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Ultrasonic techniques for quality assessment of ITER Divertor plasma facing component

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ABSTRACT

The divertor is one of the most challenging components of ITER machine. Its plasma facing components contain thousands of joints that should be assessed to demonstrate their integrity during the required lifetime. Ultrasonic (US) techniques have been developed to study the capability of defect detection and to control the quality and degradation of these interfaces after the manufacturing process. Three types of joints made of carbon fibre composite to copper alloy, tungsten to copper alloy, and copper-to-copper alloy with two types of configurations have been studied. More than 100 samples representing these configurations and containing implanted flaws of different sizes have been examined.

US techniques developed are detailed and results of validation samples examination before and after high heat flux (HHF) tests are presented. The results show that for W monoblocks the US technique is able to detect, locate and size the degradations in the two sample joints; for CFC monoblocks, the US technique is also able to detect, locate and size the calibrated defects in the two joints before the HHF, however after the HHF test the technique is not able to reliably detect defects in the CFC/Cu joint; finally, for the W flat tiles the US technique is able to detect, locate and size the calibrated defects in the two joints before HHF test, nevertheless defect location and sizing are more difficult after the HHF test.

1. Introduction

The divertor is one of the most challenging components of the ITER machine. The actively cooled plasma facing components (PFC) present thousands of heat sink to armour joints made of carbon fibre composite (CFC) to copper alloy (CuCrZr) or tungsten (W) to CuCrZr. In order to guarantee their integrity during the required lifetime, their manufacturing process, and their thermal and mechanical behaviour must be assessed.

In sight of the procurement of the ITER Divertor, the examination of these joints by non-destructive testing (NDT) is a crucial issue since this will be used to assess the quality of the PFC before acceptance. Ultrasonic (US) methods are one of the NDT foreseen to contribute to these tasks.

Different sets of samples containing calibrated defects have been fabricated with the aim of setting up experimental basis for the development of appropriate NDT procedure and definition of final acceptance criteria. The samples include defects of different size and in different joint location. US techniques have been developed to detect and characterise the calibrated defects for the three different joints to be examined: CFC/Cu, W/Cu and Cu/CuCrZr.

To check the thermal behaviour of the joints, the samples have been high heat flux (HHF) tested and examined by US two times: before and after the HHF test [1,2]. Therefore, the US technique is intended to characterise the defect parameters and study their evolution due to the HHF test.

In the section that follows a description of the divertor samples with calibrated defects and the US inspection system are presented. Then, the inspection results of the samples are described and discussed pointing out the capabilities and limitations of the ultrasonic techniques.

2. Description of mock-ups and ultrasonic inspection system

2.1. Mock-ups description

Three types of mock-ups, manufactured by two different technologies, have been considered: CFC monoblocks, W monoblocks, and W flat tiles. The mock-ups of the two first sets are made of a monoblock, in one case of CFC and in the other of W, and a piece of Cu alloy tube joined together by means of two joints: CFC/Cu or W/Cu joint and CuCrZr/Cu (see Fig. 1). Each sample has a defect

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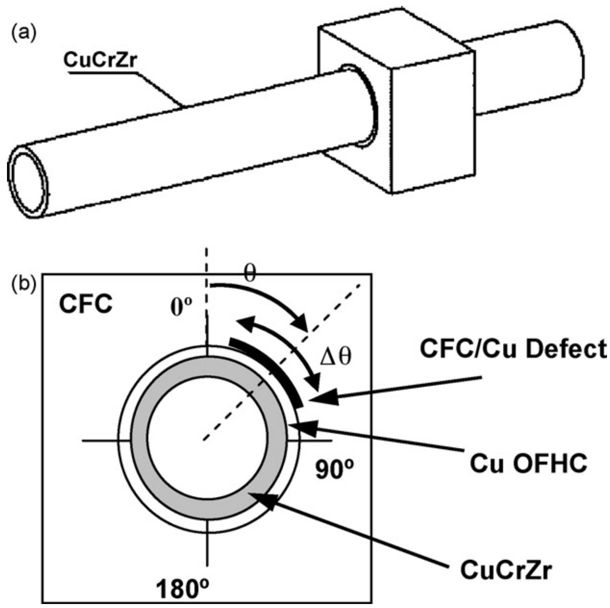

Fig. 1. CFC monoblock (a) mock-up geometry and (b) defect parameters.

implanted either in the first (CFC/Cu or W/Cu) or in the second (Cu/CuCrZr) joint. Regarding circumferential location (θ) the defect could be placed in a range: -45° to $+45^\circ$ and its size ($\Delta\theta$) varies from 15° to 65°; the definition of defect location and size is shown in Fig. 1.

The W flat tiles samples have a similar morphology to those above: a piece of tube with a monoblock of Cu alloy with four W tiles joined to one of the faces of the monoblock by means of a pure copper layer being those the joints examined (see Fig. 2). Each sample has a defect of different size (from 2 to 6 mm) implanted either in the first (W/Cu) or in the second (Cu/CuCrZr) joint.

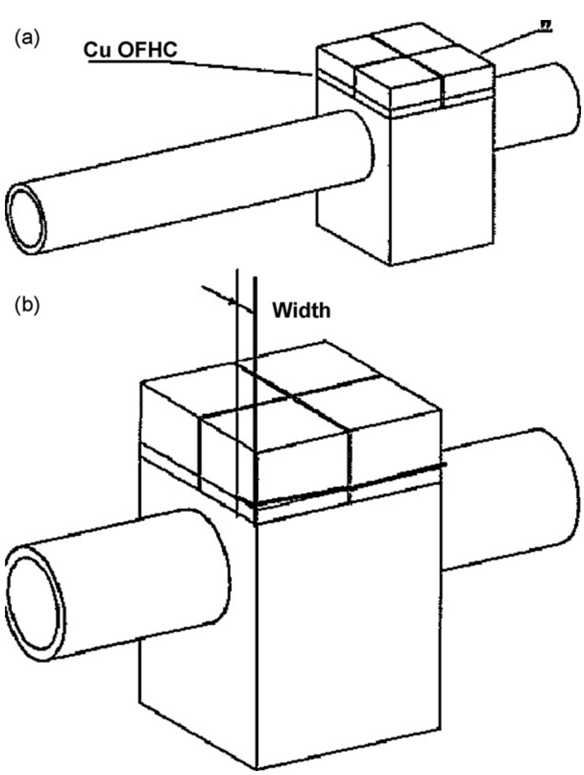

Fig. 2. W flat tile (a) mock-up geometry and (b) defect width.

2.2. Ultrasonic inspection techniques

In order to design the inspection technique it is necessary to know the geometry of the mock-ups, their materials and the characteristics of calibrated defects. An ultrasonic method using high frequency probes (of 5 and 10 MHz) and normal incidence of the US beam (to the joint interface) have been developed; it is named pulse echo because the transducer acts as emitter and receiver. The examination of the monoblock samples is made from inside the tube, and the examination of the W flat tile samples is made pointing the US beam to the tiles from outside the mock-up (see Fig. 3).

The US probe is scanned to inspect the entire joint surface with circumferential resolution of 1° and axial resolution of 1 mm. The inspection is carried out automatically by means of a multi-axes table and the MIDAS [3] data acquisition and analysis system.

The amplitude calibration of the US method is made with the mock-ups with calibrated defects; the aim is to define an amplitude threshold that discriminate the echoes coming from a defect/no defect zone. The amplitude threshold depends on the reflectivity of the scanning surface, interface and materials structures. At the

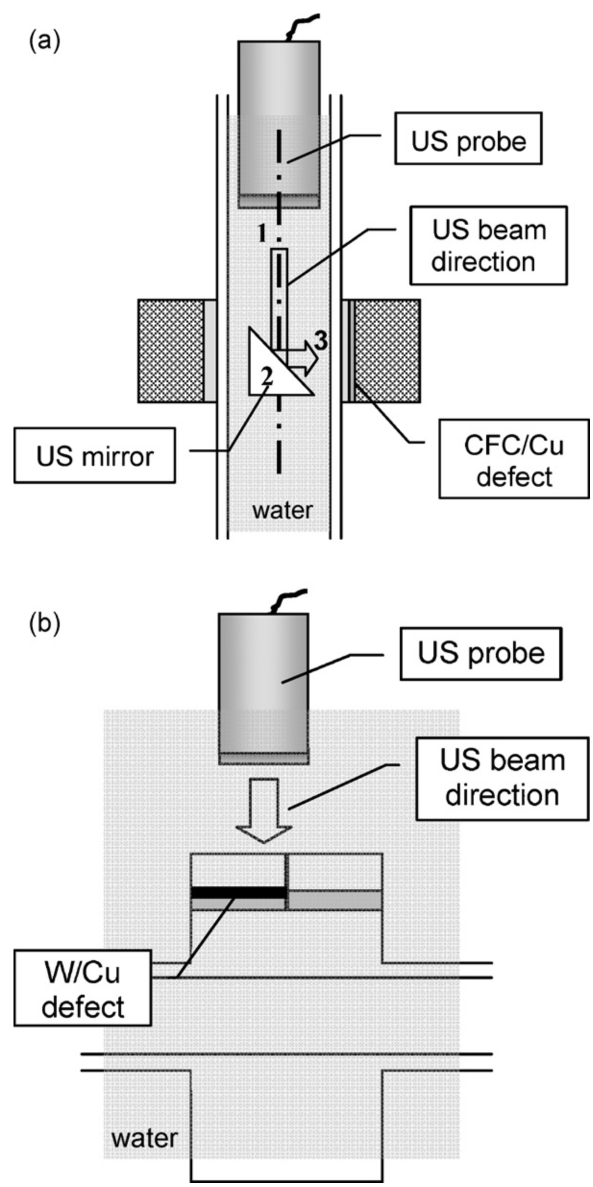

Fig. 3. Principle of ultrasound method for (a) monoblocks and (b) flat tiles.

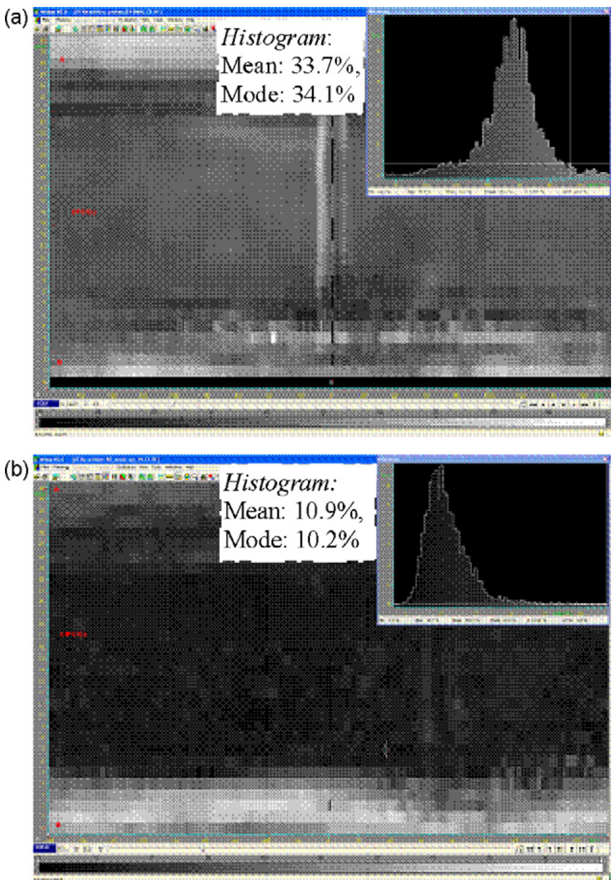

Fig. 4. C-scan and amplitude histogram of a CFC monoblock sample (a) before and (b) after HHF test. Amplitude scale appears horizontally at the bottom of each C-scan; black colour means the lower amplitude value and white colour means the higher amplitude value. Higher amplitudes appear before the HHF than after the HHF.

time of analysing US data for detecting defects, three conditions are sought: (a) signal within a temporal gate (to discriminate whether it comes from the first joint or the second joint), (b) signal above an amplitude threshold, and (c) minimum defect size.

3. Inspection results

The US results are given graphically as 2D maps called amplitude C-scans that represent a plant view of the volume scanned. White and grey pixels in the C-scan mean points in which the US is reflected back and with amplitude above the recording threshold. For monoblocks, the C-scan horizontal axis shows the circumferential coordinate, from 0° to 360°; the C-scan vertical axis shows the axial coordinate, through the total length of the monoblock and a few millimetres more, from 0 to 25 mm. Every point of the image represents the amplitude of the ultrasonic signal in this point of the mock-up. For the W flat tile monoblocks, the horizontal coordinate corresponds to the monoblock width (28 mm), and the vertical coordinate corresponds to the monoblock height (25 mm).

As it has been mentioned above, to check the thermal behaviour of the joints, the samples have been HHF tested and examined by US two times: before and after the HHF test. Details of HHF testing protocol are given in [4]. In the inspection of the monoblocks a number of difficulties appeared due to

- *Monoblock geometry*: The small dimensions of monoblocks (that force to use high frequency probes) and the scanning surface deformations (that alter the ultrasonic pattern).

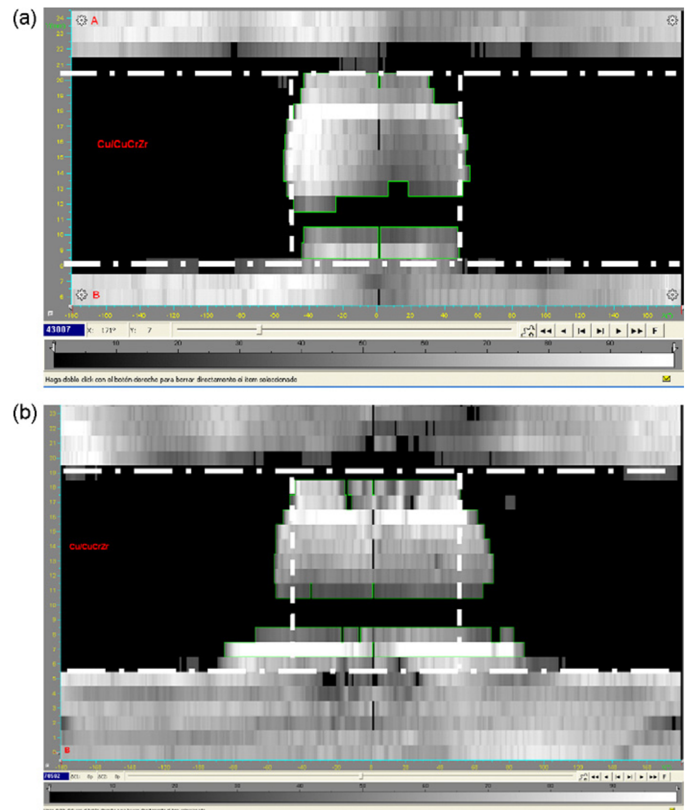

Fig. 5. US C-scan of a W monoblock Cu/CuCrZr joint (a) before and (b) after HHF test. Horizontal axis represents circumferential coordinate and vertical axis axial coordinate. Grey and white pixels represent points of monoblock with amplitudes above the analysis threshold; at the centre of the image is the defect, the pixels at the upper and lower borders correspond to tube wall. Area between the horizontal dash doted lines indicate the zone of interest; area between the vertical dashed lines mark the postulated defect area. Defect size after the HHF is larger than before the HHF.

- *Material structure*: The US inspection of CFC material is difficult to carry out due to its anisotropy and the large acoustic impedance difference between the CFC and the copper layer [5]. In addition to this, HHF tests could produce: (a) micro structural changes in copper and copper alloy layers that give place to US attenuation increment, and (b) damage in the materials that could enlarge the defect. However, the final assessment is not straightforward because these two effects can superimpose.

The increment of US attenuation after the HHF tests could be seen comparing the C-scans and the amplitude histograms of a same monoblock mock-up, examined applying the same calibration, before and after the HHF test. The images show that after the HHF test (Fig. 4b) the amplitudes of the received signals are smaller than the amplitudes before the HHF test (Fig. 4a); the C-scan before the HHF contains more pixels above the recording level than the C-scan after the HHF, and the amplitude histogram peak before the HHF has a higher amplitude than the amplitude histogram peak after the HHF.

3.1. W monoblock samples

Two sets of 28 samples each and fabricated by two different manufacturers have been examined. Each set has 14 samples with defects in the W/Cu joint and another 14 samples with defects in the Cu/CuCrZr joint. The US method was able to detect, locate and size all the implanted defects; in one of the sets, the US measurements are in agreement with the specified defect sizes (see Fig. 5a),

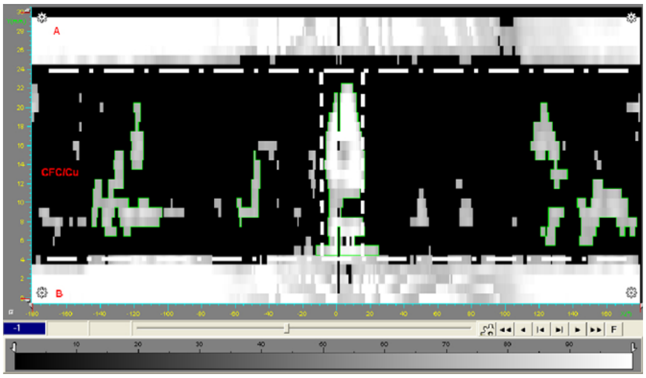

Fig. 6. US C-scan of a CFC monoblock CFC/Cu joint C-scan (a) before and (b) after HHF test. Horizontal axis represents circumferential coordinate and vertical axis axial coordinate. Grey and white pixels represent points of monoblock with amplitudes above the analysis threshold; at the centre of the image is the defect, the pixels at the upper and lower borders correspond to tube wall, and the pixels around the defect are spurious indications. Area between the horizontal dash-dotted lines indicate the zone of interest; area between the vertical dashed lines mark the postulated defect area.

however in the other set the US results found the defect sizes are larger than the specified defect sizes.

The US inspection after the HHF test revealed micro structural changes in the copper layers, and increment of some calibrated defect sizes. Thus, it could be said that the HHF test produced, on the one hand, micro structural changes that increased the US attenuation and, on the other, damage in the defect that enlarged its size (see Fig. 5a). The US method was able to detect and locate all the implanted defects. The defect sizes have also been measured and in all the cases but one they have increased.

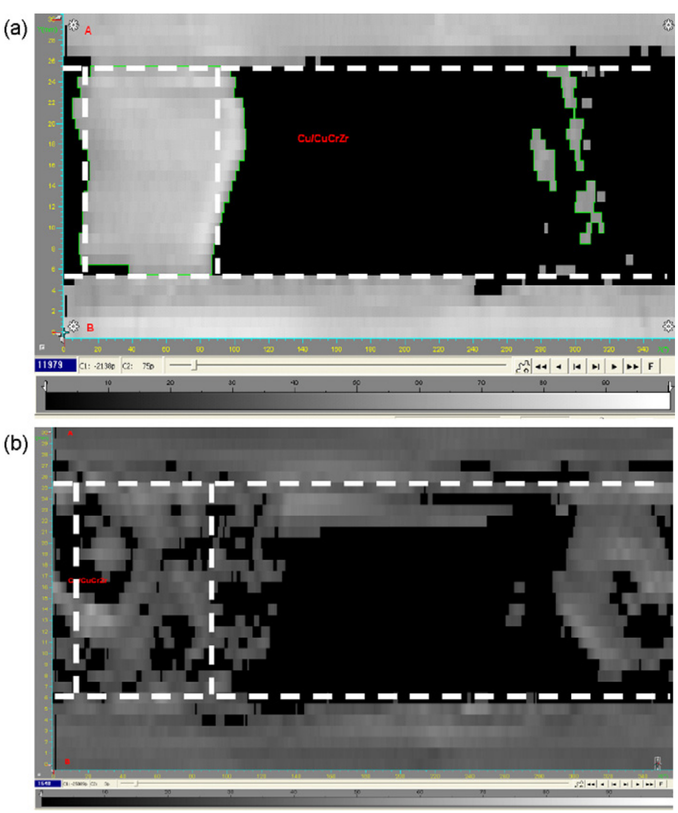

Fig. 7. US C-scan of a CFC monoblock Cu/CuCrZr joint C-scan (a) before and (b) after HHF test. Horizontal axis represents circumferential coordinate and vertical axis axial coordinate. Grey and white pixels represent points of monoblock with amplitudes above the analysis threshold; to the left of the image is the defect, the pixels at the upper and lower borders correspond to tube wall, and the pixels to the right side correspond to a new indication. Area between the horizontal dash doted lines indicate the zone of interest; area between the vertical dashed lines mark the postulated defect area. Defect size after the HHF is larger than before the HHF and reveals the anisotropy of joint materials.

3.2. CFC monoblock samples

Two sets of more than 24 samples each one and fabricated by two manufacturers have been examined. Half of the samples have defects in the Cu/CuCrZr joint and the other half have defects in the CFC/Cu joint. In the Cu/CuCrZr joint all defects have been detected, located and properly sized (see Fig. 7a). In the CFC/Cu joint, for the machined defect samples all defects have been detected and properly measured and, however, for the so called stop-off defect samples the 70% of the defects have been detected due to a low signal to noise ratio and spurious signals coming from the CFC structure produced by the anisotropy of the CFC and the significant acoustic impedance difference between the Cu and the CFC [5]

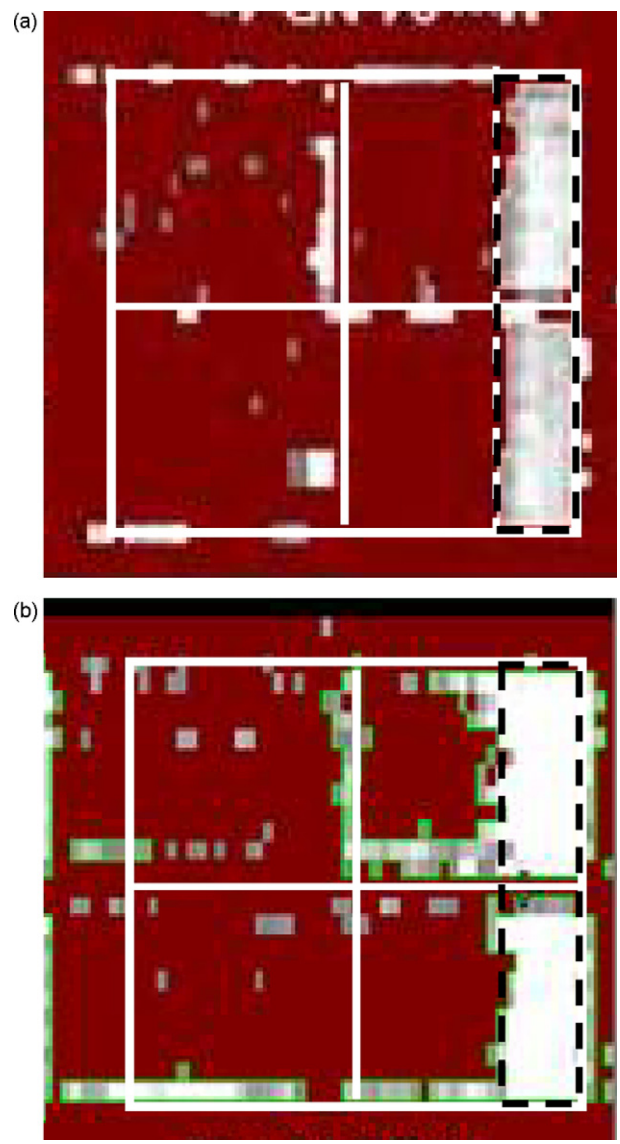

Fig. 8. US C-scan of a W flat tile W/Cu joint C-scan (a) before and (b) after HHF test. Solid lines indicate the four tiles, dashed lines mark the postulated defect area. Horizontal axis corresponds to the monoblock width and vertical axis to monoblock height. Grey and white pixels represent points of monoblock with amplitudes above the analysis threshold; to the right of the image is the defect, scattered pixels are spurious indications. Defect size after the HHF is slightly larger than before the HHF.

(see Fig. 6). Stop-off defects are defects implemented by preventing the wetting of CFC surface by local lack of pre-brazed casting alloy and by a stop-off coating for defects at W/Cu and Cu/CuCrZr interfaces [4].

The US inspection after the HHF test resulted much more complicated; it can be explained by the two reasons mentioned in the paragraph above, by the damage eventually originated in the material, and by micro structural changes and anisotropy originated in the copper and copper alloy layers that produce: (1) increment of US attenuation and scattering and (2) US false calls. In all cases, the inspection gain was increased 6 dB to have a reliable signal to noise ratio to allow the data analysis. In the Cu/CuCrZr joint, all defects have been detected, located and their sizes measured; 60% of the defects have incremented their sizes (see Fig. 7b) and the rest have not changed the sizes. In the CFC/Cu joint, 60% of the defects were detected with low reliability in most of the cases; this result can be explained by the reasons given above. As in the other joint, more than 60% of defects have incremented their size.

3.3. W flat tile samples

Two sets of 14 samples each, fabricated by two manufacturers, have been inspected. Half of the samples have defects in the W/Cu joint and the other half in the Cu/CuCrZr joint. The good signal to noise ratio and the high resolution of probe movements allowed obtaining detailed C-images. In both joints, W/Cu and Cu/CuCrZr, all the defects have been detected, located and measured their sizes. These measurements are in accordance with the specified defect sizes (see Fig. 8a).

The US inspection after the HHF test manifested micro structural changes in the copper and copper alloy layers producing an US attenuation increment; this required to decrease the amplitude threshold for data analysis. In the W/Cu joint, all the defects were detected and the defect size measurements showed the defect sizes are slightly larger than before HHF (see Fig. 8b). In the Cu/CuCrZr joint, it was necessary to reduce the amplitude threshold as much as possible (due to the increment of US attenuation) for data analysis. In most of the cases, due to the HHF test, the tiles were damaged and it was not possible to examine them.

4. Conclusions

Ultrasonic techniques for the inspection of divertor components have been developed. Three types of divertor component configurations (W monoblocks, CFC monoblocks, and W flat tile) have been studied. Three sets of samples, each one corresponding to one configuration, containing calibrated defects manufactured by two different industries have been ultrasonically examined, HHF tested, and ultrasonically examined again.

For W monoblocks, the ultrasonic techniques were able to reliably detect, locate and size calibrated defects in the W/Cu and Cu/CuCrZr joints before and after the HHF test.

For CFC monoblocks, with machined defects, the ultrasonic techniques were able to detect, locate and size calibrated defects in the Cu/CuCrZr and CFC/Cu joints before the HHF; the detection of defects in the CFC/Cu joint after the HHF test was not possible to do it reliably. For the samples with stop-off defects, the ultrasonic techniques were able to detect, locate and size the calibrated defects in the Cu/CuCrZr joint before and after the HHF test; however, the detection of defects in the CFC/Cu joint in all cases in a reliable manner was not possible.

For W flat tiles, the ultrasonic techniques were able to reliably detect and size the calibrated defects in the W/Cu and Cu/CuCrZr joints before the HHF test. After the HHF test the Cu and Cu alloy layers experienced micro structural changes and several tiles were damaged which made very difficult the inspection of these samples.

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