Non Destructive Testing along the Manufacture of High Heat Flux Components for the Nuclear Fusion Experiment Wendelstein 7-X

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Summary

The performance conditions of nuclear fusion experiments define extreme requirements for different features of plasma facing components. These requirements are met in case of the project Wendelstein 7-X by actively cooled components armed with flat tiles made of CFC on the plasma facing surface. Most important features of such components are heat transfer capabilities, thermal shock resistance and leak tightness. To guarantee the performance of the components considerable efforts are taken in the field of non destructive testing. The variety of methods reaches from established non destructive testing methods like ultrasonic testing, X-ray inspection or leak testing to recent developments like thermography inspection applied as transient or lock method. The different methods are applied not only for the finished components but also in various production steps in order to withdraw the non-conforming components as soon as possible from production. Specific inspection techniques can only be applied for simple geometries which is another reason for inspection during early production steps.

Keywords

Non destructive testing, first wall components, Wendelstein W7-X

1. Introduction

Since the mid 80ies PLANSEE is involved in the development, design, manufacture and non-destructive testing of plasma facing components for nuclear fusion experiments. These plasma facing components are typically actively cooled by pressurized water and are designed to absorb out of the plasma heat fluxes beyond 10MW/m². A first series-like production of such elements has been successfully completed for the French Tokamak Tore Supra, which is located at Cadrache. In the frame of this manufacture different non-destructive testing methods have been applied in order to monitor the demanding values of the specification.

In 2003 PLANSEE has been awarded by the Max-Planck-Institute for Plasma Physics to supply the target elements for the Divertor of Stellerator Wendelstein 7-X, which is under construction at Greifswald. These elements comprise a plasma facing armour made of the 3D-CFC grade SNECMA SEPCARBNB31, which is joined by the so called Active Metal Casting (AMC) process onto a soft OF-Cu compliant layer, see Figure 1. Such a way obtained tiles, which are the heart of the components, are then joined onto a CuCrZr heat sink by either electron beam welding or Hot Isostatic Pressing. After this joining one section of the cooling system is machined into the heat sink. The second section is machined into a cover plate, which is assembled with the heat sink and joined by electron beam welding. The final sub-component to be joined are electron beam welded composite tubes made of CuCrZr/Ni/316L. The different non-destructive testing methods applied during this manufacture as well as the final tests to check the performance of the component at PLANSEE shall be described hereinafter. A sketch illustrating the diversity of material joints in the component which are focused by different inspection techniques is shown in Figure 2.

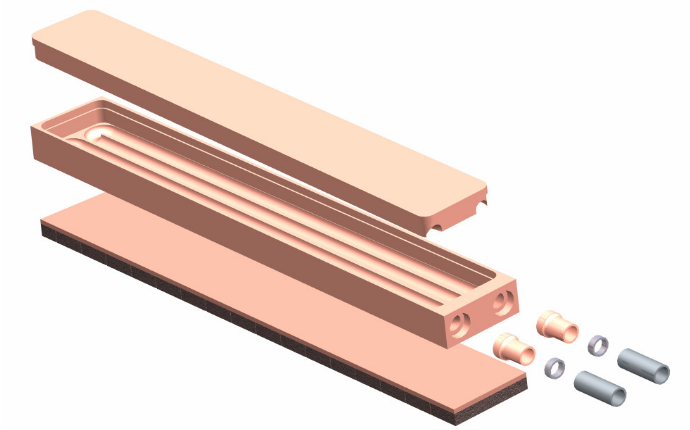

Figure 1: Exploded view of a typical design of a plasma facing component.

2. Description of the applied NDT methods

2.1 The inspection concept

The variety of material joints realized by different bonding techniques requires a complex NDT concept which is visualized in Figure 2. For many joints NDT is already performed along the manufacture of the component. This is necessary since some of the joints are no more accessible for inspection on the finished component. Additionally possible repair processes on the finished component are avoided.

2.2 Radiographic testing (RT)

The radiographic examination is applied for the inspection of the AMC interlayer joint to the CFC tiles and shall give evidence on the infiltration of the AMC copper into the CFC. For that reason the AMC-CFC tiles are placed on a film followed by the radiographic examination of a flat component in accordance to the relevant standard [1].

2.3 Ultrasonic inspection (UT)

The ultrasonic inspection is applied for several material joints of the component and is performed in immersion technique. Test bodies with different artificial defects are used for adjustment. A special procedure has been developed for the inspection of the electron beam weldment of the OFHC compliant layer and the heat sink. Attention must be paid to the extreme local differences of the extinction of sound waves in CuCrZr which leads to differences in the amplitude of the back reflection up to 16 dB. These variations must be taken into account for the reproduction of the defect size from the back reflection amplitude. Therefore the inspection is done in two steps. As a first step the local sound wave extinction of the CuCrZr prematerial is recorded by the ultrasonic scanning equipment. After welding the OFHC with the CFC tiles attached onto the CuCrZr heat sink a second scan is performed. From these two C-scan images the attenuation of the ultrasonic wave caused by defect scattering is computed.

2.4 Leak testing (LT)

Helium leak testing is carried out during the manufacture to detect and locate possible defects for a timely corrective action thus reducing the risk of an unsuccessful final

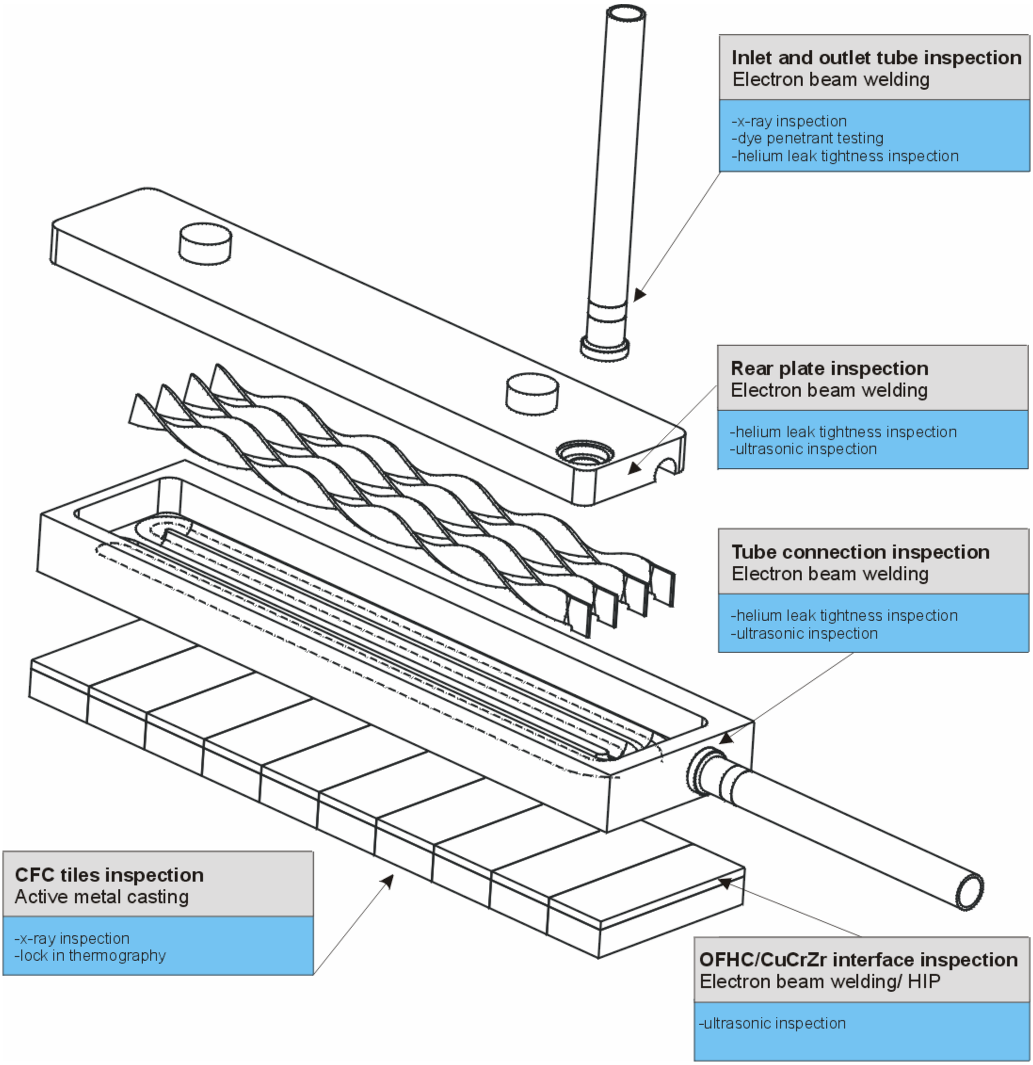

Figure 2: Overview of the material joints of the first wall component focused by the NDT concept.

acceptance test. The technique is applied in accordance with the relevant standard [2]. Additionally LT is performed on the whole component before delivery. In this case the test is performed in a cyclic way with respect to the test temperature and pressure in the cooling system of the component. The consecutive order of the test steps is listed in Table 1. The cyclic procedure simulates the operating conditions of the component and is performed as a load test for final acceptance.

Phases	**Acceptance Criteria**
1. Preparation Cleaning of the chamber and of the component. Proof of the sensitivity of the leak detector.	min. detectable leak < 10^{-9} mbarl/s
2. Control of the vacuum chamber Pump out of the chamber. Control of the He leak tightness of the chamber at RT. Baking of the chamber at 160℃. Control of the He leak tightness of the chamber at 160℃.	vacuum chamber < 10^{-3} mbar
3. leak tightness at RT Installation of the component into the vacuum chamber. Pump out of the chamber. Control of the Helium leak tightness at RT.	vacuum chamber < 10^{-3} mbar maximum leak rate: Target Element: $5x10^{-9}$ mbarl/s
4. Leak tightness at RT and under pressure Pressurization of components water circuit. p=38 bar at RT for 30min. Control of the He leak tightness at RT. Depressurisation of the water cooling circuit.	vacuum chamber < 10^{-3} mbar maximum leak rate: Target Element: $5x10^{-9}$ mbarl/s
5. Leak tightness at 160℃ Baking of the chamber and the component up to 160℃ with atmospheric pressure in the water circuit. Check that the whole component has reached 160℃. Control of the He leak tightness at 160℃.	vacuum chamber < 5 x 10^{-3} mbar maximum leak rate: Target Element: $5x10^{-8}$ mbarl/s
6. Leak test at 160℃ and under pressure Pressurization of components water circuit. Loading to p=25 bar at 160℃ for 30min. Control of the He leak tightness at 160℃ and 25bar. Depressurisation of the water circuit and cooling of the chamber to RT.	vacuum chamber < 5 x 10^{-3} mbar stable temperature: 160℃ maximum leak rate: Target Element: $5x10^{-8}$ mbarl/s Target Module: $5x10^{-8}$ mbarl/s
7. Repetition of phase 4, then 5, then 6 for two times.	

Table 1: Course of the cyclically performed hot helium leak test.

2.5 Dye penetrant testing (PT)

Liquid penetration examination is only applied if it does not degrade or introduce impurities in the examined surface. It is performed according to the relevant standard [3, 4].

2.6 Pressure drop testing (ΔP)

Each target element is mounted in the pressure drop test equipment. The cooling system of the element is flooded with water at a velocity of 10m/s and a static pressure of 16 bar. A pressure probe measures and records the difference between inlet and outlet pressure.

2.7 Transient thermography testing (IT-TR)

The approach to generate a temperature gradient in plasma facing components which has proven to enable reliable non destructive evaluation of the bonding of CFC tile on the heat sink is transient thermography [5]. Hot water is introduced into the cooling channels of the elements. The most important features of the method are the range of the temperature step (from $20^{\pm 2}$ to $240^{\pm 2}$ °C) and the water pressure (steam at $35^{\pm 2}$ bar). To enable the comparison of the test results for different elements, a reference element of the same geometry is tested simultaneously with any component to be tested. For each tile, the maximum temperature difference between the tested tile and the corresponding reference tile occurring during the test is evaluated to grade heat transfer capability of the tile under inspection.

2.8 Lock in thermography testing (IT-LI)

For the application of IT-LI a periodic heat flux is generated inside the component under inspection. For the present application six halogen lamps, each bearing a maximum power of 1000 W, are used. The generated heat wave penetrates into the parts under inspection and is disturbed by flaws in the material. One consequence of this disturbance is the change of the phase shift between the heat source and the temperature evolution at the surface which is recorded by an infrared camera [6]. The comparison of the results obtained at different operation frequencies and wave forms showed that a frequency of 0,6 Hz applied in a rectangular wave form enables the best results for the inspection of the bonding of tiles having a thickness of approximately 10 mm. The results with respect to the flaw detection capabilities of the IR-TR and IR-

LI method are comparable [7]. The main advantage of the application of the IT-LI method is that the cooling system is not needed and therefore the test for not properly connected CFC tiles can be performed at any production state of the component. For each tile the maximum phase shift with respect to a reference component and the span of phase values in the lock in image of the tile are analyzed.

3. Inspection results for the different material joints

3.1 Inlet and outlet tubes of the elements

The tube consists of the three different materials CuCrZr, Ni and stainless steel (316L). The first is connected to the CuCrZr component. The two connections between these materials are realized by electron beam welding. The inspection of the connections is done by the application of three different NDT methods. For the detection of surface breaking defects the PT technique is applied. A macroscopic image of a defect detected during this inspection is shown in Figure 3. Defects in the volume are detected by the RT test. The X ray image of a component containing small pores in the interface area is shown in Figure 4.

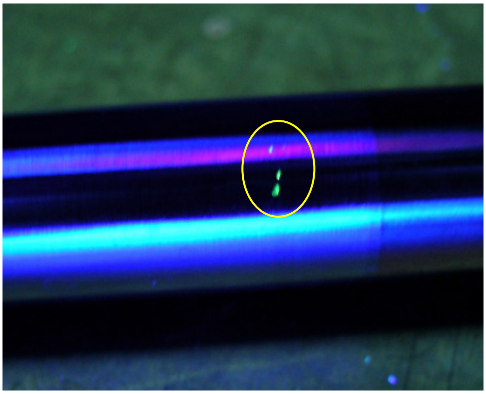

Figure 3: Picture of a PT defect indication detecten on an electron beam welded connection tube.

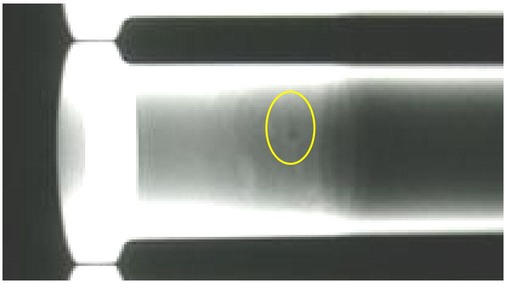

Figure 4: X ray image of an electron beam welded connection tube containing a defect indication.

Finally the performance control for the tightness of the connection tube is done by LT. The leak rate is specified to be less than 5.10^{-9} mbar.l.s^{-1}. The preliminary performed surface and volume inspection ensures that the tube contains no defect which could grow during operation until the leak tightness is lost.

3.2 Active Metal Casting (AMC)

One of the most challenging production steps is the connection of the CFC tiles to metal component. Therefore much attention is paid to NDT of the interface area. The inspection is done immediately after the AMC process. The possibility remains that tiles with unacceptable AMC layer quality can be removed from production before the connection to the heat sink is established. The inspection for voluminous defects, like pores in the copper layer or poor infiltration of the structured CFC surface during the AMC process, is covered by RT. For demonstrating the spatial defect resolution of the method the drawing of the test body designed for this test problem and the corresponding radiographic image is shown are shown in Figure 5 and Figure 6.

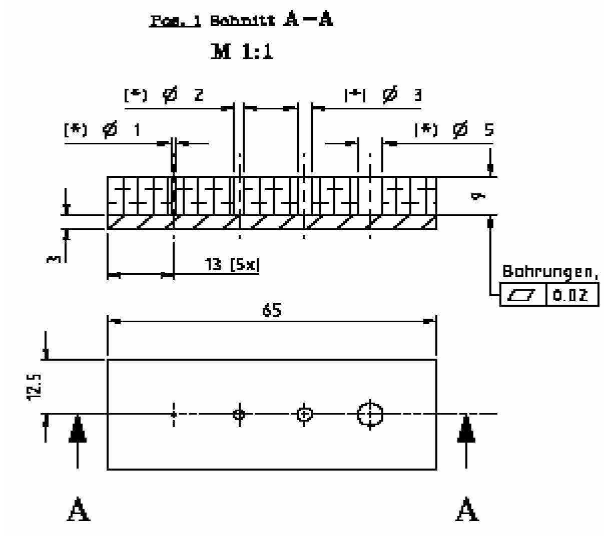

Figure 5: Drawing of a test body containing artificial defects.

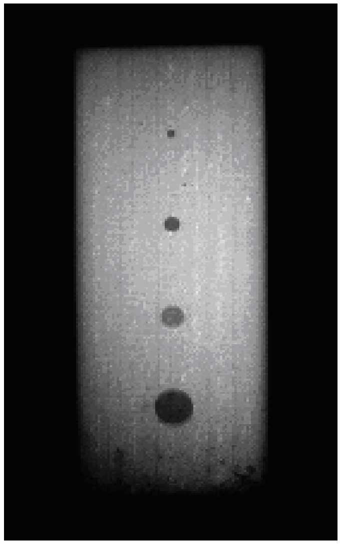

Figure 6: X ray image of the test body in Figure 5.

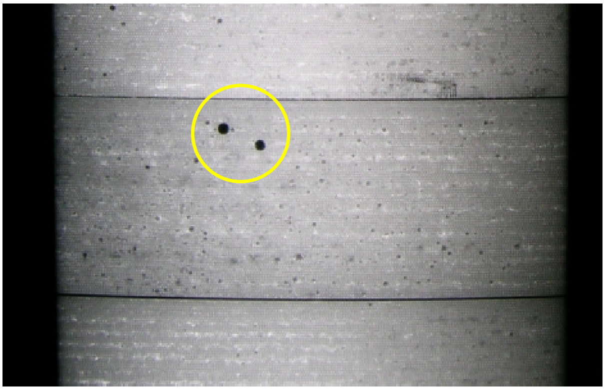

Figure 7: Detection of pores in the copper layer attached to the CFC by RT method.

An example for a defect which is reliably detectable due to the proof of defect resolution is shown in Figure 7. The demand for the inspection of the CFC copper interface for non voluminous defects like cracks is not met by established methods for two dimensional flaws, like UT. The limitations are mainly the porosity, the fiber structure of the CFC and the resulting damping properties of this material. The demand for inspection is met by the application of lock in thermography (IT-LI). This method can be applied at any production state during the manufacture of a heat exchanger component. The sketch of the interface plane of a test body containing artificial defects and the corresponding IT-LI image are shown in Figure 8 and Figure 9.

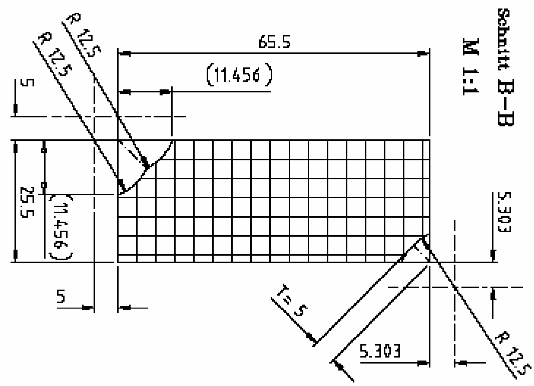

Figure 8: Drawing of a test body containing artificial defects.

Figure 9: IT-LI image of the test body in Figure 8.

The size of the two artificial corner defects in the test body is 6 and 11 mm. The smaller one represents the detection limit of the IT-LI method for this sample geometry since some noisy pixel reach comparable phase shift values.

3.3 Interface between the heat sink and the AMC tile

The inspection of this interface is tested after the connection of the AMC tiles onto the heat sink. For the inspection of the connection realized by electron beam welding or a HIP process the UT method is applied. At this production step the cooling structure of the component which would prevent the UT inspection is not implemented. A test body for the proof of the defect resolution of the method and the corresponding UT documentation are shown in Figure 10 and Figure 11.

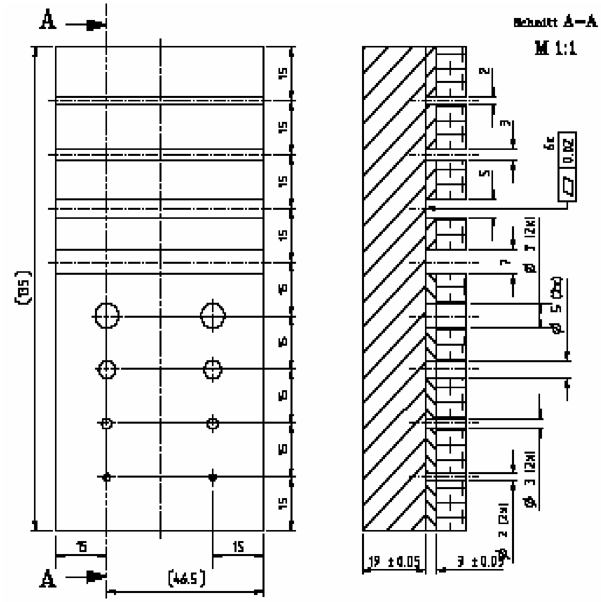

Figure 10: Drawing of a test body containing artificial defects.

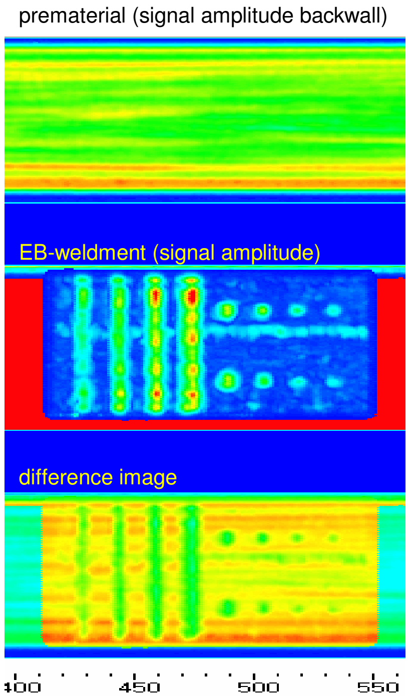

Figure 11: UT result of the test body in Figure 10.

The benefit of the signal treatment is the uniformity of the corrected signal amplitude for all artificial defects inserted in the test body, see difference image in Figure 11.

3.4 Rear plate weldment

The geometric arrangement enables the application of standard UT to solve this test problem. The test is done in immersion technique. The signal analysis concentrates on defect echoes reflected by the interface area.

3.5 Tube connection

The application on an angle beam probe inserted into the tubes enables UT inspection of the electron beam weldment joining the tubes to the component. A full turn of the probe around its axis is necessary to test the whole welding, see Figure 12.

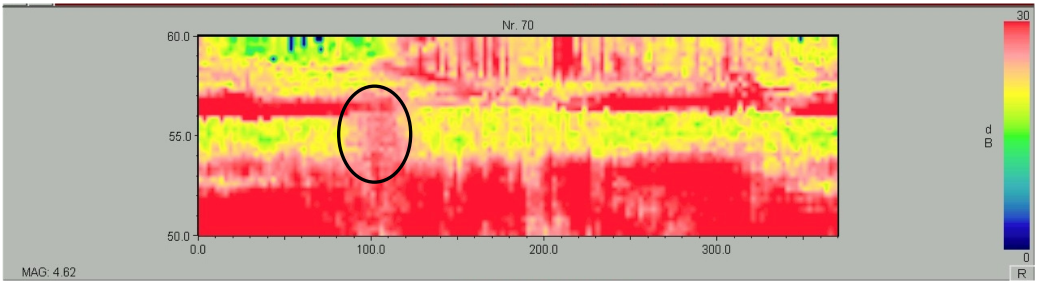

Figure 12: Documentation of the UT inspection of the joining of the tube to the component. The horizontal axis scales the angle of inspection, the vertical axis the depth range.

The horizontal yellow line in the middle of the image displays the echo amplitude of the electron beam weldment under inspection. The defect detected in the welding causes an increase in the signal amplitude, see circle in Figure 12. A functional control of the joint is done by LT which is additionally performed after joining to prevent repair operations on the finished component.

3.6 Final inspection of the finished component

An important feature for the performance of the component during operation is the pressure drop in the cooling system. For checking this requirement a test setup has been installed at PLANSEE. The test procedure includes a load test up to the nominal pressure of 38 bar. Concerning the criterion for this load test the nominal pressure must be constant inside the cooling system for 10 minutes. The specified maximum pressure drop value for flowing medium depends on the design of the target element under inspection. Values above this specified values of 4,7 to 11 bar indicate a blockade in the cooling system. Tapering in the cooling system could occur due to inappropriate adjustment of the swirl tape or to the presence of chips in the cooling system.

A further check of the finished component is LT which is performed cyclically, see Table 1. The leak rate is specified to be smaller than 5.10^{-9} mbar.l.s^{-1}at room temperature.

The IT-LI method is also applied to the finished component. The purpose is to check the integrity of the CFC tiles and their connection to the heat sink after the mechanical finishing of the component. Due to the defined penetration the method has only limited access to the AMC / component interface. The drawing of interface plane of a test body containing two artificial defects of different size is shown in Figure 13. The IT-LI image of this area indicates the defect resolution for edge defects, see Figure 14. The defect in the middle reaching 4 mm into the sample is clearly visible. The limit for reliable defect detection is 2 mm.

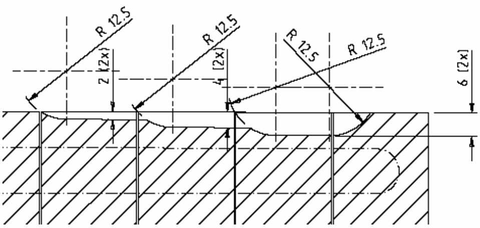

Figure 13: Scetch of the test defects inserted in a finished component.

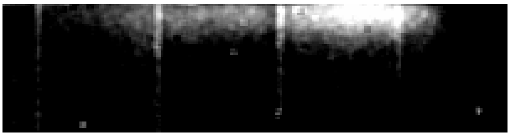

Figure 14: IT-LI image of the area of the test body in Figure 13.

UT which has been applied immediately after the connection of the AMC tiles to the heat sink cannot be applied in the finished state since the interface is no more accessible due to the cooling structure.

Finally, two performance tests are carried out not for each component but for randomly chosen samples. The heat transfer capability of the finished component is tested applying the IT-TR method. Before the installation into the divertor of W7-X the high heat flux test is performed at the customer's facilities (IPP Garching). The component must withstand 100 cycles to a heat flux of 10 MW/m^2 realized by an electron beam.

4. Summary

Tremendous effort is taken to guarantee the performance features of first wall components of nuclear fusion experiments. The wide range of NDT methods applied for this purpose reaches from established methods like dye penetrant testing or radiographic inspection to recent developments or special experimental setup like the cyclic Helium leak test or thermography methods. A similar concept for the inspection of such components has been applied during the manufacture of the components for the TORE SUPRA experiment [8-10]. The inspection concept has been confirmed as the manufactured and tested components work in the experiment without evidence of malfunction or degradation.

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