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ABSTRACT
Tritium surface distribution on the JET Mark II Septum Replacement Plate (Mk IISRP) divertor tiles was measured by Imaging Plate technique. It was observed that areal tritium concentration was higher at the entrance of inner/outer pumping slots (so called 'shadowed area'). The tritium distribution profiles were similar to those obtained in the Mk IIA divertor which was exposed to a series of D-T plasma operation (DTE1). Tritium concentration of the plasma facing surface was lower compared to that of the shadowed area. Particularly, it was very low at the outer divertor surface. In spite of the thick carbon deposition on that, tritium retention on the inner divertor surface was also low level. This could be caused by tritium release due to the temperature rise when the inner strike point was on the tiles. On the plasma shadowed area like tile gaps, high tritium retention owing to the codeposition was observed.

1. INTRODUCTION
Carbon Fibre Composite (CFC) and tungsten (W) are primary candidates for high heat flux components in next step fusion devices. W has advantages of a low erosion yield and low tritium retention, however, some serious issues are remaining such as a strong radiation loss in core plasma, easy melting and cracking under off-normal events, and blistering resulting in subsequent dust formation [1-4]. CFC is presently the best plasma facing material (PFM) withstanding enormous high heat load and avoiding radiation loss in core plasma [5,6]. The major obstacle to use of CFC as PFM is high erosion yeild due to chemical sputtering, which eventually leads to the formation of carbon-tritium codeposted layers as tritium store in the vacuum vessel [7]. In the current ITER divertor design, because of those circumstances, W will be used as PFM, except the target area where CFC be used to tolerate the highest heat load. Therefore, the erosion of CFC and the formation of redeposited layers are critical issues to estimate tritium retention in ITER. In this respect, various modeling and simulations of tritium retention in ITER have been done. However, since the codeposition phenomenon in tokamak is still not perfectly clear, tritium accumulation rate changes several orders depending on calculation condition [8-10].

From this point of view, the behaviour of the carbon material used as divertor armor tile and its contribution to tritium retention has to be investigated carefully for more reliable extrapolation of in-vessel tritium inventory build-up. As one of tritium analysis methods, we have developed and applied Tritium Imaging Plate Technique (TIPT) to measure the tritium distribution on the plasma facing wall [11-13]. In this study, we apply TIPT to determine the tritium distribution on the JET Mark II Septum Replacement Plate (Mk II SRP) tiles. From the result, characteristics of tritium retention in Mk II SRP divertor and hint for mitigation of tritium inventory are discussed.

2. EXPERIMENTAL
The Imaging Plate (IP) is a 2-dimensional radiation detector utilizing a photostimulable phosphor (BaFBu:Eu^{2+}), which gives a high-resolution image of tritium distribution on the sample surface.

Detail descriptions about IP have been presented in elsewhere [14,15].

Sample tiles measured here were a poloidal set of Mk II SRP divertor tiles used in 2001-2004 operational period of JET. During this period, no full D-T mixture discharges were made, however, a trace tritium (in deuterium) campaign using a total of 0.5g tritium was performed [16]. Tritium produced by DD reaction naturally added. The sample tiles were sent to VTT Processes in Finland, and their plasma facing surfaces have been analyzed by means of Secondary Ion Mass Spectrometry (SIMS) [17,18].

IP analysis was carried out in the radiation-controlled area of VTT Processes. The IP plate was placed on the tile surface in the glove box, and exposed to ≤-ray emitted from tritium retained on the tile surface. In order to avoid the contamination of IP with tritium, IP was fully covered a thin film made of PPS (Poly-Phenyl-Sulfide) with 1.2 μm thickness, which reduced the detection sensitivity about 10. Since some of the tiles have curvature on their surfaces, IP was pressed by some weights to ensure the contact to the surface. During the exposure, a number of F-centers are formed due to the generation of the radiation-induced excited electrons in the phosphor crystal. The number and position of F-centers are stored on IP, which makes tritium image. After about 2 hours of the exposure, IP was transported to the Laboratory of Radiochemistry, University of Helsinki, and processed by an Imaging Plate reader in order to obtain the digitized image. Not only plasma facing surfaces but also tiles side surfaces of the tiles were measured.

3. RESULTS

3.1 PLASMA FACING SURFACE

Figure 1 shows areal distributions and poloidal line profiles of photo-Stimulated Luminescence (PSL) intensities (referred as tritium images and tritium line profiles hereafter) obtained for the plasma facing surfaces of the Mk II SRP tiles. The PSL intensity given by TIPT is well proportional to the areal tritium concentration. Relative tritium concentrations on the inner divertor tiles were higher than those on the outer divertor tiles by a factor of 2~3. From the visual inspection, thicker carbon deposition was found on the inner divertor tiles, while erosion dominated the outer divertor tiles. Therefore the tritium distribution is correlated to the carbon deposition profiles in the Mk II SRP divertor.

The highest tritium concentration was found in the shadowed area of the base tiles (Tile-4 and -6), of which concentration was about 1 order of magnitude higher than those on the other plasma facing area. Figure 2 shows the tritium images and photographs of the plasma facing surface of the inner divertor base tile, together with the poloidal and toroidal sides for Tile-4. The holes found on the tile were cored for the SIMS samples. One can see the interference pattern in the photograph indicating thin deposited layers of ~ several 100 nm thickness on the poloidally inner side, where was shadowed from plasma.

3.2 POLOIDAL AND TOROIDAL SIDES AND REAR SIDE

Figure 3 shows results for side surfaces together with the plasma facing surface of the inner divertor tiles. Most of the tile sides were covered by the redeposited layers. The thickness of the carbon deposited layeres on the tiles varied depending on the direction of the side. The tritium concentration in the redeposited layers was almost the same level with that of the shadowed area of the plasma facing surface described above section.

The redeposited layers with high tritium concentration were also found on the rear side of the inner vertical target tile, Tile-3, as shown in fig. 4. The redeposited layers partly covered the rear side of the inner divertor target tile from the bottom edge to ~ 30 mm up. Taking the geometry of the divertor into account, carbon deposition was caused by repeating steps of reflections of carbon/ hydrocarbon impurities or secondary sputtering of deposition formed in the louver entrance, which is interesting from the viewpoint of material migration. Above ~ 30 mm, no deposition was observed as evidenced by the appearance of the lamella structure typical for 2-D CFC tiles. This kind of tritium distribution was already found on the rear sides of the Mk IIA divertor tiles as well, which was attributed to the difference of the retention characteristics of the matrix and the substrate [19]. It should be noted that tritium concentration on the rear sides was a little higher than that on the plasma facing surface.

4. Discussion

One should note that the tritium retention on the plasma facing surface of the inner divertor tiles was rather low in spite of the existence of the thicker redeposited layers on them. The most probable reason is temperature elevation of the tile surface during a discharge. According to the thermodynamics for the carbon and hydrogen system, the saturation concentration of hydrogen retention in carbon above 500 K decreases exponentially with temperature. In JET, fast 2-D camera was used to measure the power flux to the divertor tiles [20]. One of the results showed that the surface temperature around the strike points rose up to 700 K during a discharge. In addition, if type-I ELM occurred, the surface temperature escalated to above 1800 K [21]. Hence, such high heat load to the tile surface could reduce the tritium concentration of the deposited layers on the plasma facing surface.

Since the impurity carbon flux would be less than a few % of the total hydrogen impinging flux to the plasma facing surface, most of the impinging hydrogen must be reemitted. In addition the temperature escalation at the plasma facing surface during the shot could easily results in the hydrogen saturation. Hence isotope ratios of H, D and T in the near surface layers would be the same as those for the impinging flux avoiding tritium accumulation. At the plasma shadowed area, on the other hand, no isotope replacement could be possible until the saturation is attained. Since the temperature rise at the shadowed area must be very small, the saturation concentration there is very high and tritium would be piled up in the redeposited layers on the plasma shadowed area.

Actually, the redeposited layers formed in the inner and the outer shadowed areas and the tile gaps showed higher tritium concentration than that for the plasma facing surface. Since those regions were not exposed to the plasma directly, the temperature increase would be much less than that for the plasma facing surfaces, namely it was almost same with operating temperature: 473 K. (The divertor base structure might be lower than this temperature because of the water-cooling.) Around this temperature region, hydrogen saturation level in carbon is still high up to H/C~0.4. The tritium profile on the tile sides clearly show the less tritium retention near surface edge of the plasma facing side, which confirms the high temperature escalation only at the plasma facing side.

In the Mk II SRP divertor, however, the thickness of the redeposited layers was much less than those observed on Mk IIA divertor tiles, in which the thick redeposited layers were flaky with very high tritium concentration. During the operational phase using Mk IIA divertor configuration, the inner strike point was mainly on the horizontal target tiles (corresponding to Tile-4 and Tile-6). However, following phases of Mk II GB and Mk II SRP divertor configurations, the vertical divertor tiles (Tile-3 and Tile-7) were main target tiles. As already noted in JT-60U, carbon deposition is dominated to the inner side from the eroded area [22], the reduction of the deposition in the Mk II GB and Mk -II SRP divertor configurations is quite reasonable. The significant tritium retention at the inner side surface of the horizontal tile (Tile-4) well corresponds the carbon transport the inner side. Hence such the inner divertor configuration that the pumping slot locates below the inner divertor strike point seems good for the reduction of the carbon codeposition and dust formation in the louver entrance area [23,24].

CONCLUSION

Tritium distributions on the plasma facing surface and shadowed area of the JET Mk II SRP divertor were measured by Tritium Imaging Plate Technique.

On the plasma facing surface, tritium concentration on the inner divertor was higher than that on the outer divertor. However, the concentration on the plasma facing surface was still low level, which was about 1order of magnitude lower than that on the shadow area and even lower than that for the rear side. Such difference was probably caused by difference of surface temperature. The surface temperatures around the divertor strike points were easily raised more than 500K due to plasma heat load. On the other hand, the temperature of the shadowed area might remain operating temperature < 500K even during a discharge.

The amount of carbon deposition in the shadowed area of Mk II SRP divertor decreased as compared to that of Mk IIA divertor. Since codeposition in the shadowed area will be major concern for in-vessel tritium inventory, such reduction directly means mitigation of tritium retention. CFC is presently more responsible PFM against ELMs and/or uncontrolled disruptions. Thus, CFC is preferable PFM until stable plasma operation becomes possible. In this respect, less tritium incorporation in codeposition in plasma facing surface and reduction of amount of codeposition in the shadowed area are good news for ITER tritium inventory under using CFC divertor target.

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REFERENCES

[1]. T. Tanabe, N. Noda, H. Nakamura, Review of high Z materials for PSI application', J. Nucl. Mater., **196-198** (1992) 11-27

[2]. N. Noda, V. Philipps, R. Neu, J. Nucl. Mater., **241-243** (1997) 227-243

[3]. T. Tanabe, M. Akiba, Y.Ueda et al., 'On the utilization of high Z materials as plasma facing component', Fusion Eng. Des.**39-40** (1998) 275-285

[4]. T. Hirai, M.Rubel, V. Philipps et al., 'Testing of tungsten and tantalum limiters at the TEXTOR tokamak', Phys. Scripta, **T103** (2003) 59-62

[5]. A. Miyahara, T.Tanabe, 'Graphite as plasma facing material', J. Nucl. Mater., **155-157** (1988) 49-57

[6]. T. Tanabe, 'On the possibility of ITER starting with full carbon', Fusion Eng. Des. **81** (2006) 139-147

[7]. C.H. Skinner, G. Federici, 'Is carbon a realistic choice for ITER's divertor?', Phys. Scripta **73** (2006)1-5

[8]. J.N. Brooks, R. Causy, G. Federici et al., 'Assessment of erosion and surface tritium inventory issues for the ITER divertor', J. Nucl. Mater., **241-243** (1997) 294-298

[9]. G. Federici, R.A. Anderl, P. Andrew et al., 'In-vessel tritium retention and removal in ITER', J. Nucl. Mater., **266-269** (1999) 14-29

[10]. J. Roth, A. Kirschner, W. Bohmeyer et al., Flux dependence of carbon erosion and implication for ITER', J. Nucl. Mater., **337-339** (2005) 970-974

[11]. K. Miyasaka, T. Tanabe, G. Mank et al.,'Tritium detection in plasma facing component by imaging plate technique', J.Nucl.Mater. **290-293** (2001) 448-453

[12]. T. Tanabe, V. Philipps, 'Tritium detection in plasma facing component by imaging plate technique', Fusion Eng. Des. **54** (2001) 147-149

[13]. K. Sugiyama, K. Miyasaka, T.Tanabe et al., 'Tritium profile on surface of graphite tiles used in JT-60U', Physica Scripta **T103** (2003.) 56-58

[14]. M. Sonoda, M. Takano, J. Miyahara et al., 'Computed radiography utilizing scanning laser stimulated luminescence', Radiology **148** (1983) 833-838

[15]. Y. Amemiya, J. Miyahara, Nature (Lond.) **336** (1988) 89

[16]. The JET team, 'Trace tritium transport in JET', Proc. IAEAEXP1/07

[17]. J. Likonen, S. Lehto, J.P. Coad et al., 'Studies of impurity deposition/implantation in JET divertor tiles using SIMS and ion beam techniques', Fusion Eng. Des. **66-68** (2003) 219-224

[18]. J. Likonen, J.P. Coad, E. Vainonen-Ahlgren et al., this conference.

[19]. K. Sugiyama, K. Miyasaka, T. Tanabe et al., '', J. Nucl. Mater. **313-316** (2003) 507-513

[20]. P. Andrew, J.P. Coad, T. Eich et al., 'Thermal effects of surface layers on divertor target plates', J. Nucl. Mater., **313-316** (2003) 135-139

[21]. L.D. Horton, G.C. Vlases, P. Andrew et al., "Studies in JET divertors of varied geometry – I: Non-seeded plasma operation", Nuclear Fusion, vol.39 No.1 (1999) 1-17

[22]. Y. Gotoh, T. Tanabe, Y. Ishimoto et al., 'Long-term erosion and redeposition of carbon in the divertor region of JT-60U' submitted to Journal of Nuclear Materials.

[23]. V. Philipps, J. Roth and A. Loarte, 'Key issue in plasma-wall interactions for ITER', Plasma Phys. Control. Fusion, **45** (2003) A17-A30

[24]. H.G. Esser, V. Philipps, M. Freisinger et al., 'Effect of plasma configuration on carbon migration measured in the inner divertor of JET using quartz microbalance', J. Nucl. Mater., **337-339** (2005) 84-88

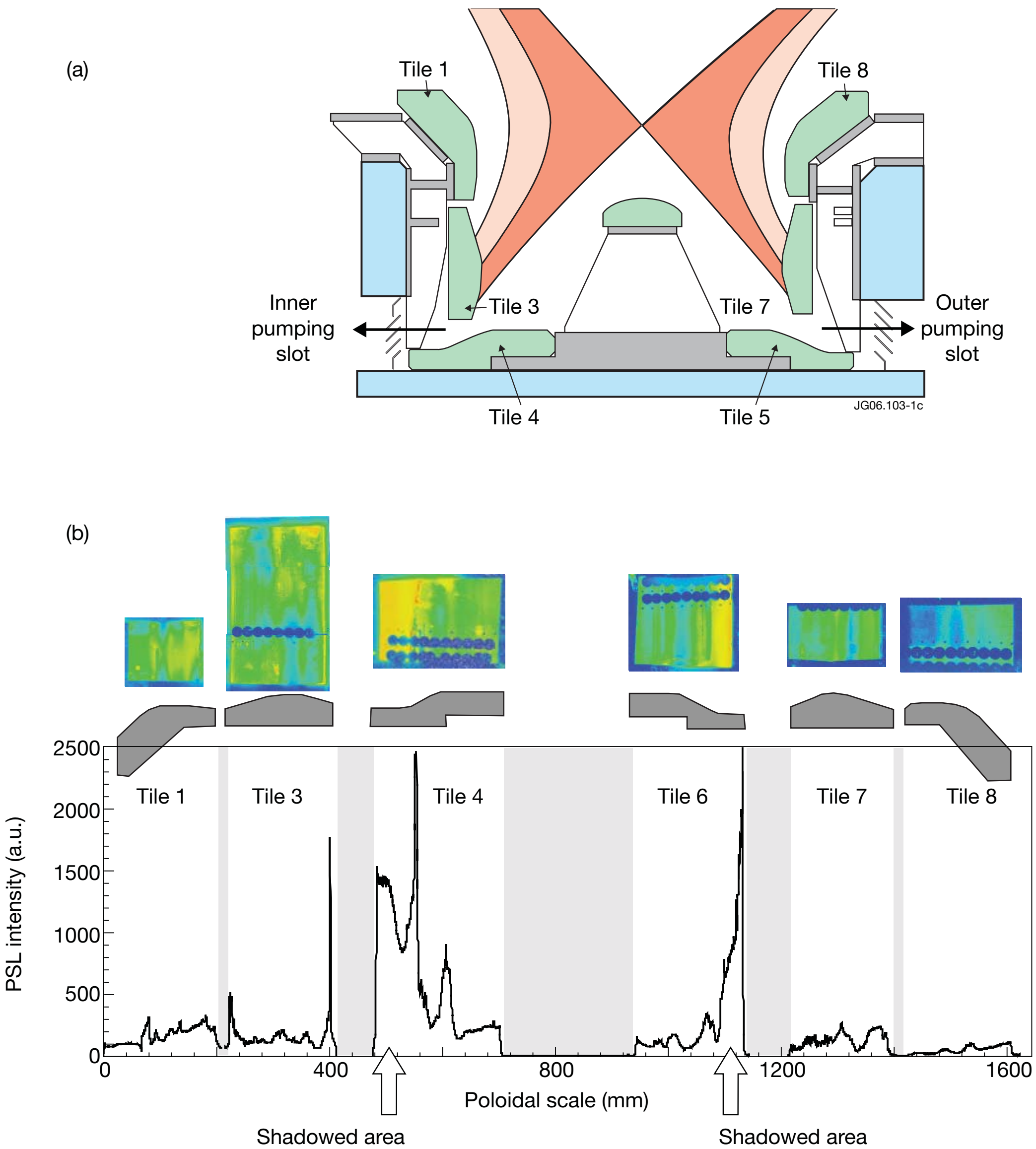

Figure 1: (a) Schematic cross sectional view of Mk II SRP divertor. (b) IP images of measured tiles and the poloidal line profile obtained from the image analysis.'PSL intensity' is a special unit used in IP, which is well proportional to the areal tritium concentration. The highest concentration is found in the shadowed area of the divertor.

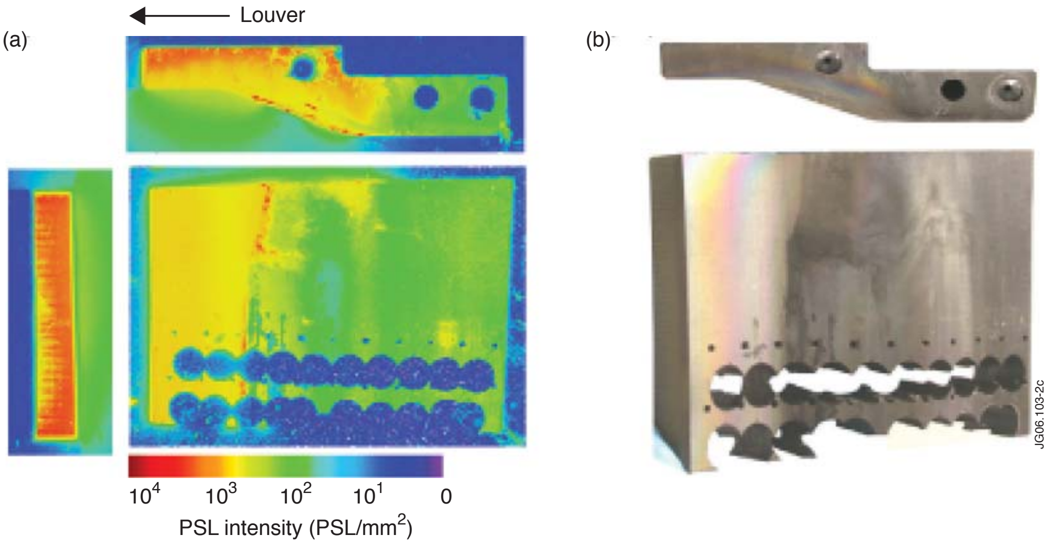

Figure 2: (a) IP images and (b) photographs of the plasma facing surface and sides of inner base tile: Tile-4. The interference pattern is found on the shadowed area.

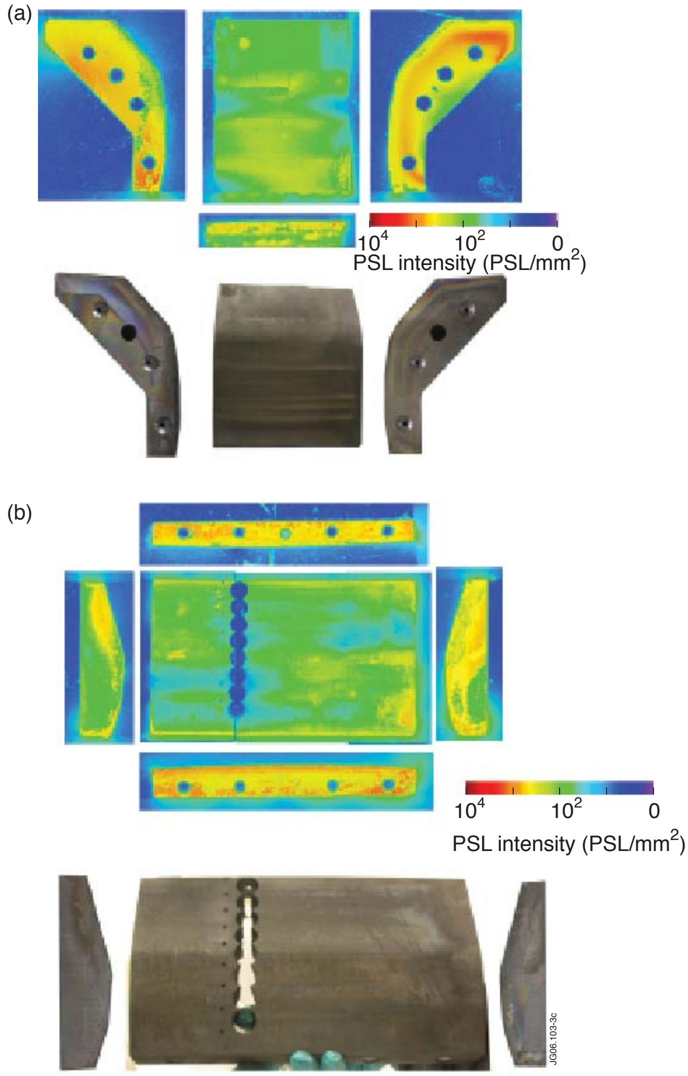

Figure 3: IP images of tile sides together with plasma facing surface of (a) Tile-1 and (b) Tile-3.

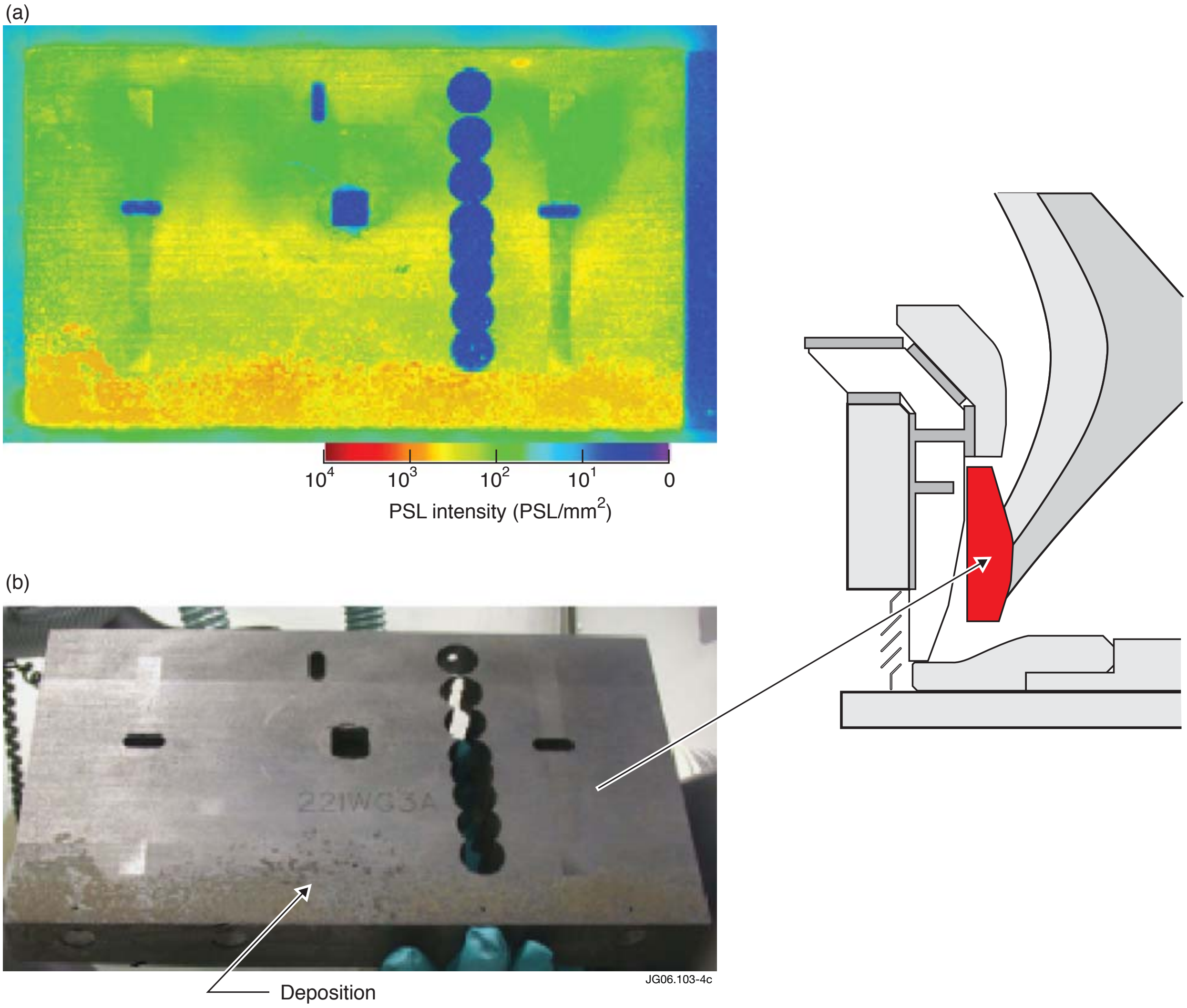

Figure 4: (a) IP images and (b) photograph of the backside of Tile-3.