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Comparison of X-ray and neutron tomographic imaging to qualify manufacturing of a fusion divertor tungsten monoblock

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ABSTRACT

Within a tokamak fusion energy device, the performance and lifespan of a divertor monoblock under high heat flux cycles is of particular interest. Key to this is the quality of manufacture, especially the material joining interfaces. Presented here is a comparative study between X-ray and neutron tomography to investigate the quality of manufactured monoblocks. Tungsten is a high attenuator of X-rays, thus X-ray tomography was performed on 'region of interest' samples where the majority of the tungsten armour was removed to reduce the attenuation path. Neutron tomography was performed on the full monoblock samples for non-destructive testing and on the 'region of interest' samples for direct comparison. Both techniques were shown to be capable of imaging the samples but having their own advantages and disadvantages relating to image accuracy and logistical feasibility. The techniques discussed are beneficial for either the research and development cycle of fusion component design or in quality assurance of manufacturing.

1. Introduction

Due to its location and function within a tokamak, the divertor is the component subjected to the greatest steady thermal load. During steady-state operation thermal fluxes are expected to be at least $10\,\mathrm{MW\,m^{-2}}$ [1]. To remain within operational temperature limits the divertor components are actively cooled [2]. This is achieved by connecting armour tiles through their centres to a pipe carrying coolant (coined a monoblock). As the function of this heat sink is to transfer thermal energy away from the armour, it is imperative that the method of joining the armour to the pipe must provide a bond that retains both structural integrity and a high thermal conductivity under large thermal loads. As this region will contribute to, and potentially dominate, performance of the component, it is of utmost importance that the armour-pipe interface is well characterised.

For ITER, the monoblock will use tungsten (W) for the armour with a copper alloy (CuCrZr) cooling pipe. The armour is bonded to the pipe to maintain thermal conduction, but a large thermal expansion coefficient mismatch between the W and CuCrZr causes high levels of stress within the part. Therefore, a functional compliant interlayer is used at the material interface to create a bond between the pipe and armour with improved longevity. For future devices, where it would be desirable to operate at higher thermal fluxes, alternatives designs are being investigated e.g. using composite materials, a functionally graded interlayer or geometric constructs [3]. ITER will use approximately 320,000 monoblocks which will require replacing after 5 full power years (fpy) of operation due to degradation [4], therefore manufacturing cost is a consideration. In addition to investigating alternative designs, various manufacturing routes are being tested which aim to reduce this cost e.g. bonding of the armour to heat sink materials via brazing rather than direct casting of copper.

Because of this, the capability to inspect the material interfaces within the monoblock is of great value. This is true for both quality assurance, when manufacturing the current generation, and informing decisions in the development of next generation monoblocks. The features of concern in this region are anything that may reduce the component's lifespan by reducing its ability to withstand high thermal loads. For example, micro-cracking or voids will act as thermal barriers which can increase peak temperatures or act as crack or interface debonding initiation sites when experiencing thermal fatigue. Deviations

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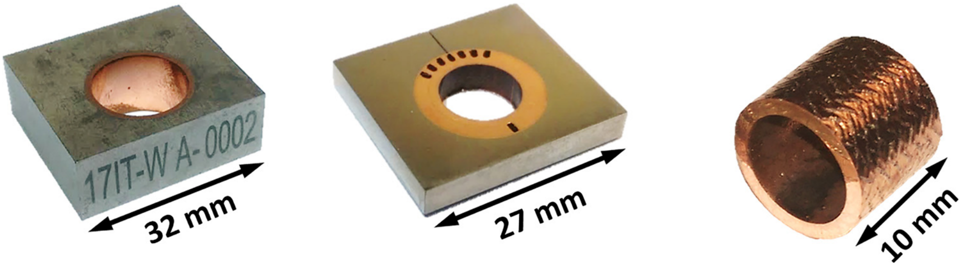

Fig. 1. Three sample types used for this work: (left) ITER reference monoblock (ITER_MB), (centre) Culham Centre for Fusion Energy thermal break concept monoblock (CCFE_MB) and (right) Max-Planck-Institut für Plasmaphysik tungsten fibre / copper matrix coolant pipe (IPP_Wf-Cu).

from design tolerance cause differences between real and predicted stress and temperature fields which may exceed safety limits. For this component, tolerances of interest are interlayer thicknesses and small-scale geometric constructs. For future designs which may include composite materials, the exact fibre placement or matrix permeation may be of importance due to localised variations in the material's performance leading to stress concentration zones or thermal hot spots. Finally, other features such as material inclusions or the flow of filler material from the brazing process is also of interest. A better understanding of the extent of the existence of these features will aid better informed decisions with regard to the suitability of particular manufacturing routes.

Currently, the main methods for investigating manufacture quality of divertor monoblocks are via conventional optical or scanning electron microscopy (SEM) and ultrasonic scanning. SEM produces nanometre resolution images and may even be used to investigate compositional makeup e.g. elemental diffusion at material interfaces [5]. However, the technique is destructive as the sample must be cut in preparation of imaging. For brittle materials like tungsten this may introduce defects that were not present within the component. Additionally, two dimensional cross-sections showing features like cracks or inclusions provide insufficient data about the size and shape of features. Serial sectioning techniques may be used for additional data for the third dimension [6] but these are extremely time consuming and have relatively low resolution through thickness. Ultrasonic scanning is very effective in providing a relatively quick verification for the quality of bonding for the current generation design of monoblock. This technique scans radially around the coolant pipe by moving a transducer along the thin edges of the monoblock [7]. A drawback of the technique is its inability to distinguish between voids or inclusions as it only measured the changes in acoustic signal from a baseline value. It is also limited in its relatively low millimetre scale resolution and could not be used to investigate fine tolerance deviations. Additionally, geometric constructs or composite fibres in future generation designs will appear as changes in signal, these may be difficult to distinguish between against component defects. A recent development of this technique is to combine ultrasonic scanning and infrared imaging for improved defect detection [8].

A method which has been increasing in its use within an industrial setting is computerised tomography (CT). This has the benefit of providing three dimensional images which give data about features size and shape. This method depends on contrast in signal attenuation which means it is not well adept for interfaces between similar materials, e.g. carbon fibres in a carbon matrix, but can easily distinguish between voids and inclusions and even determine interfaces between differing metals if there is sufficient attenuation contrast [9].

Various CT techniques use different signals which are appropriate for the medium being imaged e.g. radio signals are used for upper atmosphere studies [10]. For industrial manufacturing the most common method is X-ray tomography [11]. Depending on the precise setup this can provide nanometre resolution but is typically on the micron scale for commonly available commercial scanners [9]. The main challenge with using X-ray tomography for imaging of the divertor monoblock is that tungsten is an extremely high attenuator of X-rays. Previous work shows use of synchrotron X-rays on cylindrical tungsten samples with a diameter of 0.5 mm and states that this was the achievable limit [12]. This is relatively small in comparison to the proportion of a monoblock that would be required to provide significant data about the material interfaces. However, recent advances in CT hardware offer higher energy X-rays than previously available which may be sufficient to image portions of the monoblock providing significant data.

Other than X-ray CT, neutrons could provide viable CT signal sources that aren't attenuated excessively by tungsten to such a level that impedes imaging. Neutron CT is a relatively immature technique and can only be performed at a handful of facilities globally [13]. Additionally, when the samples interact with the beamline they become activated. Depending on the materials used in the samples the time required for the samples to reduce sufficiently in activity may be prohibitive in the feasibility in their wide-scale use for component qualification. The neutron damage from the beamline will be insignificant compared of in service use and can therefore be disregarded. Depending on the level of detail provided by this technique the benefits could far outweigh the disadvantages.

This paper investigates and compares the advantages and disadvantages of X-ray and neutron CT imaging of current and future generation divertor monoblocks. This includes the quality of the images themselves, detailing characteristics such as resolution and noise, and the logistical feasibility requiring consideration due to steps such as sample preparation.

2. Sample manufacturing

For this study three sample types were used: ITER reference monoblock (ITER_MB), Culham Centre for Fusion Energy thermal break concept monoblock (CCFE_MB) and Max-Planck-Institut für Plasmaphysik tungsten fibre / copper matrix coolant pipe (IPP_Wf-Cu), as shown in Fig. 1.

The 'ITER_MB' sample is manufactured by first producing a bar of sintered tungsten which is rolled to yield elongated grains whose longitudinal orientation are aligned such they shall not be parallel to the surface. The tungsten armour is then machined to shape before oxygen free high conductivity (OFHC) copper is directly cast into the internal hole. A drill is then used to machine the copper layer to leave the desired interlayer thickness. For use within the divertor, a series of monoblocks would be placed along a copper alloy (CuCrZr) coolant pipe and joined by hot radial pressing. The main ITER_MB sample used in this instance only included the armour and interlayer. A second sample, 'ITER_HHFT', which had been subjected to high heat flux testing prior to imaging also included the coolant pipe.

The 'CCFE_MB' sample was fabricated using a two-stage vacuum braze process. Copper sleeves (for interlayer material) were first brazed to CuCrZr pipes and the geometric constructs (grooves) machined into the outer surface of the subsequent assembly. Tungsten monoblocks were cast with copper into the central bore (with similar specifications