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Potential approach of IR-analysis for high heat flux quality assessment of divertor tungsten monoblock components

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HIGHLIGHTS

- HHF performed tests with 100 cycles at 10 MW/m^2 on 13 components or mock-ups manufactured for ITER, for the DEMO divertor development and for the WEST project.
- The IR analysis of the local temperature evolution of W blocks during the first 100 cycles at 10 MW/m^2 was statistically assessed.
- Development of a correction algorithm of the large variability of the W emissivity in the middle- and of long-wavelength IR.
- Approach of IR-analysis for HHF quality assessment of divertor tungsten monoblock components.
- Discussion of a statistics based method for the application to the high heat flux testing of a large number of industrially manufactured W monoblock plasma-facing components.

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ABSTRACT

The paper discusses a potential approach of infrared (IR)-analysis for high heat flux quality assessment of divertor tungsten monoblock components. The aim of these activities is the development of a statistics based method for the general application to the high heat flux testing of industrially manufactured W monoblock plasma-facing components. We have performed tests with 100 cycles at 10 MW/m^2 on 13 components or mock-ups manufactured for ITER, for the DEMO divertor development and for the WEST project. For eight W monoblock components with grinded surfaces, the statistical high heat flux (HHF) quality assessment method originally developed for the series manufacturing of carbon fibre reinforced carbon flat tile divertor components for Wendelstein 7-X was applied.

The large variability of the emissivity of W as well as the monoblock geometry require a careful emissivity correction of IR camera data. The emissivity is strongly dependent on the W surface quality and final machining and influences the apparent temperature measured by an IR camera. Therefore we have applied a pragmatic correction algorithm based on two-colour pyrometry.

Finally we propose a possible HHF testing strategy of a large number of industrially manufactured W monoblock components.

1. Introduction

The industrial fabrication of divertor components for future fusion devices requires the manufacturing of plasma-facing components (PFCs) equipped with several ten- to hundred thousands of W monoblocks (the inner and outer vertical target of ITER will be equipped with about 300,000 W monoblocks for example). The presently preferred design of the highly heat loaded divertor PFCs in ITER, WEST and a water-cooled DEMO consists of Copper-Chromium-Zirconium (CuCrZr) tubes inserted into and bonded to individual W monoblocks with dimensions of about $23 \times 28 \times 12\,mm^3$ [1–3].

Currently, the applicability of the world-wide developed manufacturing technologies of W monoblock PFCs has been confirmed

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by intensive high heat flux (HHF) testing, 5000 cycles at 10 MW/m^2 and 1000 cycles at 20 MW/m^2 e.g. mock-ups of ITER divertor PFCs from various manufacturers [4].

The challenge for establishing an industrial fabrication is the successful technology transfer from the mock-up and prototype manufacturing to the series production of PFCs to achieve the same high thermal performance as achieved for the mock-ups and prototypes.

The thermal performance and lifetime of the PFCs mainly rely on the quality of the W monoblock-heat sink bonding. Only HHF loading can generate thermo-mechanical stress in the component similar to the expected operating conditions in a fusion device. From this point of view, the assessment of the industrially fabricated components requires HHF tests complementary to the non-destructive examination and quality assessment employed at the manufacturer. Other non-destructive examinations like ultrasonic-, x-ray inspection or thermography methods employed at the manufacturer as quality assurance do not consider this complex thermo-mechanical behaviour during heat loading. Therefore, non-destructive HHF tests of delivered components are indispensable to assess the quality and predict the expected thermal performance. A statistical assessment of a subset of the delivery would minimize the risk of the installation of undetected defect components with reasonable HHF testing effort.

In this study we investigate the applicability of an approach of infrared (IR) analysis originally developed for the HHF testing quality assessment of the industrially manufactured divertor components for Wendelstein 7-X (W7-X). These highly heat loaded PFCs are equipped with carbon fibre reinforced carbon (CFC) tiles as plasma-facing material. In particular, we discuss a procedure to establish reliable surface temperature data from IR measurements on W surfaces.

2. Statistical quality assessment approach of W7-X high heat flux components

The series manufacturing of the W7-X divertor targets for long pulse operation was finally completed in 2014 [5]. The actively water-cooled divertor targets are made of CFC NB31 tiles bonded by bi-layer technology (based on Active Metal Casting®) and electron beam welding onto a CuCrZr structure [6]. Finally, 890 components covered with 14,300 CFC standard flat tiles of typical dimensions $55 \times 25 \times 8$ mm^3 will be installed in W7-X.

2.1. Method of IR analysis of CFC tiles

This section gives a short introduction to the applied IR analysis. The detection of growing CFC/CuCrZr interface defects is based on IR analysis of the surface temperature evolution during thermal cycling at 10 MW/m^2. The analysis of the steady-state temperature distribution for each tile and each cycle allows the detection of growing hot spots due to bonding defects. Taking the pixel wise temperature difference of consecutive IR images eliminates stable surface inhomogeneities induced by the local variation of the material properties, in particular emissivity, thermal conductivity and density of the CFC. Furthermore, the analysis of the temperature evolution of the two outer tile edges compared to the tile centre eliminates slight fluctuations of the loading or cooling conditions. The assessment criterion ΔT_N describes the development of the difference between regions of interest (ROIs) at the tile centre and the outer edges during N = 100 cycles.

$$\Delta T_N = (T_{edge} - T_{centre})_N - (T_{edge} - T_{centre})_1$$

A more detailed description of the algorithm and the image processing is published in the literature [7]. The histogram of ΔT_{100} of all tested CFC tiles generates the input for the statistical analysis.

2.2. Statistical approach as quality assessment

The release of the industrial production was based on the achieved HHF performance of the last pre-series components and the development of a statistical method to describe this quality. Initially, before further HHF tests, 100 cycles of 10 s loading at 10 MW/m^2 on each CFC tiles of all 19 pre-series components were applied. The aim of these tests of components as delivered was to assess the manufacturing quality of the individual CFC tile bonding on the basis of local surface temperature evolution ΔT_N between heat cycle N = 1 and N = 100. The Gaussian of ΔT_N characterizes the achieved manufacturing quality. The initial result confirmed the selected manufacturing technologies and indicated potential high thermo-mechanical performance. Subsequently heat loading tests were extended up to 10,000 cycles of 10 MW/m^2 and additional tests were performed at heat loads considerably exceeding the nominal heat load of 10 MW/m^2 [8,9].

Therefore we can assume for the assessment of the series production; If the ΔT_N distribution results in the same Gaussian for the series components, then the thermal performance remains the same as for the pre-series components.

Once the variance of the Gaussian distribution for the series elements is established and acceptable, the quality of the delivered elements would then be judged based on the mean and the standard deviation of the ΔT_{100}–distribution. It is not necessary to test all of the elements to determine these parameters as this could be done statistically. The number of elements to be tested can be determined on the basis of a χ^2-test as a function of an acceptable broadening of the Gaussian distribution taking into account a possible quality degradation during long-term manufacturing, the number of delivery batches, design variants or other criteria as described in the references [10]. Therefore, the HHF test of a subset of the series production is sufficient to assess the manufacturing quality of delivered components.

Finally, 8% of the total delivery was HHF tested and assessed (including 20 components of the first batch to establish the reference Gaussian for the series manufacturing). The resulting mean of $\Delta T_{100} = 8.3 \pm 0.2$ K and the standard deviation $\Delta = 10.5 \pm 0.5$ K of the 900 tested CFC tiles confirms the high quality of the delivered elements. According to the W7-X specification limit of $\Delta T_{100} = 75$ K the expected number of undetected defect tiles $< 5 \times 10^{-6}$ is negligible. Reference [11] describes in more detail the definition of the W7-X specification limits.

3. HHF assessment of tungsten monoblock components

3.1. High heat flux tests

The methodology of the statistical assessment of components covered with CFC flat tiles could be carried over to the testing of other industrially manufactured PFCs. Therefore we have performed HHF tests of 13 W monoblock components as delivered in the HHF test facility GLADIS [12] before further HHF evaluation. These components were manufactured in China, Europe and Japan in the framework of prototype development for ITER and DEMO. Fig. 1 shows two typical W monoblock mock-ups for ITER. Two divertor PFCs manufactured in China for the WEST project [13], each equipped with 35 W monoblocks, were tested before installation in the tokamak WEST. Different bonding techniques (hot isostatic pressing, hot radial pressing, brazing or combined techniques) between cooling tube and W monoblocks were applied

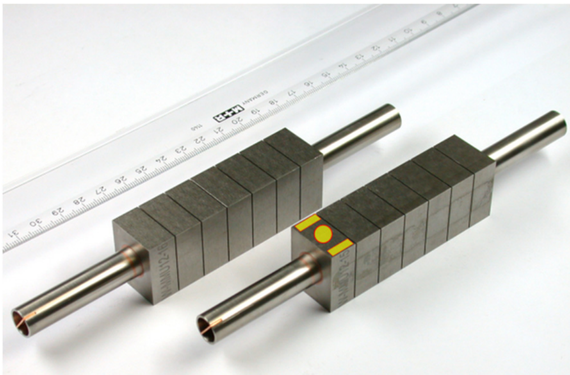

Fig. 1. Examples of ITER W monoblock mock-ups HHF tested in GLADIS. Seven monoblocks of $23 \times 28 \times 12\,mm^3$ are bonded onto a cooling tube made of CuCrZr. For one W monoblock, the ROIs for the IR analysis are marked in yellow.

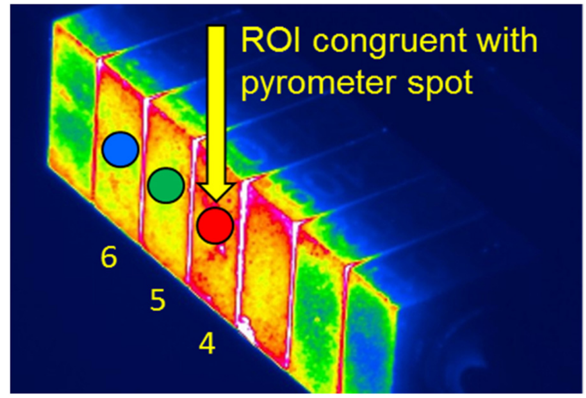

Fig. 2. Principle arrangement of the analysed ROIs. The used numbering of monoblocks starts on the outer right monoblock.

depending on the manufacturer. Irrespective of the used interface materials we always refer to W/CuCrZr in the following. Grinding after electro discharge machining (EDM) was applied for eight of these components as final surface machining.

HHF loading with 100 cycles at 10 MW/m^2, 10 s loading following by 50 s cooling down, on each W monoblock was performed. The comparison between the calorimetrically measured absorbed power and the calculated incident power is in an agreement within ±5% according to the comparison method described in [14]. The applied cooling conditions (11 m/s water velocity, 15 °C inlet temperature and 1 MPa static pressure) ensure the safe heat transfer in the regime of sub-cooled boiling.

For the surface temperature measurements an IR camera Infratec VARIOCAM HD ($\lambda \sim 10\,\mu m$) and a two-colour pyrometer ($\lambda \sim 1.6\,\mu m$, temperature range 500–1700 °C) [15] were used. One IR image was taken in the stationary phase of each HHF cycle. The Ø 8 mm pyrometer spot was placed on the central monoblock of the component at the respective test position.

3.2. Challenges of monoblock geometry

In contrast to the flat tile design where the local surface temperature increase directly corresponds to the size of debonding of the plasma-facing material, the monoblock geometry causes no well-defined surface temperature response due to debonding. The geometry results in three free parameters for the size and location of a debonded area: the angle θ, the radial extension $\Delta\theta$ and the axial extension as described in reference [16]. The typical surface temperature during 10 MW/m^2 loading is about 900–1000 °C. To detect bonding defects of $\Delta\theta = 30°$ at this temperature the reliable measurement of the individual temperature evolution $\Delta T = 20$–$100\,K$ is necessary, as FEM calculations have shown.

3.3. Emissivity correction of IR data

The main challenge of a reliable IR measurement is the high variability of the emissivity ε. The emissivity can be very different from component to component and also vary with pulse number. It depends strongly on the machining quality and in the range of long-wavelength IR also on the surface temperature itself. For the latter see e. g. reference [17]. The application of a fixed uniform ε value from literature, e.g. in [18], is not possible. Therefore we devised a temperature correction method to extract useful temperature values from the IR raw data.

In the case of monoblocks produced by electro discharge machining (EDM) there is a significant evolution of the emissivity with pulse number which results in an apparent decrease of the surface temperature during cycling in GLADIS. In the case of W oxides this cleaning effect can occur due to reduction as well as evaporation of the oxides. Removal of the chemical elements carbon, oxygen, copper and lead by the application of 100 HHF cycles was confirmed by energy dispersive x-ray analysis. The EDM process should be improved to achieve lower surface roughness and impurity contamination. For this reason data from EDM machined samples were not employed for our further analysis. However they can serve as an extreme example for the correction method of the apparent IR temperatures, which we want to describe in the following:

1. For each component we assume the same emissivity for all W monoblocks of the component. This can be justified by the fact that all monoblocks of one component have been prepared using the same surface machining process.
2. The surface temperature is measured at the centre position of the central monoblock using a two-colour pyrometer. In parallel the IR camera takes a frame of the surface temperature distribution.
3. Using the Planck formula we can determine an IR emissivity value such that the two temperatures become equal on the measurement location of the pyrometer (central spot in Fig. 2).
4. We correct the IR temperature values for all other ROIs with the same ε value.
5. The correction of jitter due to random or irregular variations of IR data, e.g. slight displacement of the mock-up during heat loading is performed according to the reference [7].
6. Determination of two ΔT_N values on each tested monoblock as input for the statistical assessment.

Figs. 2 and 3 illustrate the applied method of emissivity correction. As an example we show the surface temperature evolution of an EDM machined mock-up with very strong variation of the IR raw data. The pyrometrically measured temperatures are significantly less affected by the above mentioned surface cleaning process.

As mentioned above the temperatures measured on surfaces prepared by EDM are strongly affected by the described cleaning effect. Here the raw temperature variation can generate differences of 100–200 °C after 100 cycles at 10 MW/m^2. For the grinded surfaces we measured a smaller variation of the IR raw data during thermal cycling in the range between 10 and 50 K typically. Depending on the surface machining process we obtained $\varepsilon = 0.10$–0.48 as initial values for the IR raw data.

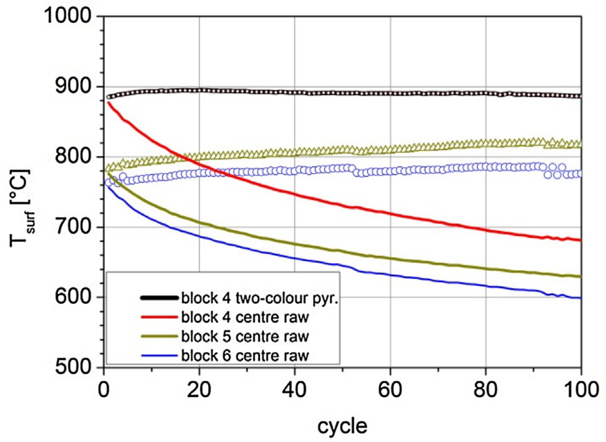

Fig. 3. A pronounced example of surface temperature variation with pulse number on an EDM machined component (see text). The solid lines represent IR raw data. For the IR raw data a constant $\varepsilon = 0.36$ was applied. The open symbols represent the same dataset after correction with the procedure described in the text. Therefore the data of the two-colour pyrometer and the corrected IR data of monoblock 4 centre are congruent. The different block temperatures correspond to the heat flux profile of the beam.

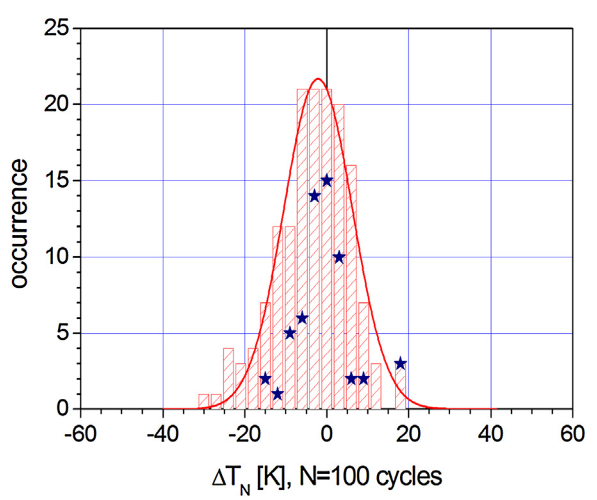

Fig. 4. Histogram of ΔT_{100} for all tested W monoblocks.

4. Application of ΔT analysis and statistical assessment to W monoblock components

As already written, we performed the statistical analysis of ΔT_{100} of components manufactured with grinding as final surface treatment. We assessed all these data together independent of the specific manufacturing methods or slightly different geometries of the W monoblocks. The resulting histogram of ΔT_{100} of 156 data of 78 monoblocks is shown in Fig. 4. It is well described by a Gaussian with -2.1 ± 0.25 K mean and 8.2 ± 0.5 K standard deviation. The highest measured temperature increases are far from the preliminary specifications limits of ITER published in reference [16].

The Gaussian distribution deduced from the set of components indicates a manufacturing process without significant outliers independent of the specifically applied W/CuCrZr bonding technique. The manufacturing quality was confirmed by the results of later tests up to 5000 cycles at 10 MW/m^2 and 300 cycles at 20 MW/m^2 (performed by ITER in the electron beam facility Russian IDTF [19]) and complementary tests in GLADIS up to 500 cycles at 20 MW/m^2. The ΔT_{100} of these further tested samples are marked in Fig. 4 as blue asterisks. The main variable of the scatter of ΔT_{100} data is a variation of the central temperature. The slightly shifted mean to negative could be explained by the fact that the stress concentration in the W/CuCrZr bond during loading preferentially occurred in the monoblock centre. This result indicates that the thermal expansion in the W/CuCrZr interface at 10 MW/m^2 loading is not fully reversible. The fluctuation of operation and diagnostic parameters of $\pm$ 5% causes small additional effects.

5. Summary and outlook

The paper discusses a potential approach of IR-analysis for HHF quality assessment of divertor tungsten monoblock components. The aim of these activities is the development of a statistics based method for the application to the HHF testing of industrially manufactured W monoblock PFCs.

For the eight W monoblock components with grinded surfaces, the statistical HHF quality assessment method originally developed for the series manufacturing of CFC flat tile divertor components for W7-X was applied. The high variability of the emissivity of W as well as the monoblock geometry require a careful emissivity correction of IR camera data. The emissivity is strongly dependent on the W surface quality and final machining and influences the apparent temperature measured by an IR camera. Therefore we have applied a pragmatic correction algorithm based on two-colour pyrometry.

The data set of the W monoblock components equipped with 78 monoblocks shows a Gaussian distribution of the ΔT_{100} surface temperature evolution. The test results indicate stable manufacturing of these components. This is confirmed by the results of later tests performed by ITER Organization in the electron beam facility IDTF up to 5000 cycles at 10 MW/m^2, 300 cycles at 20 MW/m^2 and tests up to 500 cycles at 20 MW/m^2 performed in the GLADIS facility.

The proposed 100 cycles at 10 MW/m^2 HHF testing procedure could be suitable as complementary non-destructive examination method of W monoblock components and assessment of the delivered quality.

The further HHF test activities should be focussed on the extension of the data base for the statistical assessment of W monoblock components. It would be desirable to perform the 100 cycle test at 10 MW/m^2 in GLADIS as an initial test of other W monoblock mock-ups or prototypes before further HHF tests in other facilities.

A general HHF testing strategy of a large number of industrially manufactured W monoblock components could be:

- Once the specification limits for an allowed ΔT_{100} at 10 MW/m^2 heat load are defined it is possible to estimate the HHF test effort for the assessment on the basis of a statistical approach.
- To determine the number of components to be tested a possible quality degradation during the long term series production, the number of design variants, number of manufacturer should be taken into account.
- Determination of the probability of undetected defect W monoblocks in the "untested" part of delivery according to the Six-sigma approach as described in the literature, e.g. [20].

Disclaimer

The view and opinion expressed herein do not necessarily reflect those of the European Commission or the ITER Organization, respectively.

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References

[1] M. Merola, et al., Fusion Eng. Des. 89 (2014) 890–895.
[2] A. Grosman, et al., Fusion Eng. Des. 88 (2013) 497–500.
[3] J.H. You, et al., Fusion Eng. Des. 109–111 (2016) 1598–1603.
[4] T. Hirai, et al., J. Nucl. Mater. 463 (2015) 1248–1251.
[5] J. Boscary, et al. Summary of the Production of the Divertor Target Elements of Wendelstein 7-X, this conference.
[6] J. Boscary, et al., Fusion Eng. Des. 84 (2009) 497–500.
[7] H. Greuner, et al., Phys. Scr. T138 (2009) 014063.
[8] H. Greuner, et al., Fusion Eng. Des. 84 (2009) 848–852.
[9] H. Greuner, et al., Fusion Eng. Des. 86 (2011) 1685–1688.
[10] H. Greuner, et al., Fusion Eng. Des. 88 (2013) 581–584.
[11] H. Greuner, et al., J. Nucl. Mater. 386–388 (2009) 772–775.
[12] H. Greuner, et al., J. Nucl. Mater. 367–370 (2007) 1444.
[13] M. Missirlian, et al., Fusion Eng. Des. 89 (2014) 1048–1053.
[14] H. Greuner, et al., Fusion Eng. Des. 82 (2007) 1713–1719.
[15] Dr. Georg Maurer GmbH, Kohlberg, type QKTD 1075.
[16] T. Hirai, et al., Phys. Scr. T159 (2014) 014006.
[17] J.C. de Vos, Physica 20 (1954) 690.
[18] Y.S. Touloukian, D.P. DeWitt, Thermophys. Prop. Matter 7 (1970) 796.
[19] V. Kuznetsov, et al., Fusion Eng. Des. 89 (2014) 955–959.
[20] D.C. Montgomery (Ed.), Introduction to Statistical Quality Control, 3rd edition, John Wiley, New York, 1997.