Infrared Images Data Merging for Plasma Facing Component Inspection

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Abstract

The data merging study of the two infrared thermography non-destructive techniques on W7-X divertor targets allowed to improve significantly the sensitivity and reliability of detecting the fault size and location at the tile interfaces. This was possible due to the merging of infrared images. This original method of tile interfaces inspection has been validated using calibrated defects and then applied on fabricated components. The data merging method of infrared thermal images using the fuzzy logic method and Dempster-Shafer's model is presented in the paper.

Keywords: Data fusion – Dempster & Shafer model – W7-X Divertor target – Infrared Non Destructive Inspection

1- INTRODUCTION

A large experience has been gained at Tore Supra with the qualification of Plasma-Facing Components (PFC) armoured with carbon fibre reinforced composite flat tiles. These actively cooled PFC are devoted to sustain the heat and particle fluxes during normal and off-normal plasma operation. Such elements are used with success for the toroidal pump limiter, designed as a major part of the CIEL project [1]. In this frame, the infrared thermography test bed (Fig.1a) named SATIR (french acronym of Infrared Data Processing Facility), based on thermal transient method, was developed by CEA in order to evaluate the quality of manufacturing processes of actively water-cooled PFC before their installation in TORE SUPRA [2]. The next generation of large fusion machine will use actively cooled PFC (W7-X, JT60 SA, ITER) and the thermal and mechanical behaviour of the PFC's must guarantee the integrity of the components during the required lifetime. Therefore, an appropriate quality control methodology of actively cooled PFC becomes a key issue for fusion devices. In view of the procurement of the WENDELSTEIN 7-X (W7-X) divertor, Non-Destructive Techniques (NDT) will be used [3]. In addition to the thermal discontinuity detection capability of the SATIR NDT, the possibility of infrared data merging with LOCKIN NDT (Fig.1b), based on modulated photothermal thermography, has been studied [4]. A data merging of these two techniques led to an improvement of the tile interface inspection, providing a more accurate and reliable failure size estimation and location of the defects.

2- DATA MERGING METHODOLOGY

A data-merging module has been developed with the aim to improve the confidence on the measurement. The concept of data merging was developed in order to offer user-friendly machine interfaces and give decision capacities to non-experts in complex multi-sensor environments. This concept was widely used for military applications [5,6], and then in other domains where the complementarity of the information improves the decision: first medicine and more recently the NDT [7]. This study aims at the coupling of the two NDT of infrared thermal imaging previously mentioned. The data merging method is based on the theory of evidence, which was defined by Shafer based on the work of Dempster [8] on the generalization of the theory for the management of uncertainty and ignorance. This method assigns degrees of confidence, so called "sets of masses" to simple hypotheses, or combination of simple hypotheses for each NDT. Afterwards the merging of the experimental knowledge provided from different sources is performed through the Dempster orthogonal summation rule. This methodology has the advantage to be adapted to the concept of decision thresholds used in the domain of non-destructive inspection. Firstly a pixel-by-pixel merged method, which is more demanding than relative repositioning of the two infrared images, was chosen [9]. In the architecture of the model, the resizing part is essential because it is necessary to ensure that merged data come from the same spatial zone. A module was set up by using the matrix interpolation method, which allowed to create new pixels on infrared images of different size. Secondly the probabilities on hypotheses accuracy, needful for the Dempster-Shafer method, were defined

for each NDT. This requires a far-reaching experimental training. In our application, the hypothesis H1 corresponds to the presence of defect; the hypothesis H2 characterizes the absence of defect; and the hypothesis H3 corresponds to the ignorance. For each measurement, thresholds were established based on whether the pixel will be classified as defective, or not defective or ignorance (Fig.2). From two thresholds three zones are defined, which represent the regions where the decision is one of the three hypotheses H1, H2 or H3 with a certainty, which will be weighted by the sets of masses (to balance the importance of hypotheses): $m_n(H_i)$. If the transitions between zones are used alone, the decision changes are very abrupt and will be too sensitive to measurement noise. To obtain a more continuous behaviour from the transitions, fuzzy logic functions are used. Lower (lowL) and upper (UpL) limits then need to be defined for each zone. The Dempster orthogonal summation rule, which enables to combine two sources of data, is given in expression (1).

$$m(H) = m_1 \oplus m_2(H) = \frac{\sum\limits_{Hi \cap Hj = H} m_1(H_i).m_2(H_j)}{1-K} \qquad (1)$$

The purpose is to calculate the sets of masses after combination of the sources for each hypothesis. The combination of two or more NDT allows to increase the confidence of defect detection by reducing the uncertainties. It is also necessary to introduce the term K (2) for conflict between the sources when they are contradictory. For example, if the sets of masses involve a strong confidence in the measurements and that the portion of hypotheses H3 (ignorance) is weak, then the conflict term K increases.

$$K = \sum\limits_{Hi \cap Hj = \varnothing} m_1(H_i).m_2(H_j) \qquad (2)$$

3- APPLICATION

3.1- Components Used

The data merging study was performed on a stellarator W7-X divertor PFC composed of 3D carbon reinforced carbon composite NB31 tiles. The W7-X divertor will use the flat tile concept. It will be assembled with approximately 890 actively cooled target elements covering a total area of 19 m², designed to withstand heat fluxes up to 10 MW/m² for steady state operations. The 8mm thick tiles are attached via a soft copper layer (3mm thick), performed by AMC$^{®}$ (Plansee) to the CuCrZr heat sink by electron beam welding (Fig.3). The CuCrZr cooling structure contains four parallel channels connected in series. The straight channel part is equipped with a twisted tape as a turbulence promoter to enhance the critical heat flux limit.

3.2- Infrared Thermography Facilities Description

Two infrared thermal facilities were used for the inspection of bonded interfaces of actively PFC. The first NDT so called SATIR is based on a thermal transient induced by an alternative hot/cold water flow in the heat sink structure. The tile surface temperature transients are compared with those of an assumed defect free reference element and the maximum temperature difference for each tile called dTref_max. The description of SATIR facility was the subject of several papers [10, 11] and its principle will not be detailed here. Experimental data based on qualification experiences were obtained during a pre-series fabrication with calibrated defects. A crosschecking analysis, between the high heat flux performance tests (GLADIS ion beam facility) and SATIR test bed has been performed. It allowed to set a detectable limit for SATIR close to 1.5K as well as

to define an acceptance limit with a maximum tolerable value of dTref_max of 4K for the flat tile standard target elements. It corresponds to a strip (corner) failure size respectively of 3.5mm (resp. 5mm) [12].

The second NDT is an inspection method based on the study of thermal imaging modulated by external excitation, so called modulated photothermal thermography or LOCKIN thermography [11]. The measurement principle consists of the exposure of the component tile surface by a periodic external light source while recording its temperature response by infrared thermal imaging, and then calculating the phase shift (dφ) between the measured signal and the source by synchronous demodulation. A study performed in 2005 allowed to compare 3D calculations results with experimental phase shift contrast measured on the W7-X PFC with calibrated defects. These studies indicated that the minimum size of a detectable strip defect is 4 mm at the CFC/Copper interface]. The maximum tolerable value of phase shift contrast has been evaluated at 7° [4].

For each infrared facility, Table 1 reviews a general description of data merging thresholds for our application.

4- EXPERIMENTAL RESULTS

Each result is represented in the form of maps of the hypothesis H1, H2, H3 and K (conflict). The H1 map represents information on the confidence in the presence of the defect. In the W7-X target pre series case, specific tiles (#5, 6, 7, 8, 9) of the target element - 4S008 - showed an abnormal evolution of their tile surface temperature during the heating cycles at 10MW/m² due to

apparently bonding failures. Figure 4 shows the dTref_max mapping after HHF testing. Sequentially, SATIR and LOCKIN techniques were not able to identify the rupture under the tile #9 before the heat loading.

Figure 5 shows the positive data merging effect of probability in case of a defect. The tiles #5, 6, 7, 8 and 9 were detected as tiles with probability of defect presence higher than 50%. This presence of the defect was confirmed by HHF tests on these tiles previously mentioned and visual inspection in [12]. It validated the decision criteria of 50%. The sets of masses obtained after merging must be optimised and a decision criterion made.

A preliminary study carried out on calibrated defects allowed to validate the method [9] and showed the benefit of the data merging on the detection of defects (Fig.6).

5- CONCLUSION AND PERSPECTIVES

The rupture detection of armour to the heat sink joints is a critical issue for actively cooled PFCs. Up to now NDT's are sequentially used to assess the quality of the PFC's and their acceptability. In order to check this critical point, a study about the data merging of the two infrared images improved significantly the detection sensibility and reliability of defect location and size. This original study, using the fuzzy logic and Dempster-Shafer's model, showed a detection improvement of LOCKIN and SATIR techniques. The data merging method is now in operation. From the experimental know-how gained during the development of each individual NDT, it will be possible to implement a data merging process with fairly reduced training. This data process brings an

improvement even for a technique that is already very reliable like SATIR. The merging of additional NDTs, like the ultrasonic inspection applied to ITER monoblocks and planned in 2007, should improve the reliability of the decision-making.

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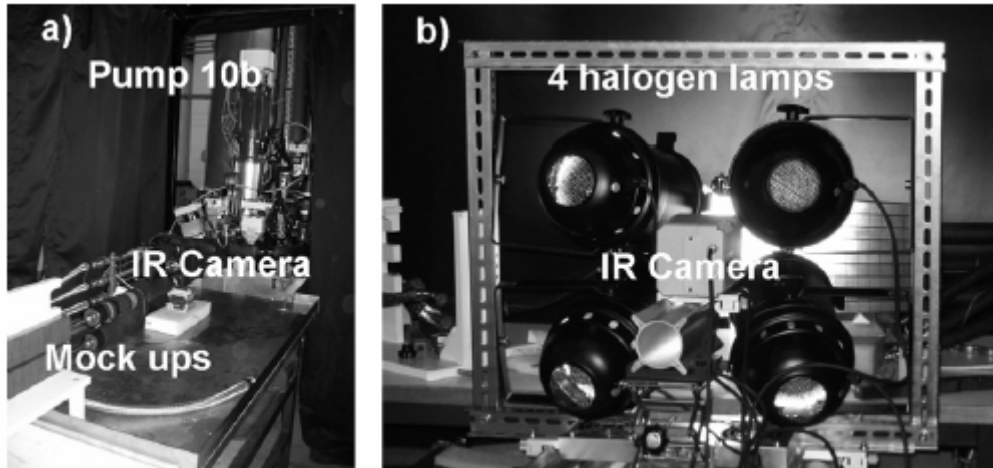
Figure and table captions

Fig.1: (a) SATIR test bed – (b) LOCKIN test bed
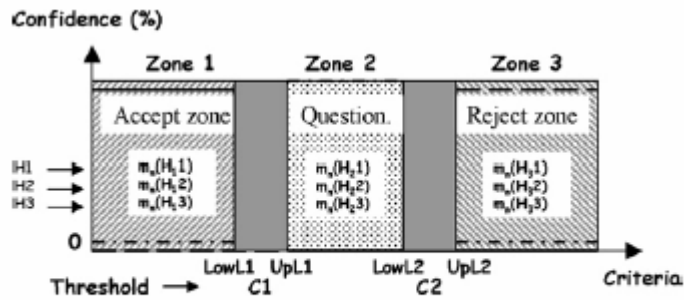
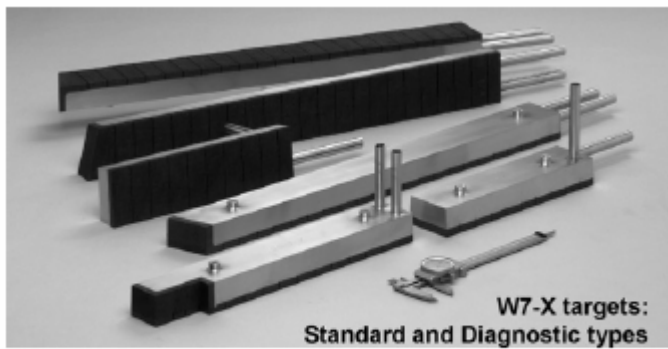Fig.2: Definition of zone limits and associated hypotheses for n NDT

Fig.3: View of various types of Wendelstein 7-X Target Elements

Fig.4: SATIR test for W7-X target element 4S-008: i.e. bonding rupture of tile #9 after HHF testing

Fig.5: Data merging application for W7-X target element 4S-008: Probability of defect presence >50% on tiles (5, 6, 7, 8, 9)

Fig.6: Infrared Data Merging Synopsis illustrated on single tile (target 5B-1V): Probability of presence of defect (H1) expected to 99%

Table 1: Thresholds and sets of mass $m_n(H_i)$ for SATIR (dTref_max) and LOCKIN (dφ)

Fig. 1. (a) SATIR test bed; (b) LOCKIN test bed.

Fig. 2. Definition of zone limits and associated hypotheses for n NDT.

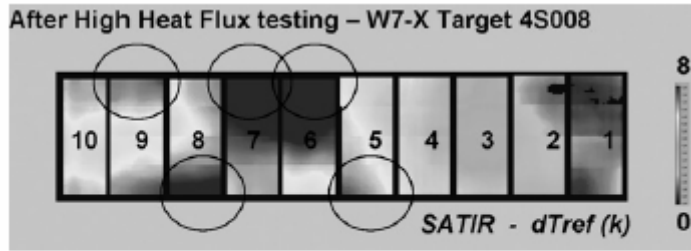Fig. 3. View of various types of Wendelstein 7-X target elements.

Fig. 4. SATIR test for W7-X target element 4S-008: i.e. bonding rupture of tile #9 after HHF testing.
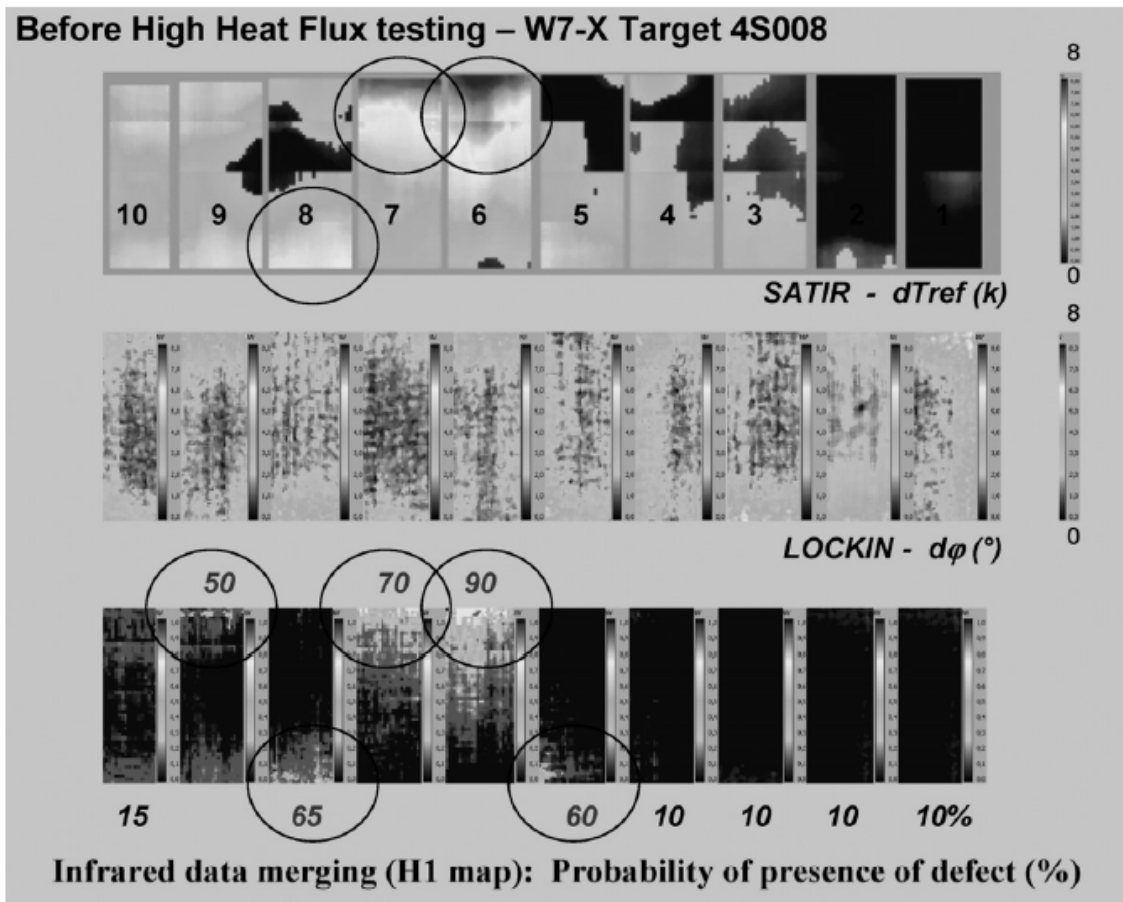

Fig. 5. Data merging application for W7-X target element 4S-008: probability of defect presence >50% on tiles (5–9).
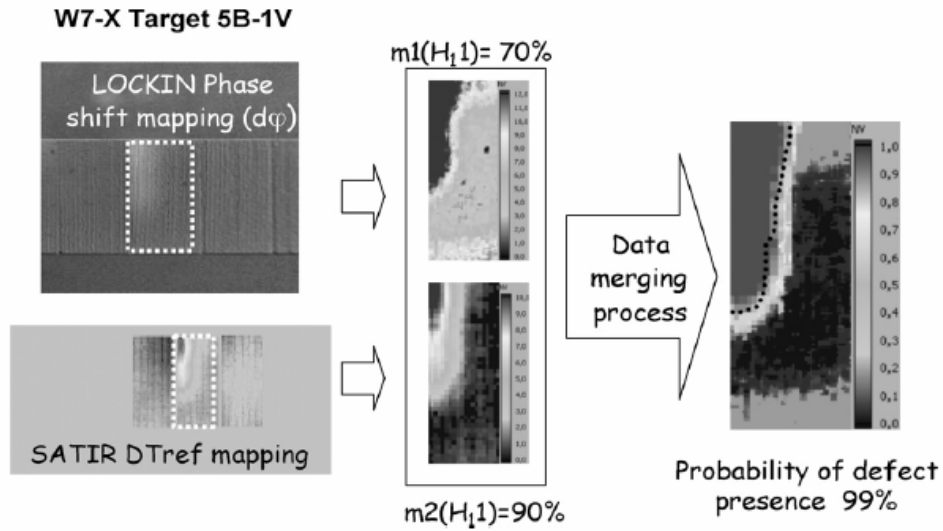
Fig. 6. Infrared data merging synopsis illustrated on single tile (target 5B-1V): probability of presence of defect (H1) expected to 99%.

Table 1

Thresholds and sets of mass $m_n(H_i)$ for SATIR (dTref_max) and LOCKIN (dφ)

Criteria	LowL1	C1	UpL1	LowL2	C2	UpL2
dTref (K)	**1.5**	1.75	**2**	2.5	3.25	**4**
dφ (°)	**4**	4.25	**4.5**	5.5	6.25	**7**

dTref	$m_1(H_i1)$	$m_1(H_i2)$	$m_1(H_i3)$
Zone 1	0	0.9	0.1
Zone 2	0.3	0	0.7
Zone3	0.9	0	0.1

dφ	$m_2(H_i1)$	$m_2(H_i2)$	$m_2(H_i3)$
Zone 1	0	0.7	0.3
Zone 2	0.3	0	0.7
Zone 3	0.7	0	0.3

Bold values correspond to the thresholds (Low and Up) of each NDE sources.