

Dust Removal from Next Generation Tokamaks by Laser and Flashlamp Cleaning

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Abstract

Next generation tokamaks offer the possibility of highly efficient energy generation from the fusion of tritium and there is a large scale international effort to develop this technology. Part of the wall linings of the tokamak reactor are carbon-carbon fibre composite tiles and during operation these tiles become liberate a carbonaceous debris ('dust') comprising flake like particulates and more continuous 'soft' carbon (polymeric CH) and 'hard' carbon (diamond-like) layers. Since this dust contains tritium, the build up leads to an increase in the allowable tritium load if the dust is not periodically removed.

Amongst candidate removal methods, photonic based techniques employing pulsed xenon flashlamps and Q-switched Nd:YAG laser pulses have been investigated. The flashlamp based work has been carried out at UCSD and the laser based work at Liverpool using carbon-carbon fibre composite tiles coated with simulated CH ('soft' carbon) films of thickness 7 microns. It has been shown that at a fluence of 3.4 J/ sq cm and a pulse length of 200 microseconds, the xenon flashlamp pulses were effective in removing the coating without damaging the substrate. Similarly a 300W Nd:YAG laser giving pulses of 6ns was also effective in removing the film. Substrate condition after cleaning was observed by SEM. A simple model to account for the temperature rise produced during cleaning has been developed and possible removal mechanisms have been proposed. Details of further work in this continuing project will be presented.

Introduction

1.1 Background on fusion

Plasma must be heated to about fifty million degrees kelvin to induce and sustain the fusion reaction required to produce usable amounts of energy. At these temperatures, the nuclei in the plasma move rapidly enough to overcome their mutual repulsion and fuse. The mass difference between the separate light elements and the newly produced heavier elements is released as energy. This is the energy that sustains stars such as the sun and which offers the possibility of abundant, relatively pollution free energy for practical use. Whereas the fusion reaction that powers the stars is based on the fusion of hydrogen nuclei to form deuterium:



where β^+ represents a positron and ν stands for a neutrino, the reaction exploited for practical power generation fuses deuterium and tritium nuclei and produces helium ($4/2\text{He}$) and a neutron ($1/0n$)



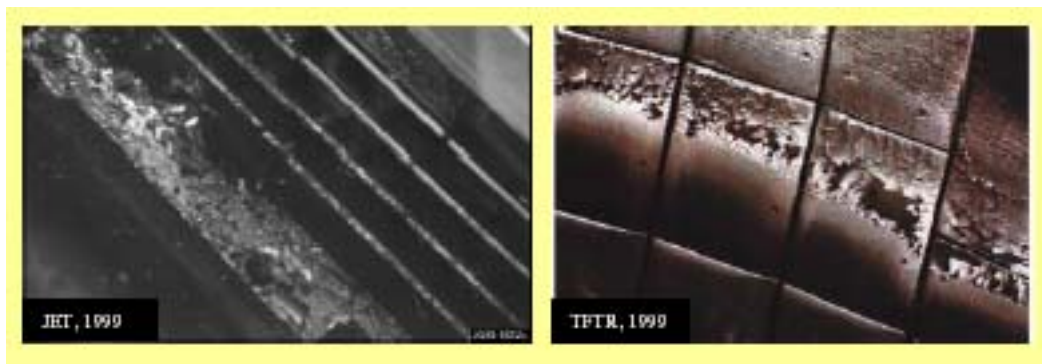
This reaction has a positive Q-value of 17.58 MeV. If one metric ton of deuterium is consumed through burning via fusion reaction (2) with tritium, the energy released would be 8.4×10^{20} joules. This can be compared to the energy content of one ton of coal (2.9×10^{10} joules). One ton of deuterium has the energy equivalent of approximately 29,000,000,000 tons of coal. Deuterium is readily available from sea water.

The development of the tokamak - a toroidal magnetic confinement system in which the plasma is kept stable both by an externally generated, doughnut-shaped, magnetic field and by electric currents flowing within the plasma itself - has offered the most realisable means of achieving the containment of the fusion reactants at the extraordinarily high temperatures required. Significant fusion power has been achieved in two large tokamak devices, TFTR (10.7 MW) and JET (16 MW) [1]. A much larger (1500 MW) next step device (ITER) has been designed as a result of international effort but awaits implementation in its full scale.

1.2 Materials issues and hydrocarbon film deposition in tokamaks

In tokamak operation where the high temperatures for fusion must be accommodated in the working (core) plasma, the edge plasma and the surrounding material surfaces are required to provide a buffer between the high temperature core and the normal environment. The edge plasma must provide good thermal insulation and prevent impurities from reaction with the containing environment from denaturing the core plasma. The wall must withstand the high heat load and high particle flux from the core as well playing an important role (via preconditioning treatments) in the recycling of hydrogen isotopes. In order to achieve the first of these aims, the limiter and divertor concepts were developed. The limiter which is made from refractory material is positioned to ensure a gap of some several centimetres between the edge plasma and the vacuum walls. In the divertor concept, the source of first plasma contact is removed to some remote location away from the core plasma where impurity generation from interaction with the wall materials could be contained and retained in the divertor. The divertor is also used to exhaust He.

Control of the plasma-material interactions (PMIs) is required for commercial operation in next step tokamaks. A central issue is thus the selection of materials for the plasma facing (PFC) components. Typical materials in use in different PFC regions of the limiters and divertors are molybdenum, tungsten and C-C fibre composite material. Carbon is a favoured material since any carbon atoms reaching the core will be fully stripped, hence reducing core radiation associated with W impurity atoms. While this strategy has met with success in terms of the purity of the core plasma, significant erosion of carbon (and the other materials) has been found to occur during operation, forming deposits known as tokamak 'dust' [2,3]. Redeposition of the eroded carbon with tritium is observed [4,5]. As a result co-deposited hydrocarbon films form as a result of the operation of the reactor (Figure 1).



(a)

(b)

Figure 1 Hydrocarbon films (a) as flaking deposition on the louvres at the inner corner of the JET Mk-IIA divertor [1], b) as particulates in TFTR [1]

The deposits have been found to form as well adhered hard films (with low D/C), as loose, soft films (with high D/C) or as flakes (0.1 – 5.0 mm x 30 – 60 μm). Typical locations for dust formation of this type are shown in Figure 2.

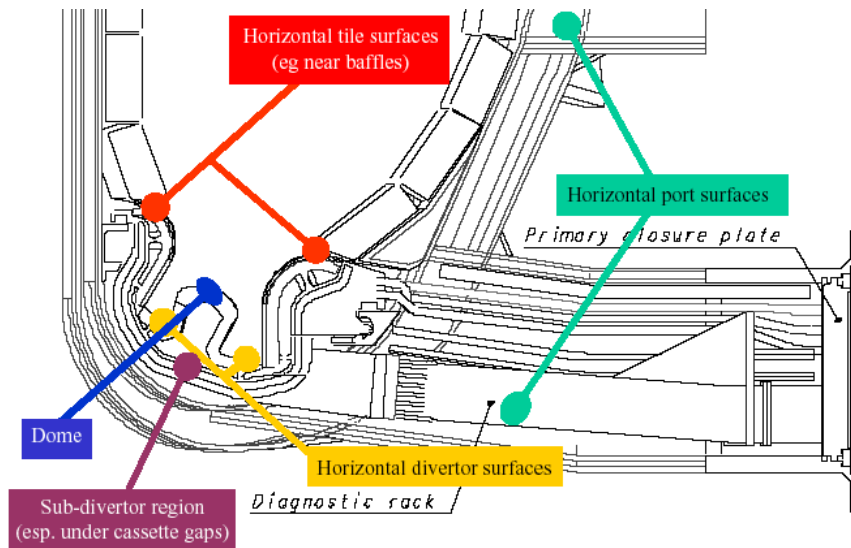


Figure 2. Typical sites for dust formation in a tokamak environment [1].

The principal problem associated with the formation of the H-C dust is the uptake of radioactive tritium within it. During operation, a maximum tritium inventory is allowed which cannot be exceeded for safety reasons. As shown in Figure 3, a simple estimate predicts that the tritium inventory limit associated with the formation of C-H dust is exceeded in 50 – 250 pulses.

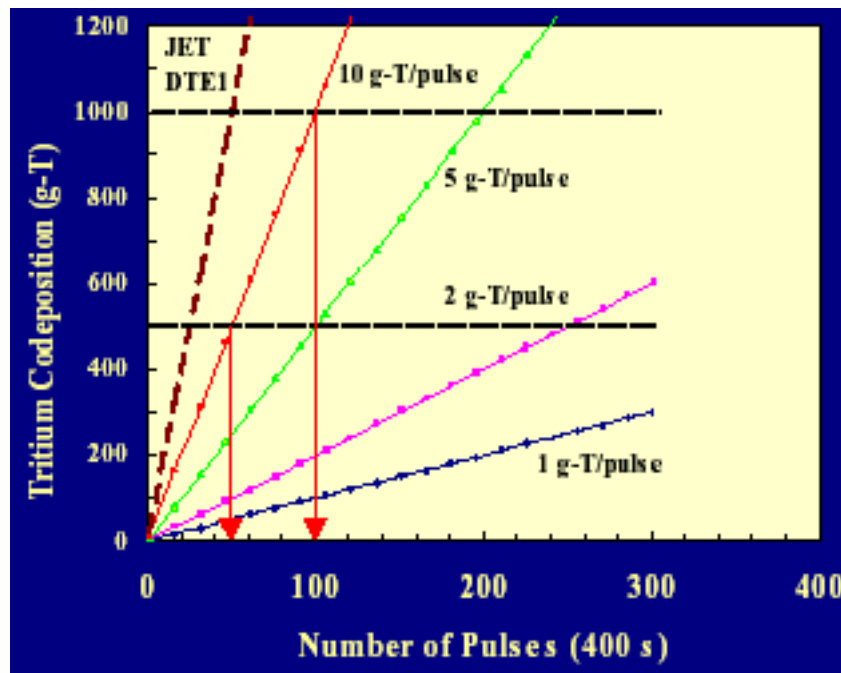


Figure 3 Upper and lower bound limits of tritium inventory versus number of pulses for operational tokamak [1]

In late 1998 EFDA created a task (Task DV7a-T438) aimed at investigating the design of equipment for the detection of dust in a next-step device (to allow real time extrapolation of total

in-vessel inventories) and for the removal of dust from the vessel, both with the minimum possible impact on operations and maintenance. It was required to remove the dust in three steps:

- Detach debris from surface
- Collect and transport mobilised material
- Exhaust material from vessel

The following ideal conditions were required to be met:

- Little or no impact on vacuum conditions
- To be carried out high field conditions (without warming superconducting systems)
- With minimum vessel access requirements.

The work reported here concerns a preliminary study of the laser based and flashlamp based approaches developed in Task DV7a-T438.

2. Experimental

Simulated soft HC deposits on carbon-carbon fibre composite tile samples (4 cm x 3 cm) were deposited to a thickness of 7 μ m by a sputtering technique. A scanning electron microscopy image of the as deposited film is shown in [Figure 4](#) and reveals that the film is made up of many coalesced sub-micron spherical deposits; this morphology is believed to be typical of soft HC deposits in tokamaks.



Figure4. SEM micrograph of as deposited soft H-C film

For flashlamp cleaning experiments, the experimental system used comprised a linear xenon flashlamp of 8 mm bore and 7.5 cm arc length mounted in a reflective aluminium housing. The lamp was controlled by a 500W Analogue Modules laser / flashlamp controller, resulting in 100J stored energy in driver at 1.5 kV. Maximum repetition rate was 5 Hz and the pulse length was 200 μ s. This resulted in a flux of 3.4 J /sq cm on the target. Tests were carried out at ambient pressure and in vacuum at about 50 millitorr.

For the laser based experiments, a 300W Lynton Lasers Q-switched Nd:YAG Paragon laser with a pulse length of 6 ns and a repetition rate of 10 Hz was used. The beam was delivered to the workpiece using a mirror based articulated arm and experiments were carried out at ambient pressure.

Assuming typical values for the physical properties of soft HC and hard C films, a simple one dimensional surface heating model was used to predict the peak surface temperature and the penetration depth of the cleaning effect.

3. Results and discussion

3.1 Flashlamp based cleaning

Under the above conditions, it was found that the simulated 'soft' HC film was almost completely removed in 5 pulses in air and in vacuum. Scanning electron microscope (SEM) observations of the samples before and after treatment (Figure 5) showed that while the HC film was completely removed from most regions of the surface, islands of retained material (possibly redeposited after initial removal) remained.

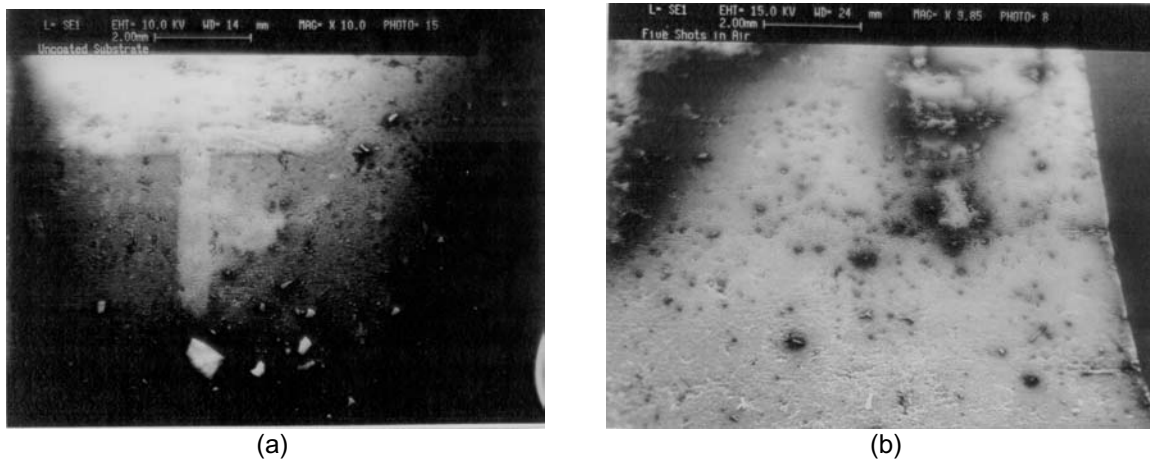


Figure 5. SEM micrographs of C-C composite tiles (a) as received (uncoated), b) after flashlamp cleaning with five 200 μ s pulses at 5 Hz and at 3.4 J/cm² per pulse

The width of the cleaned region was approximately 1 cm across the whole width of the sample (3 cm). Given that the cleaned region would be 1 cm x 7.2 cm (the lamp length) if using larger samples, the cleaning rate could be estimated as 7.2 cm² /s (or 2.6 m² /hr). On scale-up to a more powerful controller delivering the same fluence per shot at 500 Hz, the cleaning rate would be 260 m² /hr which would be practical. Further study is required to determine the mechanism of removal. A significant finding (compared with alternative suggested method of HC film removal in tokamaks employing oxygen induced reactions) is that the removal method did not depend on the presence of oxygen (at least down to the vacuum levels available in these preliminary experiments).

3.2 Laser based cleaning

Use of the Q-switched Nd:YAG laser resulted in complete removal of the HC film in 2 –3 shots per position with the area cleaned being approximately 1 cm². The method of removal was not determined, but is unlikely to have involved much heating effect since the pulse duration was so short.

3.3 One dimensional surface heating model

For the “soft” form of HC, the following values were assumed, based on typical values for polymeric materials:

$$\kappa = 0.2 \text{ W / m.K}$$

$$\rho = 1.42 \times 10^3 \text{ kg / m}^3$$

$$C_v = 1090 \text{ J / kg.K}$$

where

κ = thermal conductivity
 ρ = density
 C_v = specific heat

Since

$$\alpha = (\kappa) / (\rho \cdot c_v) \quad (1)$$

where

α = thermal conductivity

$$\alpha = (0.2) / (1.42 \times 10^3) \cdot (1090)$$

$$\alpha_s = 1.29 \times 10^{-7} \text{ m}^2 / \text{s}$$

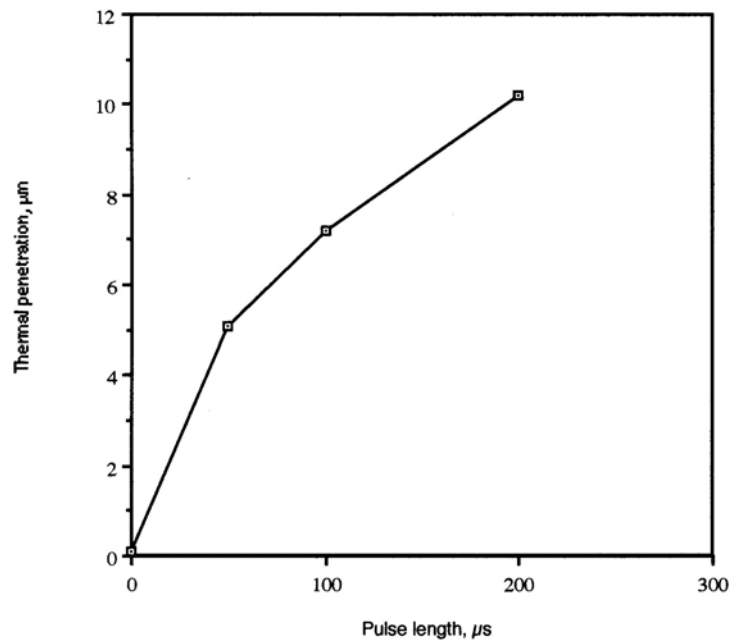


Figure 6 Approximate variation of thermal penetration depth with pulse length for 'soft' HC layer

For one dimensional surface heating in which the area of the beam at the surface is much larger than the thermal diffusion distance, z , to a first approximation, z is given by:

$$z \sim 2(\alpha_s \cdot t)^{0.5} \quad (2)$$

where

t = pulse length.

The flashlamp used in the tests had a pulse length of 200×10^{-6} s. Controllers are available that can pulse the lamp at 100×10^{-6} s or 50×10^{-6} s. For a pulse length of $200 \mu\text{s}$ the depth of penetration of the thermal wave as given by equation (2) is:

$$\sim 2 [(1.29 \times 10^{-7}) \cdot (200 \times 10^{-6})]^{0.5}$$

$$\sim 2 [2.58 \times 10^{-11}]^{0.5}$$

$$\sim 2 [5.079 \times 10^{-6}] \text{ m}$$

$$\sim 10.2 \mu\text{m}$$

Figure 6 shows a plot the results of this calculation to give the variation of thermal penetration depth with pulse length for lamps operating at shorter pulse length and for the 10ns Q-switched Nd:YAG laser.

The predicted thermal penetraton distance for the Nd:YAG laser is 72 nm. This suggests that in the practical removal of the film, it would be advantageous to use the laser in normal mode in order to achieve a greater depth of penetration as a result of the longer pulse length.

For the 'hard' form of C deposit, the following values were assumed, based on lower bound typical values for diamond-like C (DLC) films:

$$\kappa = 400 \text{ W / m.K}$$

$$\rho = 2.1 \times 10^3 \text{ kg / m}^3$$

$$c_v = 520 \text{ J / kg.K}$$

Again, since

$$\alpha = (\kappa) / (\rho \cdot c_v) \quad (1)$$

$$\alpha = (400) / (2.1 \times 10^3 \cdot 520)$$

$$\alpha_h = 3.66 \times 10^{-4} \text{ m}^2 / \text{s}$$

The thermal penetration distance for a 200 μs pulse, given from (2), is 540 μm . The predicted thermal penetration distances for shorter pulse length lamps and for the Q-switched laser pulse are shown in Figure 7. Since the thermal conductivity of the 'hard' film is much larger than that of the 'soft' film, there is a considerable increase in thermal penetration in the former case.

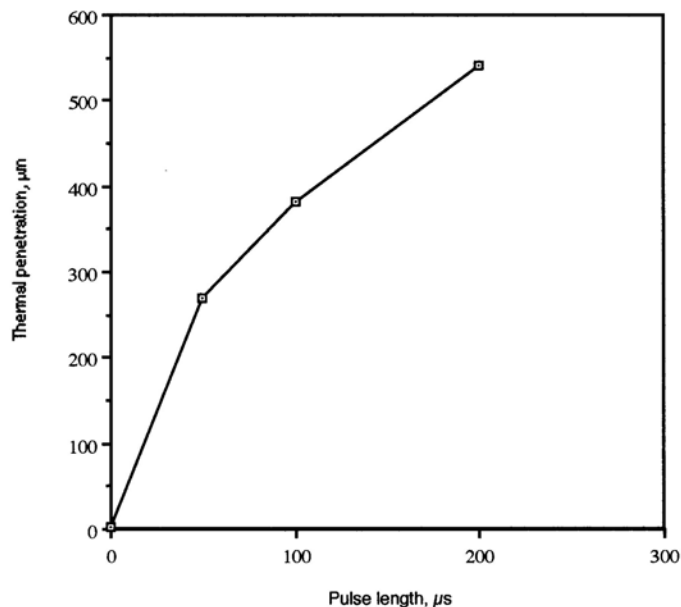


Figure 7 Approximate variation of thermal penetration depth with pulse length for 'hard' C layer

For the one dimensional heating model, the peak surface temperature can be predicted from:

$$T_{(0,t)} = [2 \beta \cdot I_0 / \kappa] \cdot [\alpha t / \pi]^{0.5} \quad (3)$$

where

- $T_{(0,t)}$ = peak surface temperature (K)
- α = thermal diffusivity (m^2 / s)
- t = pulse length (s)
- κ = thermal conductivity (W / m.K)
- β = absorption coefficient
- I_0 = incident intensity (W / m^2)

For the 'soft' HC film and assuming that $\beta = 0.8$ and that the physical property values are as before, at a pulse length of $200 \mu s$

$$\begin{aligned} T_{(0,t)} &= [2 \beta \cdot I_0 / \kappa] \cdot [\alpha t / \pi]^{0.5} \quad (3) \\ &= ([2] \cdot [0.8] \cdot [I_0] / [0.2]) \cdot ([1.29 \times 10^{-7}] \cdot [200 \times 10^{-6}] / [\pi])^{0.5} \\ &= ([2] \cdot [0.8] \cdot [I_0] / [0.2]) \cdot (8.211 \times 10^{-12})^{0.5} \\ &= ([2] \cdot [0.8] \cdot [I_0] / [0.2]) \cdot (2.865 \times 10^{-6}) \\ T_{(0,t)} &= 2.29 \times 10^{-5} I_0 \quad (4) \end{aligned}$$

The peak surface temperature for the 'soft' film predicted by equation (4) for lamp fluence in the range $1 - 20 J / cm^2$ is shown in [Figure 8](#).

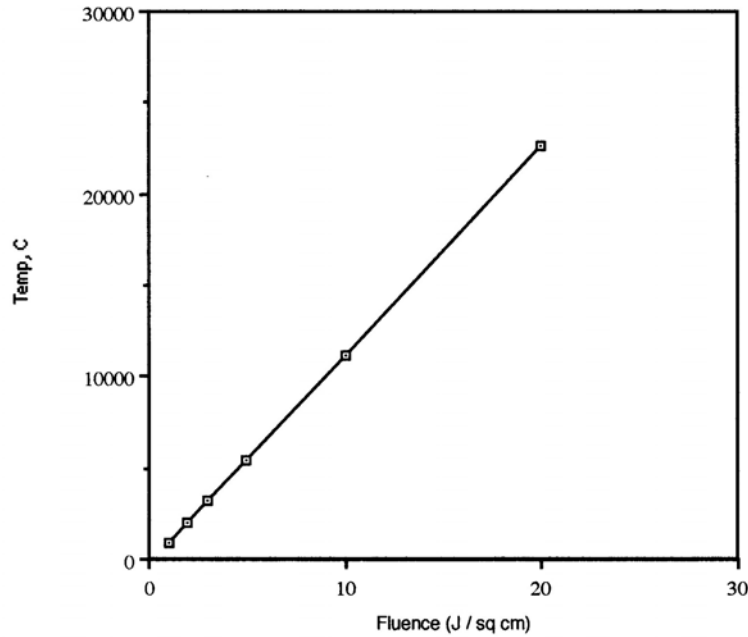


Figure 8 Predicted variation of peak surface temperature with fluence for a pulse length of $200 \mu s$ for 'soft' HC layer

For the fluence and pulse length used in the flashlamp experiments (3.4 J / cm² and 200 μs), a peak surface temperature of 3,620 C is predicted. The effect of shorter pulse length pulses is to increase the peak surface temperature for a given fluence.

For the 'hard' C film and assuming that β = 0.8 and that the physical property values are as before, at a pulse length of 200 μs

$$T_{(0,t)} = [2 \beta \cdot I_0 / \kappa] \cdot [\alpha t / \pi]^{0.5} \quad (3)$$

$$= ([2] \cdot [0.8] \cdot [I_0] / [0.2]) \cdot ([3.66 \times 10^{-4}] \cdot [200 \times 10^{-6}] / [\pi])^{0.5}$$

$$= ([2] \cdot [0.8] \cdot [I_0] / [0.2]) \cdot (2.33 \times 10^{-8})^{0.5}$$

$$= ([2] \cdot [0.8] \cdot [I_0] / [0.2]) \cdot (1.69 \times 10^{-4})$$

$$T_{(0,t)} = 6.76 \times 10^{-7} I_0 \quad (5)$$

The peak surface temperature for the 'hard' film predicted by equation (5) for lamp fluence in the range 1 – 20 J / cm² is shown in Figure 9. It can be seen that the predicted temperature rise is much lower than for the 'soft' HC film. For the fluence and pulse length used in the flashlamp experiments (3.4 J / cm² and 200 μs) little effective surface heating is predicted.

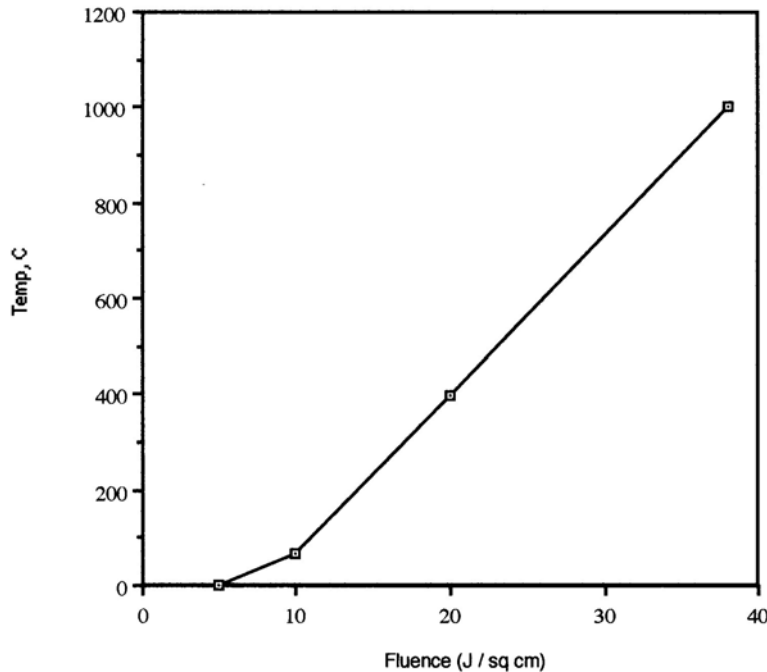


Figure 9 Predicted variation of peak surface temperature with fluence for a pulse length of 200 μs for 'hard' C layer

This simple one dimensional model shows that for the "soft" coating the peak surface temperature reached by a 200 μs pulse length lamp operating at a fluence of 2 or 3 J / sq cm is predicted to be sufficient to remove the CH layer by volatilisation / sublimation (assuming that this is complete by 3,000 C). In contrast, the same fluence applied to the "hard" coating would have little heating effect. A different removal method (such as mechanical stress waves generated by very short pulse radiation) might be required. A Q-switched Nd:YAG laser may be useful for this purpose.

Conclusions

1) Simulated 'soft' HC films of thickness 7 μm on a C-C fibre composite substrate were removed by 5 pulses of duration 200 μs and a fluence of 3.4 J / cm^2 using a xenon flashlamp at 5 Hz. A similar effect was observed using a Q-switched Nd:YAG laser.

2) Based on reasonable assumptions about the physical properties of the 'soft' and 'hard' C films, a simple one-dimensional model predicts that removal of the "soft" film by relatively long duration flashlamp pulses should be possible by localised surface heating leading to volatilisation / sublimation. At the same time, a different removal mechanism (such as mechanical stress wave production) may be required for the 'hard' C film.

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Dr Ken Watkins is Reader and Head of the Laser Group at University of Liverpool and Director of the Lairdside Laser Engineering Centre. He is an expert in research and development in laser materials processing, a keen advocate of education in the lasers field and a proponent of technology transfer for the benefit of industrial applications of optical energy. His research interests include uses lasers in a range of novel processes, including: industrial applications, the cleaning and restoration of art works and medical applications.