Detritiation of tiles from tokamaks by laser cleaning

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Abstract

Laser ablation has been used to clean surfaces or to decontaminate hot cells by removing paint [1], and has been tested on deposited carbon layers from the TEXTOR tokamak. This paper reports on successful trials in the Beryllium Handling Facility of a pulsed laser cleaning system to remove H-isotope containing carbon deposits on tiles from the JET tokamak. The laser beam is rastered over the surface of the tiles to remove the deposit. Two types of JET carbon-fibre composite (CFC) tiles were treated. The first was covered with carbon-based deposits up to 300μm thick with high H-isotope content, the other was covered with a mixed Be/C film ~50 microns thick. One scan of the laser was sufficient to completely change the appearance and expose the fibre planes. From cross-sectional micrographs, it was found that overall three scans provided the most effective settings for complete film removal. An area 250cm^2 of the second tile was cleaned in ~20 minutes, clearly demonstrating the efficiency of laser cleaning for the removal of tokamak deposits such as likely to occur in ITER.

KEYWORDS:
De-tritiation, lasers, tokamaks, cleaning, carbon-based deposits

1. Introduction

The deposition of hydrogen (H) isotope rich carbon layers on tokamak surfaces is of increasing concern for fusion reactors. In particular the retention of T by this mechanism is a major driver of the choice of ITER wall materials and could be a limiting factor operationally [2]. Thus within the fusion community increasing efforts have been directed at the detritiation of tokamak surfaces. In principal the complete removal of co-deposits is preferential to the desorption of T from coated surfaces, as any remaining co-deposit will re-absorb T during the subsequent operation of the reactor. Here we report on the efficacy of laser ablation as a method for removing co-deposited material.

Laser ablation has been used to clean surfaces, for example, to decontaminate hot cells by removing paint [1], as well as being used to remove carbon layers from TEXTOR tiles. Trials of a pulsed laser cleaning unit (LCU) developed to remove carbon co-deposits containing H-isotopes from JET tiles were performed in the Beryllium Handling Facility at JET. The laser beam was scanned over the surface of the tiles to remove the deposit. The results show that the system is effective for the removal of carbon co-deposits containing H-isotopes and would therefore be a useful tool in the management of tritium retention in fusion reactors, such as ITER.

2. Experimental details

Three tiles removed from the JET divertor structure were treated using a LCU developed at CEA, Saclay. The LCU consisted of a pulsed Nd:YAG 1064nm laser with a pulse energy of 1mJ, pulse length of 120ns and repetition rate of 20 kHz. The laser beam was focused using a lens to give a spot size at 1/e^2 of 150μm diameter delivering a peak fluence of 10.4J/cm^2 at a focal length of 496mm. The beam was directed on to scanning mirrors allowing the laser to be scanned over a maximum area of 500mm x 500mm on the target surface. In addition, there was a HeNe guide laser which allowed the scan path to be tested prior to cleaning with the main laser. A camera was mounted in the LCU which enabled the target and the laser positions to be viewed remotely.

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As the tiles for cleaning were possibly contaminated with beryllium (Be), the trials were performed in a facility designed to handle Be contaminated items based at JET; referred to as the Beryllium Handling Facility (BeHF). The LCU was wrapped in polythene to reduce the risk of contamination and placed on a table inside the BeHF with the beam directed into a ventilated slit box. Each of the tiles to be cleaned was mounted on a stand in the slit box such that the surface of the tiles was at (or close to) the focal plane of the beam, which was 458mm from the window of the LCU. Once the tile was suitably positioned, the BeHF was vacated of all staff to avoid exposure to Be, T and laser radiation. The laser scan path was controlled using a computer from outside the BeHF via bulwark connection in the wall of the facility. Throughout the trials the T content discharged from the tile was monitored using an ion chamber as it was exhausted through the ventilation pipe from the slit box.

During the laser cleaning trials it was possible to alter the scan speed (v) of the laser using the following parameters: the distance travelled between laser pulses (ΔX), pitch (ΔY) and the offset pitch (δY). By altering these parameters a series of four scanning regimes were investigated (regimes 1 to 4). For regimes 1 and 2 v=0.2m/s, with ΔX=10μm and ΔY=100μm. For regime 1 the laser was scanned across the surface of the tile twice with the second scan being offset by δY=50μm. This gave an overall treatment rate of $36\times10^{-3}m^2$/hr. For regime 2 the second scan was not used giving an overall treatment rate of $72\times10^{-3}m^2$/hr. A similar relationship exists between regimes 3 and 4 where v=1.0m^2/s and regime 3 had two laser passes per scan cycle and regime 4 had one. It was also possible to change the laser-tile distance and thus assess the effect that distance from the focal plane had on the efficacy of the LCU.

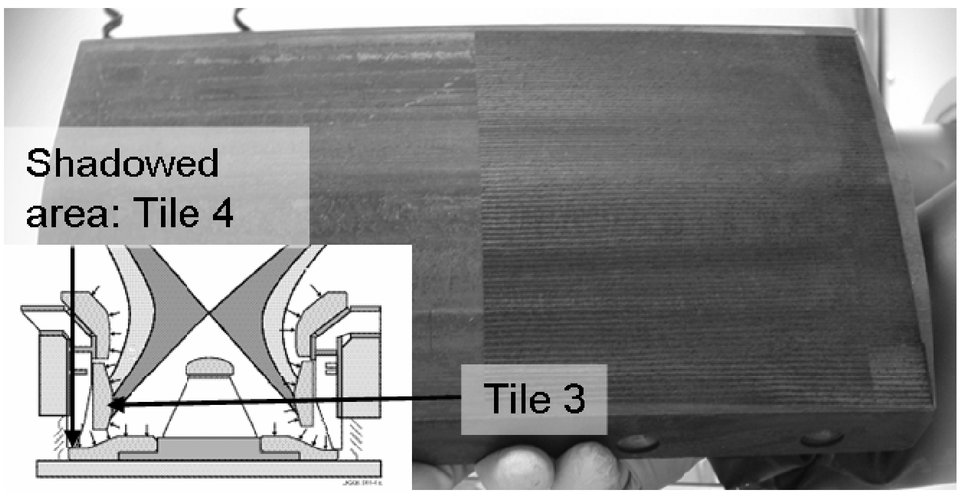

Fig.1. Shows tile G3B14IN after half of the surface has been laser cleaned. Fibre planes are visible on the right hand side of the tile photograph. The insert shows the positions of tile 3 and tile 4 in the JET MkIIGB divertor.

Three tiles were cleaned during the trials, namely G4A5BW (an example of tile 4), G3B3IN and G3B14IN (both examples of tile 3). The results presented here are predominantly from tiles G4A5BW and G3B14IN. The position of these tiles in the JET Mark II Gas Box (MkIIGB) divertor is shown on the insert of Fig. 1. In order to investigate the efficacy of the four scanning regimes, initial cleaning trials were performed on small areas (20x20mm^2) in the shadowed region of tile G4A5BW, where the co-deposit is known to be 200-300μm in thickness. Variations in the laser-tile distance were also made. From these trials the most suitable scanning parameters were established. These were then used to clean larger areas on the remaining tiles. Areas cleaned on tile G4A5BW are shown in Fig. 2a.

Treated tiles were subsequently analysed with IBA techniques, SIMS and cross-sectional optical microscopy. Some of these results are reported here.

3. Results

From the trial areas in the shadowed region of tile G4A5BW it was found that a single scan was sufficient to completely change the appearance of the treated regions; instead of the smooth film the fibre planes of the CFC substrate were clearly visible, as seen in Fig. 2a. However more scans were generally required to completely remove the co-deposited material. For example, at positions 9 and 10 in Fig. 2a, it was found that three scan cycles using scanning regime 1, the slowest scanning regime, at a distance of 448mm from the LCU window (equivalent to a peak fluence of 4.8J/cm^2) were required to remove all co-deposit. This is shown in the cross section in Fig. 2b where all the co-deposit has been removed. The results were also confirmed from analysis of the deuterium (D) peak in Nuclear Reaction Analysis (NRA) and the concentration of hydrogen species and Be in SIMS analysis. However when using a faster scan speed (regime 4) at position 5, with the surface of the tile in the focal plane, it was found that four repeats of the laser scan cycle were insufficient for removing all the co-deposit. This is visible in Fig. 2a where a darker region in the centre of position 5 remains. From cross-sectional microscopy the remaining co-deposit was found to be ~20μm in thickness. Analysis of area 5 by NRA also confirms that the co-deposit was not completely removed from area 5. For example, in Fig. 3 curve (a) shows that D is still present in the central region of the cleaned area 5, whereas negligible D remained in the bottom part of area 5 (see curve in Fig. 3b), thus showing that the deposit had been removed: for comparison the curve in Fig. 3c shows the D feature from an untreated region. The results of the various scanning regimes used on tile G4A5BW established a suitable operating regime, and the remaining scans were performed using either regimes 1 or 2.

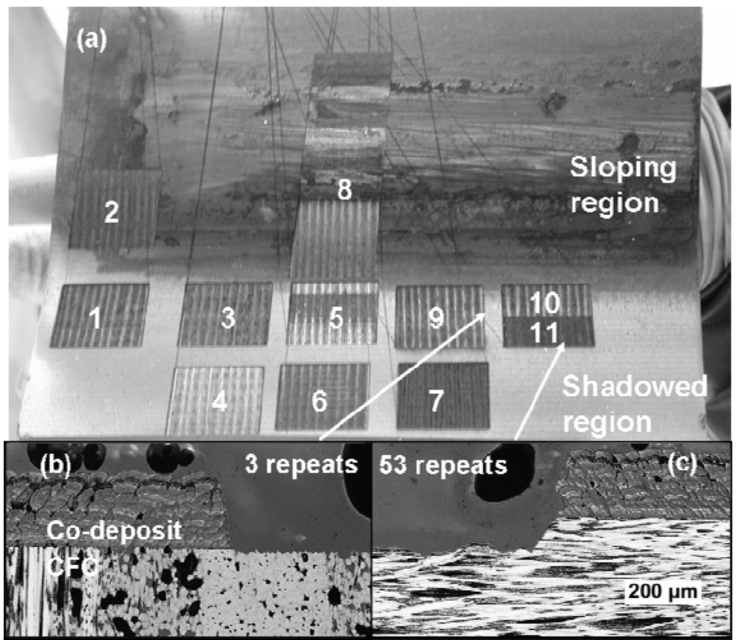

Fig.2a. Photograph showing areas cleaned on tile G4A5BW using different scanning regimes. Figs. 2b and 2c show cross-sectional micrographs at the interfaces indicated by the arrows.

The effects of the deviation of the target surface from the focal plane on the efficiency of the laser cleaning were observed on the sloping region at position 8. Due to the way in which the tile was mounted, as the laser was scanned vertically on area 8 the laser-target distance decreased and consequently the efficiency with which the co-deposit was removed also decreased. This is visible by eye in Fig. 2a where the CFC becomes obscured by the co-deposit approximately one third of the way along the scanned area (60mmx20mm). From the geometry of the tile and its distance from the laser window it is estimated that the laser was no longer effective at removing co-deposit at a laser-tile distance of ≤445mm, i.e. ≥13mm from the focal plane, showing the depth of focus limit for the system.

The effect of the laser cleaning on the CFC substrate was also investigated by completing a further fifty scan cycles in the lower half of region 10 (i.e., region 11 in Fig. 2a) bringing the total number of scan cycles in this area to fifty three. It was found that between 10 and 110μm of CFC were removed (see Fig. 2c) and within the resolution of the micrographs no preferential erosion was seen between the fibres and filler.

Tile G3B3IN was mounted for cleaning with the toroidal fibre planes of the tile placed vertically. A series of bands were scanned along the poloidal direction of the tile using all four scanning regimes. As for tile G4A5BW it was confirmed that regime 1 was most efficient at removing the ~50μm co-deposit, however it was found that regime 2 also gave satisfactory removal. Since the overall treatment rate of regime 2 was twice as fast as regime 1, it was used to treat half of tile G3B14IN and thus demonstrate that laser cleaning of larger areas could be achieved on a practical time scale. For this trial the time to clean an area $25\times10^{-4}m^2$ was ~20 minutes

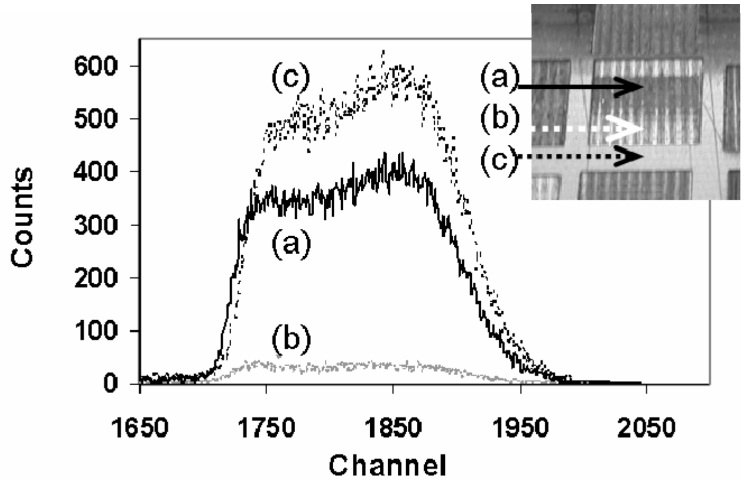

Fig.2a. Photograph showing areas cleaned on tile G4A5BW using different scanning regimes. Figs. 2b and 2c show cross-sectional micrographs at the interfaces indicated by the arrows

Fig. 1 shows tile G3B14IN after laser cleaning with the toroidal fibre planes (running horizontally in the image) visible on the right of the image. By eye the majority of the co-deposit appears to have been removed, however further analysis revealed that some co-deposit remained on the top section of the tile and towards the bottom edge of the image in Fig. 1. Cross sections showed that in one region the film remaining was of a similar thickness to the original deposit whereas another showed a powdery deposit remaining which is likely to be debris resulting from the laser cleaning. These results indicate that the laser flux applied during the single scan was marginal for complete removal of the film across the poloidal profile of the tile surface. The maximum height variation in the tile profile is 22mm, thus the positioning of the tile is clearly important in order that the surface remains within ±10mm of the focal plane to ensure effective removal of the co-deposit. Some optimisation to obtain the most efficient parameter for cleaning is required.

Throughout the trials the T discharged from the tile was monitored at the ventilation shaft from the slit box. A burst of T was observed for each laser scan repeated on a fresh surface. The sensitivity of the monitoring system was not sufficient to detect T from subsequent scans on an area that had already been cleaned once. This suggests that the majority of the film was removed during the first scan cycle. From the integrated data it was possible to calculate the amount of T released from each tile during laser cleaning. However it was found that this was ≤10% of the estimated release calculated from off-gas measurements [3]. The expected activity of the surface co-deposit was calculated based on off-gas measurements of the tile and the distribution of T determined from total combustion data, SIMS and IBA measurements of representative tiles [4,5] which show that a majority of the T on type 4 tiles is found in the co-deposit in the shadowed area. Thus the estimated release from the areas cleaned on tile G4A5BW was calculated as ~5.5GBq (0.015mg T), whereas only 0.5GBq was detected during the cleaning process.

Evidence for the removal of the co-deposit as micro-particles <10µm in diameter has been observed during additional cleaning trials on TEXTOR tiles. It was thought, therefore, that during the cleaning of the JET tiles the micro-particles released from the surface would become lodged in the particle filter present in the ventilation duct of the slit box. Such micro-particles, still containing their T could then be accounted for by measuring the activity of the filter after the laser cleaning trials. However the T inventory of the filter was insufficient to account for the material removed from the surfaces of all three tile surfaces. In addition, the activity of any material that may remain in the ventilation system would be obscured by the background levels of 0.5GBq/day for the entire BeHF and not just the laser cleaning experiment. The T may have been driven into the bulk of the tile by the laser whilst the film was being removed. This latter seems unlikely since the dwell time at any point is very short and there is no evidence of significant heating of the substrate; however cores taken from treated and untreated regions are being analysed for T content to check this point. Thus at the time of writing it is not possible to resolve the discrepancy observed in the values between calculated and measured T release.

4. Discussion

The removal of co-deposit from JET divertor tiles by pulsed laser cleaning was successfully demonstrated during these trials. For the laser parameters available a laser routine was established for the effective removal of material, this was a scanning speed of 0.2m/s with a cleaning rate of $36x10^{-3}m^2$/hr for one scan cycle, for deposits up to 300μm in thickness, provided the surface of the tile was within ±10mm of the focal plane of the laser. During the cleaning of tile G3B14IN a higher cleaning rate of $72x10^{-3}m^2$/hr was used; however not all the co-deposit was removed. Although the removal of co-deposit was largely successful, once the co-deposit was removed the laser energy densities used during these trials were also sufficient to damage the CFC tile surface. The damage caused was approximately 0.2-2.0μm per scan cycle using scanning regime 1. Further studies have shown that the threshold fluence of the CFC tile substrate is not only dependent on the fluence but also on the scan speed, i.e., the step size between pulses. Work carried out at CEA, Saclay has shown that for scan speeds ≥0.5m/s the threshold fluence of the CFC was $8J/cm^2$. During the laser cleaning trials the damage to the CFC was observed for the slower scan speed 0.2m/s. No cross-sectional microscopy has been completed on the areas cleaned at the faster scanning speed of 1.0m/s as these scanning regimes were not successful in removing all the co-deposit.

Clearly for laser cleaning to be a successful method for the detritiation of tiles the threshold for removal of the H-isotope containing co-deposit must be less than the substrate. From the trials on tile G4A5BW a 300μm co-deposit was removed effectively by three scan cycles, equivalent to a cleaning rate of $12x10^{-3}m^2$/hr. In comparison the CFC removal using the same scanning parameters was significantly less. However it is still important to minimize damage to the tile surface to ensure longevity of the machine which should be able to withstand many laser detritiation cycles without causing significant damage to the tile surfaces.

5. Conclusions

During the laser-cleaning trials it was found that one scan was sufficient to completely change the appearance of the treated region and expose the fibre planes of the tile. From cross-sectional micrographs, IBA and SIMS of the treated areas it was found that three scans resulting in a cleaning rate of $12x10^{-3}m^2$/hr provided the most effective settings overall for removing deposited material.

In order to demonstrate that laser cleaning can provide a practical solution for the detritiation of co-deposit a scan rate of $72x10^{-3}m^2$/hr was used to clean half the surface area (165mm x $150mm^2$) of a larger tile 3 from JET with a mixed Be/C deposit. Although a majority of the co-deposit was removed, subsequent analysis showed that some film was still present on the tile, however it is expected that the laser parameters could be optimised to maximise material removal in an acceptable time scale.

Throughout the laser cleaning trials the difference in threshold between the removal of co-deposit and CFC substrate has been clearly demonstrated, although some further optimisation is required to reduce damage to the substrate surface to a minimum. By establishing this differential the use of laser-cleaning has been proven as a practical technique for the detritiation of tokamak surfaces by complete removal of co-deposits, such as those likely to occur in ITER, provided the fine dust created can be removed by maintaining a suitable airflow.

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