment, radiation and nuclear heating by neutron irradiation [1]. Such neutron fluxes produce defects in the microstructure of the materials and pulsed operation of the reactor causes fatigue due to cyclic thermal stress variation [2, 3]. In fact, in the case of ITER and DEMO reactors, it is expected that the peak surface heat flux on divertor targets could reach up to 10 MWm^{-2} during normal operation and 20 MWm^{-2} during slow transient events such as loss of plasma detachment. To maintain structural integrity under HHF fatigue loads and demonstrate reliable HHF performance, PFCs need to be carefully inspected and qualified before their installation in the reactor. Any manufacturing defect in the component could quickly develop into a failure because of the detrimental in-vessel high radiation bombardment which might impact on the reliability of the entire fusion power plant. As such, robust non-destructive evaluation (NDE) techniques are paramount to avoid failures and they will represent a crucial step for qualifying fusion components to any fusion regulatory codes and standards required for a commercial fusion power plant. Very recently, we have successfully demonstrated the use of neutron tomography as a non-destructive volumetric inspection technique applied to PFCs [4]. However, such inspection technology can only be accessed at dedicated large-scale facilities limiting its applicability in practice. X-ray radiography and tomography (XCT) are very well-established technologies that are used routinely to non-destructively inspect engineering components across many industries (nuclear, aerospace, oil & gas, etc). These techniques might be considered the first option for qualifying critical engineering components where stringent quality controls are required. Until now, industrial x-ray radiography and tomography were never used to inspect fusion components due to the lack of penetration power into dense material like tungsten which is often used to manufacture plasma-facing components. In this work, we demonstrated the feasibility of using MeV energy range XCT for non-destructive inspect volumetric defects on a DEMO divertor mock-up.

2. DEMO divertor mock up sample and previous testing

For this pilot experiment a 2^{nd} phase thermal break mockup of the DEMO divertor target design [2, 5, 6, 7, 8] has been used and it is shown in Figure 1. This sample was previously studied via neutron tomography [4] on the IMAT beamline [9, 10, 11] at the ISIS spallation neutron source in UK. Further, recent studies have demonstrated the feasibility of using neutron tomography to assess volumetric defects on large numbers of similar components like divertor monoblocks [12] and how those results compared with XCT measurements [13]. From the neutron tomography tests [4], no major issues have been identified to the sample. Subsequently, the specimen was subjected to HHF loads with a single cycle at $\sim 8\text{MWm}^{-2}$ on the HIVE facility [14] at Culham Centre for

Fusion Energy (CCFE).

During this test, a loss of cooling flow was experienced which lead to nucleate boiling in the pipe-work and a subsequent expansion of the specimen in its central area. The rapid expansion led to a leak of the coolant and rapid migration of some of the inner pipe and interlayer materials to the surface of the tungsten armour as shown in Figure 1. To understand the damage created by the failure, we propose to test the feasibility of using MeV energy range XCT as a volumetric non-destructive inspection method for preserving the integrity of the sample.

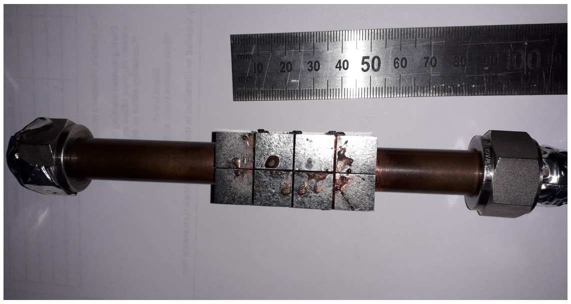


Figure 1: Photograph of the DEMO divertor target studied by means of XCT in MeV energy range.

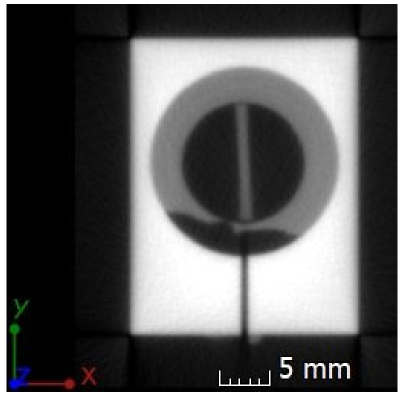
3. High energy x-ray system and testing methodology

High energy x-ray radiography and tomography at MeV energy range are emerging techniques that only recently have been used to inspect very large engineering components where conventional XCT at keV energy range lack enough penetration power into the component. Hence, this technology offers a potential new route for qualifying large fusion components very often manufactured with dense material like tungsten or where sizes prevent the use of standard keV energy range XCT.

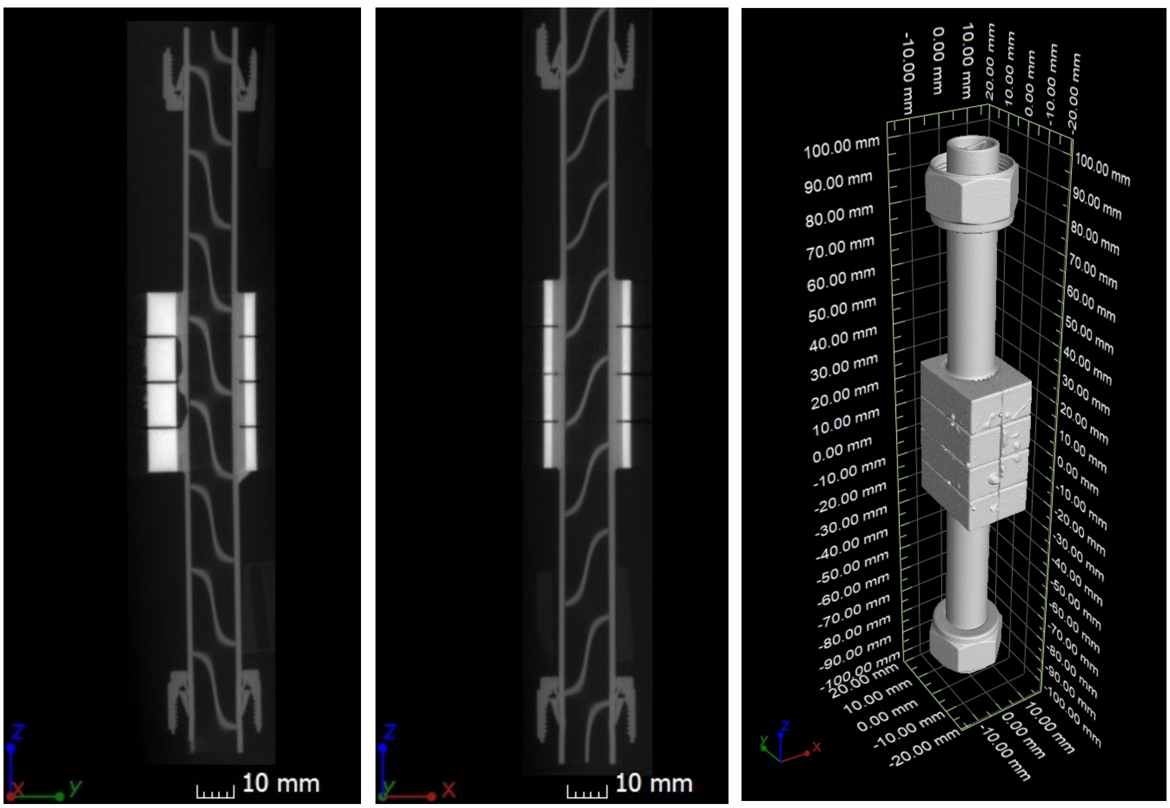
For this feasibility experiment, we have used a 6 MeV linac-based x-ray scanner equipped with a flat panel detector of 3072 x 3072 pixels with a detector pixel pitch of 139 μm. A magnification of x1.1 was chosen assuring an optimum voxel size of 125.7 μm and a geometrical unsharpness of 0.529 μm. The tomogram of the specimen was obtained after Filtered Back Projection (FBP) reconstruction via NeuTomPy toolbox [15] of the uniformly spaced angular scan of 720 projections in the range $[0°, 360°)$ with an total acquisition time of 4 hours. Additionally, a few images (3 flat field and 1 dark field image) were taken for normalization purposes (or what we consider corrections prior to starting the scan). The acquired projections largely satisfied the Nyquist-Shannon sampling theorem [16].

4. Results

In this section, we will discuss preliminary results showing volumetric defects present in the DEMO divertor mock-up caused after the high heat flux test performed on the HIVE facility [14] at CCFE. The specimen was studied non-destructively with a spatial resolution (voxel size) of 125.7 μm and geometrical unsharpness of 0.529 μm. Smaller defect sizes were considered to not be distinguishable with the current experimental



(a) X-Y cross-section view.



(b) Y-Z cross-section view. (c) X-Z cross-section view. (d) 3D volume rendering.

Figure 2: Cross-section views and volume rendering of the DEMO divertor mockup.

setup. After FBP reconstruction, some selected cross-sectional views of the specimen were reported from Figure 2a to Figure 2c and the full volume rendering of the object is shown in Figure 2d. From these preliminary results, damage of the component is clearly visible from the x-y and y-z cross-section images which have revealed multiple failures of the inner CuCrZr alloy pipe and the oxygen-free high conductivity (OFHC) copper interlayer. Such melted materials caused by the HHF load have partially deposited on the external tungsten tile surface and they are visible in the 3D volume rendering image of the specimen in Figure 2d.

The x-y cross-section image of Figure 2a has further revealed a complete loss of the structural integrity of the pipe in the proximity of the joints between monoblocks where the pressure relief after boiling has favored the formation of some holes in the pipe with the subsequent loss of coolant. The good spatial resolution achieved in the tomography scan is also testified by the level of detail in the reconstruction of the threads on the two pipe fittings used to attach the mockup to the external cooling loop used for the HHF test on HIVE, and visible in the y-z and x-z cross-section images of Figure 2. The achieved spatial resolution has allowed resolving in detail the inner structure of the divertor target mockup and the helical swirl tape that runs through the entire length of the cooling pipe as shown in the cross-section images. The resultant digital-twin copy obtained by the XCT scan of the component will allow us to further perform metrology checks and eventually highlight deviations from the CAD (computer-aided design) model. Further analysis will follow these preliminary results and a neutron tomography scan will be performed on this component in the near future to benchmark outcomes with a different image-based NDE technique.

5. Conclusions

This pilot experiment has successfully demonstrated the feasibility of using MeV energy range XCT for non-destructively assessing the manufacturing quality of a DEMO divertor mockup. Due to the great penetration power of MeV energy range x-rays and their non-destructive nature this technology could potentially be applied for qualifying large fusion components despite their large size and inclusion of dense materials such as tungsten. Further, it can be used for the inspection of additive manufacturing components where conventional NDE methods might fail, hence opening up more freedom to designers of fusion reactors. Lastly, the image-based nature of MeV energy range x-ray radiography and tomography results could impact procedures to be followed in the qualification of fusion components for current and future nuclear reactors.

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