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ABSTRACT

The retention of Tritium (T) by carbon based deposits on tokamak surfaces is of increasing concern to the fusion community as the scale of tritium retention by this mechanism could be a limiting factor for the operation of fusion reactors, such as ITER. Hence there is a need to investigate ways of mitigating T retention and also for detritiating surfaces by either desorption of T or removal of tritiated deposits. The results of the removal of co-deposits from CFC tiles by pulsed laser ablation are reported here. The results show that it is possible to completely remove a 300μm thick hydrogen isotope rich carbon film at a rate of $12\times10^{-3}m^2$/hr by this method and that with optimisation of the laser parameters there is scope to improve the treatment rates to provide a useful tool for managing T inventory in tokamaks.

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 [1]. Thus within the fusion community increasing efforts have been directed at the detritiation of tokamak surfaces. Here we report on the efficacy of laser ablation as a method for removing co-deposited material, in contrast with laser induced thermal desorption of T demonstrated elsewhere [2]. Laser ablation has been used in a variety of environments as an effective surface cleaning technique, for example the removal of paint during the decontamination of hot cells [3], and has also been demonstrated in the removal of co-deposits from tokamak tile surfaces [4]. Trials of a scanning 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 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 inventory 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 Yb-doped fiber 1070nm laser with a pulse energy of 1mJ, pulse length of 120ns and repetition rate of 20kHz. The laser beam was focused using a lens to give a spot size of 150μm diameter (defined at $1/e^2$ of peak intensity) delivering a peak fluence of 10.4J/cm^2 at a focal length of 496mm. The beam was directed on to scanning mirrors allowing it to be scanned over a maximum area of 500mm×500mm on the target surface. In addition, there was a red 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.

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 $v = 0.2$m/s, with $\Delta X = 10\mu$m and $\Delta Y = 100\mu$m. For regime 1 the laser was scanned across the surface of the tile twice with the second scan being offset by $\delta Y = 50\mu$m. This gave an overall treatment rate of 36×10^{-3}m^2/hr. For regime 2 the second scan was not used giving an overall treatment rate of 72×10^{-3}m^2/hr. A similar relationship exists between regimes 3 and 4 where $v = 1.0$m/s and regime 3 had two laser passes per scan cycle while 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.

Three tiles were cleaned during the trials, 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 former being in-vessel from 1998-2004 and the latter in-vessel from 2001-2004. The position of these tiles in the 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. The 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 initial cleaning in the shadowed region of tile G4A5BW it was found that a single scan was sufficient to completely change the appearance of the treated areas; 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 confirms that the co-deposit was not completely removed. 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 (b) in Fig. 3), thus showing that the deposit had been removed; for comparison the curve (c) in Fig.3 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.

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 (60mm×20mm). 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 ≤445mm, i.e. ≥13mm from the focal plane and equivalent to an energy fluence ≤1.7J/cm^2, showing the practical limit of depth of focus 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 at a faster rate. For this trial the time to clean an area 25×10^{-4}m^2 was ~20 minutes.

Figure 1 shows tile G3B14IN after laser cleaning with the toroidal fibre planes (running horizontally in the image) visible on the right hand side 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. Further optimisation to obtain the most efficient parameters 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 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 thermal desorption (off-gas) measurements. The expected activity of the surface co-deposit was calculated based on off-gas measurements of the tile and comparison of data with previous determinations of T from total combustion data. SIMS and IBA measurements of many other tiles [5,6,7] show that a majority of the T on tile 4 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. If such micro-particles still contained their T, the activity of the filter after the laser cleaning trials would compensate for the discrepancy observed, however the T inventory of the filter was insufficient to account for the material removed from all three tiles. It was not possible to ascertain whether the micro-particles were elsewhere in the ventilation system as the expected activity from them was low compared with the background levels of 0.5GBq/day from the entire BeHF. Alternatively the T may have been driven into the bulk of the tile by the laser whilst the film was being removed, however this seems unlikely since the dwell time at any point is very short and there is no evidence of significant heating of the substrate. 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.

DISCUSSION

Although the removal of co-deposit was largely successful, once the co-deposit was removed the laser energy densities were sufficient to damage the CFC tile surface.

The damage was found to be 0.2-2.0μm of CFC removed per scan cycle at the slowest scan speed of 0.2m/s. Clearly for laser cleaning to be a successful method for the detritiation of tiles it is important that the tiles should be able to withstand many laser detritiation cycles without causing significant erosion which would limit the lifetime of the targets. Additional studies at CEA, Saclay have shown that the threshold fluence for erosion of the CFC tile substrate is dependent on both the flux and the scan speed, i.e., the step size between pulses. For a scan speed of 0.2m/s the threshold fluence of the CFC was shown to be 8J/cm^2, significantly higher than 1.7J/cm^2 for the co-deposit determined from cleaning area 8 on the sloping face of tile G4A5BW (see Fig.2a) at the same speed. At scan speeds ≥0.2m/s, the threshold fluences are higher.

The rate of removal of T is an issue for all cleaning techniques, especially for deployment in ITER where an area of 50m^2 in the divertor, and possibly the surfaces in gaps between tiles, are expected to require detritiation. Further work on a replica of the JET divertor structure at CEA, Saclay has demonstrated that cleaning is possible with the laser beam incident on the tile surface at a glancing angle, in particular for reaching the shadowed region of tile 4. However, further work would be required to confirm the range of oblique angles for which the LCU is effective. From the trials it is clear that optimisation of the laser scanning parameters would be required to enhance co-deposit removal rates with the aim of reducing a shutdown period required for *in situ* T removal. It would also be necessary to have a method for collecting the micro-particles produced during cleaning. However the LCU have proved to be an effective method for removing co-deposits up to 300μm and could thus be a useful technique for the management of T inventory in ITER.

CONCLUSION

During the laser-cleaning trials it was found that one scan at a treatment rate of 36x10^{-3}m^2/hr was sufficient to remove a majority of a 300μm thick co-deposit exposing the fibre planes of the tile and that after three scans all deposited material was completely removed.

To demonstrate laser cleaning as a practical technique for detritiation, a scan rate of 72×10^{-3}m^2/hr was used to clean the co-deposit from an area 25×10^{-4}m^2. Although a majority of the co-deposit was removed, subsequent analysis showed that some still remained. It is expected, however, 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 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 possible 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 during the cleaning process.

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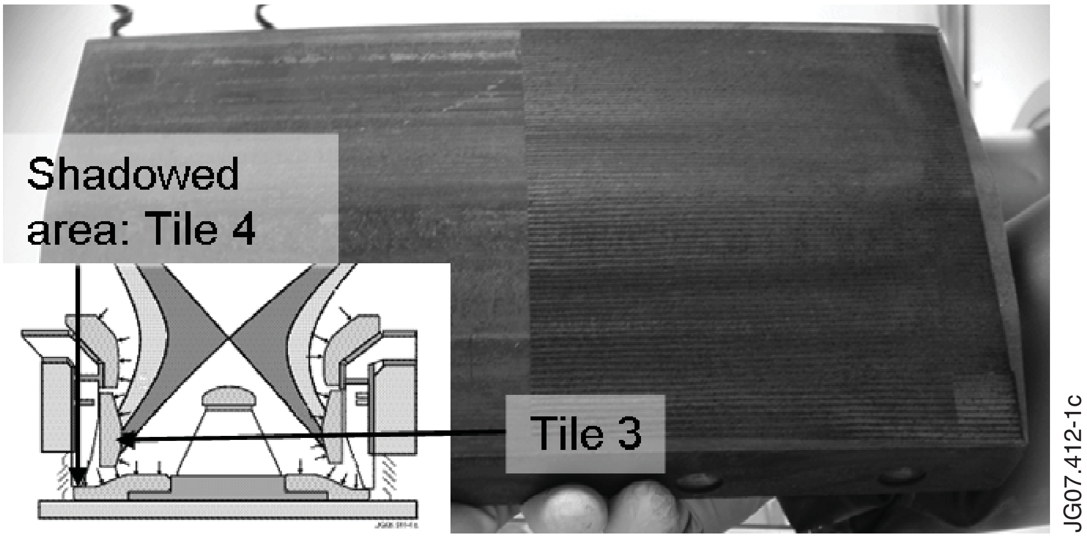

Figure 1: Shows tile G3B14IN after half of the surface has been laser cleaned. CFC fibre planes are visible on the right hand side of the photograph. The insert shows the positions of tile 3 and tile 4 in divertor (MkIIGB shown).

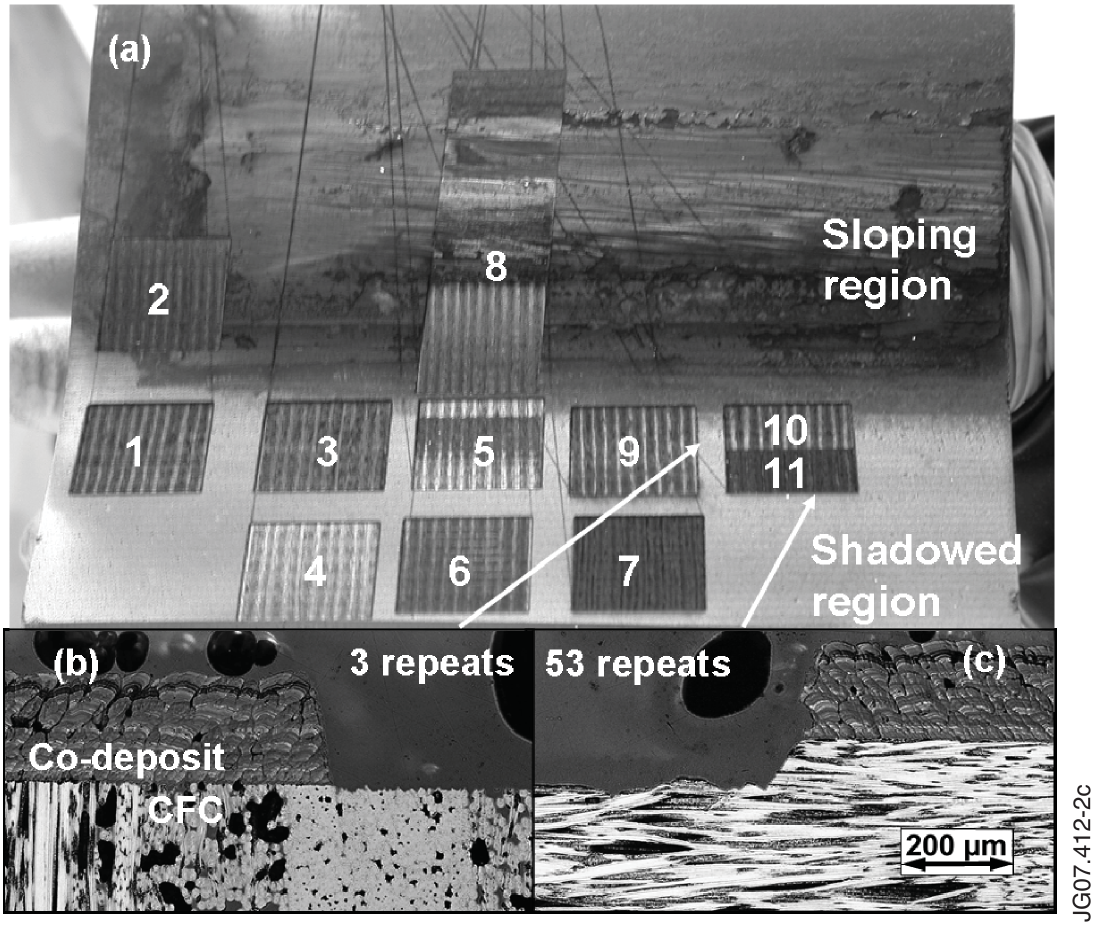

Figure 2(a): Photograph showing areas cleaned on tile G4A5BW using different scanning regimes. Figures 2b and 2c show cross-sections of the interfaces indicated by the arrows. The 200mm marker applies to Figures 2b and 2c.

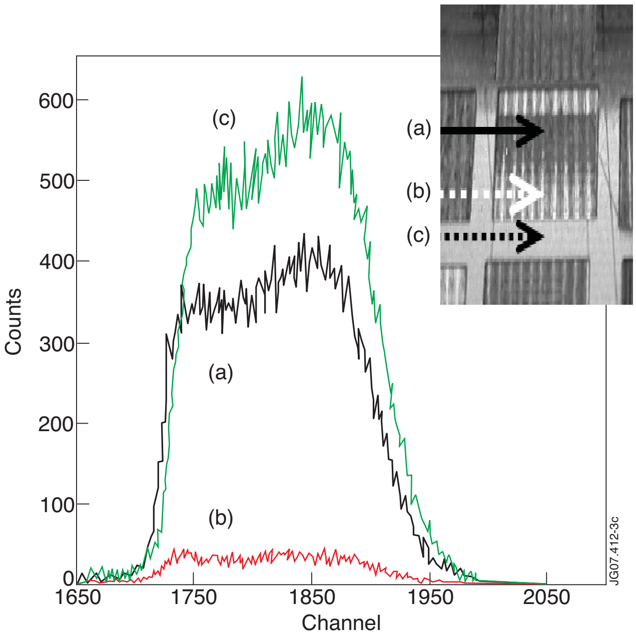

Figure 3: Deuterium peak from NRA measurements in area 5 (see Fig.2). Data set 3a is from a region where the co-deposit was not completely removed, 3b is from a region where a majority of the co-deposit was removed and 3c is from a non-treated region.