Role of Infrared Thermography for development of Divertor Plasma facing components

Yashashri Patil1, S.S. Khirwadkar1, M. S. Khan1, S. Pandya1 M. Mehta1, T. Patel1, N. Patel1, P. Mokaria1, P. Patel1
1Institute for Plasma Research, Gandhinagar, Gujarat-382428
ypatil@ipr.res.in

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Abstract.
Infrared Thermography is a nondestructive technique used for quality control of Divertor Plasma facing components (PFCs). Transient Infrared thermography by internal thermal excitation is advanced technique available today to improve quality control of many materials and structures used for heat transfer application. Transient Infrared Thermography allows to characterise the brazed joint between two materials having different thermo-physical properties. Infrared thermography is mainly used to observe the distribution of power and surface temperature monitoring on various fusion reactor components. Divertor is a most crucial heat transfer component of a ITER like fusion reactor. Macro-brush and monoblock are to design options for water cooled ITER Divetor

The Present work is focused on Transient Infrared Thermography of Divertor macro-brush as well as monoblock type of mock-ups fabricated by brazing and high temperature high pressure sinter bonding technique respectively. Tungsten and Graphite Macro-brush types of mock-ups was exposed to absorbed heat flux up to 8.54 MW/m² and 7.22 MW/m² respectively. Transient Infrared Thermography was performed on macro-brush type mock-ups before and after HHF tests. Transient Infrared Thermography results obtained before and after HHF tests and Temperature measured by infrared camera during HHF tests are used to adopted acceptance criteria limit for the small macro-brush type mock-ups. It concluded that Acceptance criteria DtRef= limit (thermal mismatch of tile w. r. t. sound tile) for the Graphite type macro-bush type mock-up is ~3°C while Tungsten macro-brush type mock-up is ~5°C. Paper also covers the Experimental procedure has established for testing small scale monoblock type of mock-ups using IPR In-house Thermography set-up. Finite element analysis was carried out to simulate copper monoblock type tile with defect located at different faces. Experimental results are validated using finite element analysis.

Introduction

Nuclear fusion is one way to harvest the nuclear energy for advance power source. International thermonuclear experimental fusion reactor (ITER) would be demonstrating the scientific and technical feasibility of fusion power [1]. Divertor is an In-vessel component of a fusion reactor designed to remove the heat and particle fluxes escaping from core plasma of reactor. Inner, Outer vertical targets and Dome are the plasma facing components (PFCs) of ITER like divertor. Divertor PFCs are exposed to steady heat loads ~20MW/m² and Off-normal transient heat loads like-wise edge localized modes (ELMs), Disruptions during operation of fusion reactor. Such critical environment Tungsten (W) and Carbon (Graphite/CFC) are selected as Plasma facing material for Divertor PFCs[2].

Plasma facing materials are joined to the CuCrZr alloy heat sink in either macro-brush or monoblock type geometry. Plasma facing material(Tungsten|Carbon) tiles with length~10mm attached to the CuCrZr alloy heat sink block is called as macro-brush type mock-up. Monoblock shaped blocks of the plasma facing material joined with an inner CuCrZr alloy heat sink tube is called as Monoblock type mock-up. Brazing, Electron beam welding and diffusion bonding are suitable joining techniques used for fabrication of Divertor PFCs. During such manufacturing processes blow holes,
delaminations, cracks type of defects are incorporate at joint integrity of PFCs[3]. A defect at joint integrity affects the heat transfers properties of PFCs as well as might be lead to component failure during reactor operation. A high heat flux (HHF) test with desirable heat load followed by Transient infrared Thermography is a suitable way for quality control of Divertor PFCs[4]. Transient infrared thermography gives internal impulse by passing hot and cold water through heat sink tube of test mock-up[5]. During transient phase of the mock-up, surface temperature is recorded by using IR camera. Defects incorporated in joint integrity as well as materials are affect the surface temperature of the test mock-up. During HHF tests the mock-up was exposed to the heat loads up to ~20 MW/m$^2$ using electron beam source[6]. During and After HHF tests defects might be created at joint integrity and plasma facing materials of the test mock-up. Hence before and after HHF tests qualitative analysis of the test mock-ups were done by transient infrared thermography. The purpose of this paper is to establish experimental procedure for testing Macro-brush and Monoblock type test mock-ups using In-house Transient Infrared thermography set-up. Acceptance criteria limit was defined for small scale macrobrush type of mock-ups using $D_{ref\text{max}}$ value and surface temperature observed by IR camera during HHF tests. Experiment procedure was estabilised for testing the monoblock type mock-ups. Image processing was carried to calculate the running contrats for the monoblock type mock-up using MATLAB software. Defect characterization and quantification was done by artificial defects created at three faces of copper monoblock type tile. Finite element analysis (FEA) is used to simulate the artificial defects created in copper monoblock type tile.

Mock-up description

**Macro-brush type mock-up:** Graphite and Tungsten macro brush type mock-ups were developed by high temperature vacuum brazing technique. Tungsten and Graphite square tiles of area 10mmx10mm were machined in 5mm and 10mm thick tiles using electric discharge machine (EDM) cut respectively. Oxygen free high conductive (OFHC) copper was casted on each tile at temperature 1125°C. OFHC copper casted tiles were brazed with CuCrZr alloy heat sink using desirable brazing filler. Figure 1 show the drawing of Tungsten macro-brush type of mock-up [7]. Tiles nomenclature was done for experimental data analysis of each tile as shown in figure1.

![Fig.1 Drawing of Macro-brush type mock-up & Tile numbering system](image)

**Monoblock type mock-up:** Tungsten monoblock type mock-up was developed by high temperature high pressure diffusion bonding process at NFTDC Hyderabad. The mock-up consists of five tungsten alloy (W-1%La2O3) monoblocks with a 0.75 mm gap joined to actively cooled CuCrZr alloy heat sink tube. All the dimensions and details of a Tungsten monoblock type mock-up are as shown in figure 2.
Transient IR thermography

Transient IR thermography of macro-brush and monoblock type mock-ups was done with the help of In-house IR Thermography set-up. It consists of hot & cold water loop and FLIR IR Camera SC5200M. The heat sink of the mock-up (Tungsten/Graphite) was connected to the water loop system. The water loop was connected to a cold water supply (that is at room temperature) and hot water supply (80°C). Temperature of water is measured using thermometers (Measurement range 20°C to 200°C). An IR camera is used to scan the surface temperature of the mock-up at 50 Hz full frame rate.

During experiment the mock-up is heated up to 80°C by circulation of hot water in the coolant tube and is known as “Hot cycle” and then it has cooled down to room temperature by circulation of cold water and is known as “cold cycle”. The surface temperature of each tile of the mock-up during cold to hot transition and hot to cold transition has been recorded by IR camera. The defect present at joint or in to materials create a thermal resistance so that surface temperature delay occur during transient phase of mock-up and recorded by IR camera.

The surface temperature of each tile (T(t)) is normalized with respect to a stable cold temperature (Tc) and stable hot temperature (Th) for realization of stable inspection. Normalized Temperature for each tile has calculated using equation (1). Maximum temperature difference for other tiles with respect to reference tile is referred as DTref. DTref of each tile has been calculated by considering good bonded tile as reference tile (using equation 2). Reference tile or defect free tile has identified by tile performance during cooling and heating of the mock-up. Tile having high heating and cooling rate as compared to other tiles, is assumed as reference tile. Thermal response of good brazed tile is calculated using FEM simulation and it nearly matches with thermal response of reference tile. This Experimental procedure was carried out on both the macrobush type mock-ups before and after High heat flux test. Tungsten monoblock type mock-up has four symmetrical faces. Experimental procedure is applied for all the faces of tungsten monoblock type mock-up.

\[
T_{normalized} = (T_{measured} - T_c) \times \left( \frac{\tilde{T}_h - \tilde{T}_c}{\tilde{T}_h - \tilde{T}_c} \right) + T_c \quad \text{(1)}
\]

Where, \(T_c\) and \(T_h\) are the cold and hot stable temperature of Tile, \(\tilde{T}_c\) and \(\tilde{T}_h\) are the averaged cold and hot stable temperature of all tiles[8].

\[
DT_{ref} = T_{ref} - T_{tile} \quad \text{(2)}
\]

Assuming reference tile as sound area of the mock-up, Running Contrast is computed using equation (3)[9]. Running contrast is uniless parameter used for defect quantification in further part of paper.

\[
\text{Contrast} = \frac{T_{tile}(t) - T_{ref}(t)}{T_{ref}(t)} \quad \text{(3)}
\]
High Heat flux tests

The graphite macro-brush type mock-up was exposed to steady state as well as cyclic head loads up to absorbed heat flux 7.22 MW/m$^2$ (correspond incident heat flux 10MW/m$^2$). The tungsten macro-brush type mock-up was exposed to steady state and cyclic head loads up to absorbed heat flux 8.54 MW/m$^2$ (correspond incident heat flux 19.5 MW/m$^2$). The HHF tests were performed using EBTS electron beam facility at Sandia National Laboratory, USA [10]. The IR camera is mounted on view port with ZnSe window on EBTS vacuum chamber. All the tiles of the mock-up were numbered according to numbering system mentioned in figure1.

IR films were recorded during HHF tests for tungsten as well as graphite macro-brush type mock-ups. IR film was analyzed using Video processing toolbox available in MATLAB Simulink. Simulink Block-set circuit was developed to process the recorded IR films. A single tile of a macro-brush type mock-up consists of IR frame 19 x 19 pixel matrix. Pixel matrix of each tile considered as region of interest (ROI) and average surface temperature across the ROI was extracted using simulink block-set diagram. Average temperature observed on the tiles of the macro-brush type mock-up is used to set the acceptance criteria limit.

Results and discussions

Macro-brush type mock-up Temperature difference is measured by comparison of surface temperature of selected tile w. r. t. reference or defect free tile. Figure 3 shows the normalized temperature and DTref plot for graphite mock-up. The Normalized Temperature (Normalized) vs time plot for graphite mock-up, tile Number 13 has shown the highest heating and cooling rate among them, therefore Tile number 13 has selected as reference tile. transient temperature difference’DTref’ for other tiles of Graphite mock-up has been calculated using equation2. The DTref max and surface temperature observed during HHF tests are used to develop the acceptance criteria[11]. Figure 4. Shows acceptance criteria limits for graphite test mock-up. Graphite Tiles having DTref$_{max}$ ~3$^°$C before HHF test shows good performance during HHF tests and surface temperature observed is around~1400$^°$C, which is expected as per finite element analysis (FEA) reported in reference 12 [12]. Tiles having DTref$_{max}$ > 3$^°$C are rejected and surface temperature observed on these tiles during HHF tests is > 1400$^°$C. Tile number 11 of the graphite mock-up shows Maximum value of DTref$_{max}$ ~5.5$^°$C before HHF, which
is greater than 3°C. Surface temperature ~ 1800°C was observed on tile number 11 during HHF test and DTref after HHF test is ~11°C. Defects are present at joint interlayer of tile number 11, which delay the heat transfer performance of tile number 11 during thermography as well as HHF test. Hence Tiles having Dtref > 3°C before HHF tests are rejected. Acceptance criteria DTref limit for Graphite macro-brush type mock-up is ~3°C as shown in figure 5. Acceptance criteria DTref limit for Tungsten macro-brush type mock-up is ~5°C.

Fig4. DTref calculated using transient thermography and surface temperature observed during HHF tests for Graphite macro-brush type mock-up

![Graphite macro-brush type mock-up DTref](image)

Fig5. Acceptance criteria defined for Graphite macro-brush type mock-up

Tungsten Monoblock type mock-up: Figure 6 shows normalized temperature versus time plot for the face 3 of a tungsten monoblock type mock-up & running contrast of other tiles w.r.t. reference tile. As per figure 6 tile number ‘1’ is having highest heating and cooling rate as compared with others. Therefore tile number ‘1’ has been assumed as reference tile for further analysis. Running contrast gives information about presence and absence of defect at joint integrity of mock-up. Higher the contrast, better the joint or in other words thermal mismatch of a tile w.r.t. reference tile. Tungsten monoblock type mock-up having four symmetric faces, hence experiment was carried out for each
face of the mock-up. Thermal performance of each face is compared with the others. Figure 7 shows running contrast for all the faces of the mock-up & running contrast plot for Tile sub-matrix of face 4.

Single tile of monoblock type mock-up divided in five matrices. Running contrast is calculated for each matrix w.r.t. reference tile matrix. As per figure 7, tile number 5 is having highest value of running contrast among the others tiles. It means that, it has poor bonding as compared with other tiles. Further investigation was carried out by experimental data analysis & Image processing to improve the confidence level. Figure 8 shows running contrast for tile number 5 calculated by Image processing using MATLAB software. It clearly shows that, face 3 and 4 of the tile number 5 having maximum values of running contrast. On the other hand face 1 and 2 of a tile number 5 having minimum value of contrast.

![Fig6. Normalization temperature & Running contrast plot for Tungsten monoblock type mock-up](image)

![Fig7. Contrast plot for tungsten monoblock type mock-up](image)

Running contrast is calculated for Tile number 5 w.r.t. reference tile using temperature versus time plot and running contrast calculated by Image processing using MATLAB are very well match with each other. Tile number 5 at face 4 of the mock-up shows maximum value of running contrast. Running contrast by image processing locate the concentration of defect on tile surface as shown in figure 8.
Fig8. Image with running contrast of tile number 5 for all faces of the Tungsten monoblock type mock-up

Quantitative analysis of defects

Quantitative analysis of defects for monoblock type geometry was done by creating artificial defects. Circular defects are artificially created into copper monoblock type of tile at different faces with different diameter like-wise 1mm, 2mm, 3mm. Forth face of a copper tile is without defect and considered as reference surface. Surface temperature versus time plot was recorded for each face of copper tile using IR camera. Normalized temperature versus time plot of copper tile is as shown in figure 9. As per figure 9 defect free surface of copper tile shows maximum cooling rate while surface with 3mm defect shows minimum cooling rate.

Fig9. Experimental results of copper monoblock type tile with artificial defects

Thermal profile along the length of copper tile shows that artificial defects affect the cooling behavior of tile surface. Artificial defect with diameter 2 and 3 mm were created the maximum thermal resistance in surface cooling path of copper tile and reflected in experimental results. Defect with diameter 1mm does not create much difference in heat transfer behavior of copper tile. Image Running contrast is calculated for artificial defect with diameter 3mm by image processing using MATLAB. Image contrast visualizes the defect location on surface of copper tile as shown in figure 9.
Finite element analysis (FEA) was carried out for Copper monoblock type tile with artificial defects using Heat transfer模块 of COMSOL Multiphysics software. Heat transfer coefficient of 17000W/m²K is applied on inner surface of CuCrZr alloy tube and applied temperature boundary conditions to copper tile. Cooling curve for each face of copper tile was extracted from FEA. Running contrast is calculated for each face using equation (3). Figure 10 show the running contrast plot for copper tile using experimental as well as finite element analysis. Experimental results very well match with finite element analysis.

![Running Contrast plot](image)

**Fig10.** Running Contrast plot w. r. t. time for copper tile using experimental as well as FEA analysis

As per figure10 circular defect having the diameter 3 mm shows maximum thermal mismatch as compare to defect with diameter 2mm and 1mm. As defect size increases contrast value w. r. t. reference increases. Artificial defects created in copper tile with known size gives the direct relation between experimental running contrasts with defect size in other wards quantify the Thermal response received from defect.

**Conclusions**

Heat Transfer behavior of Divertor plasma facing components is checked by HHF tests followed by Transient Infrared Thermography. An acceptance criteria $DT_{ref_{max}}$ limit is defined for small scale macro-brush type mock-up. Acceptance criteria $DT_{ref_{max}}$ limit for graphite macro-brush mock-up is $\sim 3^\circ C$ while tungsten macro-brush mock-up is $\sim 5^\circ C$. Defined acceptance criteria limit will be confirmed in future after several experimental trials.

We are in process to establish Transient thermography technique to check monoblock type mock-ups. Trial experiments were performed on Tungsten monoblock type mock-up as well as Copper tile with artificial defects. Image running contrast calculation was done by using Matlab software for defects visualization.

Quantification of running contrast value with respect to defect size was done by artificial defects. It is concluded that Artificial defects created in copper tile with known size gives the direct relation between experimental running contrasts with defect size in other wards quantify the Thermal response received from defect. Effects of defects on heat transfer behavior of monoblock type mock-up are validated using finite element analysis. Experimental running contrast is very well match with FEA.

Apart from transient Infrared thermography other infrared thermography techniques namely pulsed and LOCK-IN thermography will be utilized for quality control of divertor PFCs. IPR Transient
Thermography set up will be upgraded to minimize the experimental uncertainties and improve the sensitivity. In-suit Infrared Thermography of Divertor PFCs before and after HHF test will be established for newly developed HHF Test facility.

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