Fusion Engineering and Design 103 (2016) 38–44

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Cleaning of carbon materials from flat surfaces and castellation gaps by an atmospheric pressure plasma jet

C. Stancu[a], D. Alegre[b], E.R. Ionita[a], B. Mitu[a], C. Grisolia[c], F.L. Tabares[b], G. Dinescu[a,*]

[a] National Institute for Laser, Plasma and Radiation Physics, Atomistilor Str. 409, PO Box Mg36, Magurele-Bucharest, 077125, Romania
[b] Laboratorio Nacional de Fusión, As. Euratom/Ciemat, Avda. Complutense 22, 28040, Madrid, Spain
[c] CEA, IRFM, F-13108, Saint-Paul-lez-Durance, France

HIGHLIGHTS

- Atmospheric plasma jets operated with nitrogen, oxygen and their mixtures are used for cleaning surfaces of carbon residues
- Efficient plasma jet cleaning of carbon deposits from flat surfaces and inside gaps of castellated surfaces is demonstrated
- Plasma jet cleaning is more effective at the gaps entrance and on their bottom

ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form 5 October 2015
Accepted 11 December 2015
Available online 29 December 2015

Keywords:
Cleaning in gaps
Carbon erosion
Plasma jet
Atmospheric pressure plasma
Wall cleaning
plasma torch

ABSTRACT

A study of the removal of carbon layers from flat and castellated surfaces by a plasma jet source operated in open atmosphere is presented. Amorphous hydrogenated carbon films deposited on silicon substrates, on aluminium made castellated surfaces, and graphitic carbon plates were used. The erosion effects of plasmas generated either in pure argon, nitrogen or in their mixtures with hydrogen, ammonia, oxygen are compared. Highest erosion was obtained with nitrogen and nitrogen/oxygen plasmas. Plasmas in argon and containing hydrogen, and ammonia have shown a low erosion rate. A large removal rate by pure nitrogen plasma jet of 3.2 mg/min was found by scanning graphitic carbon flat surfaces for optimum process parameters. Adding small quantities of oxygen led to a removal rate enhancement by a factor of 3. Finally, the integral removal rate of amorphous hydrogenated carbon deposited in gaps 23 mm deep and 0.5 mm wide was of the order of 0.35 mg/min. The layer elimination was more efficient at the top and at the bottom of the gaps, precisely where the thickest codeposits develop in a nuclear fusion device.

1. Introduction

In nuclear fusion reactors some of the fuel, tritium gets retained inside the vacuum vessel in the plasma facing materials. In the case of carbon-based reaction vessels, the codeposits produced during their operation retain significant amounts of tritium, so that a treatment becomes necessary in order to recover the adsorbed tritium. However, this needs to be achieved without creating deleterious products, such as: tritiated water, reactive dust, residual films that can trap/absorb tritium again easily, etc.

Due to these issues, carbon materials were excluded from ITER strike points in spite of their good resilience to heat loads. The removal of carbon codeposit is still worth investigating due to the potential failure of tungsten tiles at the strike points in which case carbon materials must be implemented. Moreover, there are many important experimental nuclear fusion devices in the world operating with carbon plasma facing materials (DIII-D, TCV, etc.), as well as new ones (JT-60SA, KSTAR, Wendelstein-7X), which may eventually require a control of the development of carbon codeposits to maintain optimal device operation (mainly to avoid major disruptions caused by the increase of the area where carbon can be ejected in the plasma [1]).

Many techniques have been developed in laboratory and nuclear fusion devices to clean codeposits and to reduce their side-effects: glow discharges [2–5], laser and flash lamp [6–9], thermo-oxidation [10–13], etc. Amorphous hydrogenated carbon codeposits (a-C:H) are easy to eliminate as they develop volatile compounds that can be pumped out, but the codeposits on plasma-shadowed surfaces, such as those inside castellation gaps, are more difficult to treat due to limited accessibility. We propose a different technique, based on an atmospheric pressure plasma jet [14], to clean thick carbon codeposits from open surfaces, which can also be applied

* Corresponding author.
E-mail address: dinescug@infim.ro (G. Dinescu).

http://dx.doi.org/10.1016/j.fusengdes.2015.12.024
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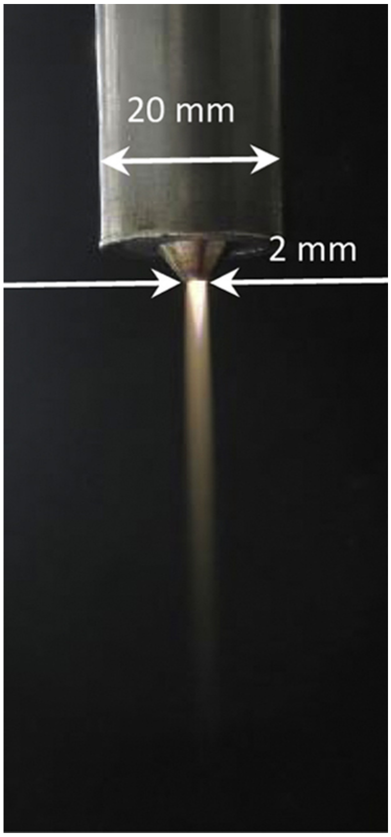

Fig. 1. Image of the plasma jet source.

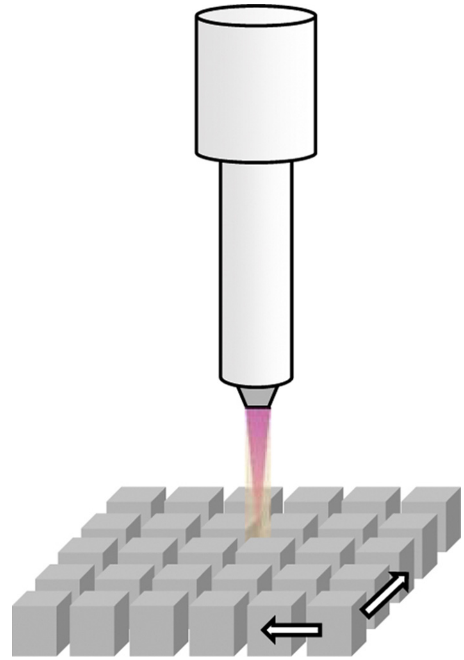

Fig. 2. Schematic of a scanning experiment.

inside castellation gaps (see [15] for the usual carbon codeposits distribution along the vessel). However, no technique is capable of eliminating all carbon codeposits without large side effects. Therefore an integration of the previously mentioned techniques is necessary, see for example [16,17] and references therein.

Atmospheric pressure plasma sources have a variety of applications, for example: surface etching [18,19], surface modification [20], for erosion, deposition and cleaning of surfaces [21–23] or it can also be used in medicine [24]. For carbon codeposits, cleaning with the atmospheric pressure plasma jet is based on the scanning of the surface with a small-size plasma source. In this paper the efficiency of removal of carbon layers from flat surfaces using an atmospheric pressure plasma source working in different reactive gases at room temperature in open atmosphere is demonstrated. Cleaning from narrow gaps is also investigated. The assessment of the cleaning efficiency is performed by profilometry. The removal rates of carbon are calculated from the erosion profiles.

2. Experimental details

The atmospheric pressure plasma jet source used for carbon cleaning experiments is based on a capacitive discharge sustained (at 13.56 MHz) in flowing gas in a space confined between an RF electrode and a grounded nozzle. The plasma jet is obtained by discharge expansion outside the discharge space through the nozzle. A detailed description of the device and its operation principle can be found elsewhere [14,25]. The nozzle has 2 mm diameter. In total, the plasma source has a diameter of 20 mm, it has active water cooling at both electrodes, and can be powered by up to 500 W. An image of the plasma jet source is presented in Fig. 1.

The gases used in the discharge are: air, N_2, O_2 and mixtures of N_2/O_2, Ar/NH_3, Ar/O_2, Ar/H_2. The nitrogen and nitrogen-based mixtures have good carbon erosion properties [13]. Hydrogen and ammonia have also been used in other cleaning experiments [3,17].

The test layers are amorphous hydrogenated carbon films (a-C:H). Layers with a thickness of 1-3 μm and density of 1.85 g/cm^3 were deposited. The layers were produced by Plasma Assisted Chemical Vapour Deposition (PACVD) in a parallel plate radiofrequency discharge reactor. Argon was used as carrier gas, and acetylene as precursor. The substrates were placed at the grounded electrode. Si substrates were used for the experiments devoted to flat surface cleaning. In some cases, erosion rates were found to be very high, and, thick graphitic carbon plates (4 mm thickness, density of 2.2 g/cm^3) have been used instead of the a-C:H layers. In order to assess the capability of the plasma jet device for cleaning inside gaps, the a-C:H layers were deposited on to the faces of aluminium cubes (having edge lengths of 10 and 23 mm, respectively) which were subsequently assembled in castellated structures with defined gap widths (in the range of 0.5-2 mm).

An automatic scanning system has been developed for the erosion experiments. The system consists of a XY translation table, with computer-controlled stepper motors. The experiments were performed by horizontal translation of the coated substrate in front of the fixed vertically positioned plasma source. Various translation speeds and distances between the plasma jet tip and substrate were investigated. In the case of castellated surface, scanning was performed along the gaps using the plasma jet, as indicated in Fig. 2.

Profilometry was used to measure the erosion profile created by exposing the samples to plasma jet. The section of the profile multiplied by the scan length and by the material density allowed the calculation of the removed mass. The erosion rate was determined by the mass of material removed in the processing time.

3. Results and discussion

3.1. Test of carbon erosion capability of various plasma gas mixtures

A preliminary study of the cleaning capability of plasma jet fed with various gases was performed on a 2.2 μm a-C:H film deposited on silicon. First, the gas flow rate and the RF-power were