ITER-LIKE WALL PROJECT AT JET: OPTIMIZATION AND MANUFACTURING AND TESTING OF 10 μm W -COATINGS FOR CFC TILES TO BE INSTALLED IN JET JW6-TA-EP2-ILC-01 (EFDA/06-1507)

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1. Introduction

Currently, the primary ITER materials choice is a full beryllium main wall with CFC (carbon fiber composite) at the strike points and tungsten at divertor baffles and dome. Since this combination has never been tested in a tokamak, ITER-like Wall project has been launched at JET (Joint European Torus) with the aim to replace the actual CFC first wall with a new one, comprising the same materials choice as it planned for ITER operating with the same materials planned for ITER. In the R&D phase of this project (EFDA Task Agreement Code: JW5-TA-EP-BEW-02), seven PVD and CVD technologies have been developed for 10 μm W coating of CFC material by EURATOM Associations from Germany, France, Finland and Romania in cooperation with European coating Companies. As a result of High Heat Flux (HHF) tests carried out in the hydrogen beam facility GLADIS at IPP Garching, Combined Magnetron Sputtering and Ion Implantation (CMSII) technology, proposed by MEdC, was selected for 10 μm W coating of about 1,000 tiles, of different size and dimensions, under industrial conditions

2. Objectives

The main objective of the present project is the coating with 10 μm W approximately 1,000 CFC tiles for installation in JET. About 10% of the coated tiles will be tested at IPP Garching in GLADIS facility in order to check the reproducibility of the deposition process.

In order to achieve this objective, the following deliverables and milestones have been defined for 2007:

- D2/M2 Optimization of the coating method, as applied during the R&D phase, in order to apply it to the JET relevant larger scale production

- D3/M3 Designing, building, commissioning and operating the new W-coatings facilities required for the JET relevant larger scale production and quality control.

3. Results and discussions

The CMSII technique involves simultaneous magnetron sputtering and high energy ion bombardment. In the deposition process, three low pressure electrical discharges (magnetron discharge, DC bias discharge and high voltage pulse discharge) are superposed. Typical parameters for the high voltage pulse discharge are: $U = 30 - 50$ kV, $\tau = 20$ μs, $f = 25$ Hz. The DC bias up to – 900 V is applied between pulses.

The plasma ions from the magnetron discharge are accelerated during the high voltage pulses and strike initially the substrate and then the coating itself during its growing with energies of tens of keV. As a result of the periodical ion bombardment the following effects occur:

- An increase of the surface mobility of the deposited atoms which leads to a high densification of the layer.

- An extremely dense, pore free nano-structure is produced. TEM analyses have shown crystallites with a size of less than 10 nm [1].

- A stress relief at the interface and within the layer. Due to this effect, coatings with a thickness of 10 – 30 μm can be produced. In comparison, the maximum W coating thickness which can be deposited on fine grain graphite substrate is 3 μm.

The deposition rate for CMSII technology is in the range of 4 – 8 μm/h depending on the coating to be deposited.

3.1. Optimization of the coating method

The tiles tested in the R&D phase of the project were coated in a relative small experimental unit (Φ300 x 420 mm) with only one magnetron, using CMSII technique.

The transfer of this technique from this small unit to an industrial unit with 24 magnetrons was an important and difficult task of this project. Many scientific and technological aspects, particularly the plasma interaction from two or more magnetrons were unknown. In order to get information about these aspects an existing vacuum chamber (Φ500 x 450 mm) was transformed into a CMSII deposition chamber with 4 magnetrons.

The experiments carried out with this chamber were focused on the following targets:

- Control of the CMSII discharge produced by two and four magnetrons running simultaneously

- Coating uniformity obtained with two magnetrons

- Optimization of the processing parameters in order to obtain W coatings with a thickness of 9 – 12 μm and the same properties like those produced with the small experimental unit.

The main results of these experiments can be summarized as follows:

a) A four channel power supply has been designed, manufactured and successfully tested as a preliminary version of the power supply for the industrial coating unit. The main characteristics of this power supply were: voltage range: 200 – 1,000 V, current intensity: 0.1 – 2.0 A, current stability: > 98%, number of channels: 4, independent control of each channel, protection to transients to arc discharge.

b) The processing parameters have been optimized and a coating area of approx. 200 x 100 mm where the thickness non-uniformity is in the range of ± 10% was established.

c) The HHF tests carried out at IPP Garching in September 2007 with a lot of CFC samples coated with the intermediary chamber were successfully. The tiles coated perpendicular to fiber planes have been subjected initially to a thermal screening with increasing power densities from 10 MW/m^2 up to 23 MW/m^2 for 1.5 s. This test was followed by a cycling loading of 100 pulses at 16.5 MW/m^2 for 2 s. Microscopic examination of the tested samples reveals no hints of buckling or delamination. Only small tensile cracks have been detected (Fig.1).

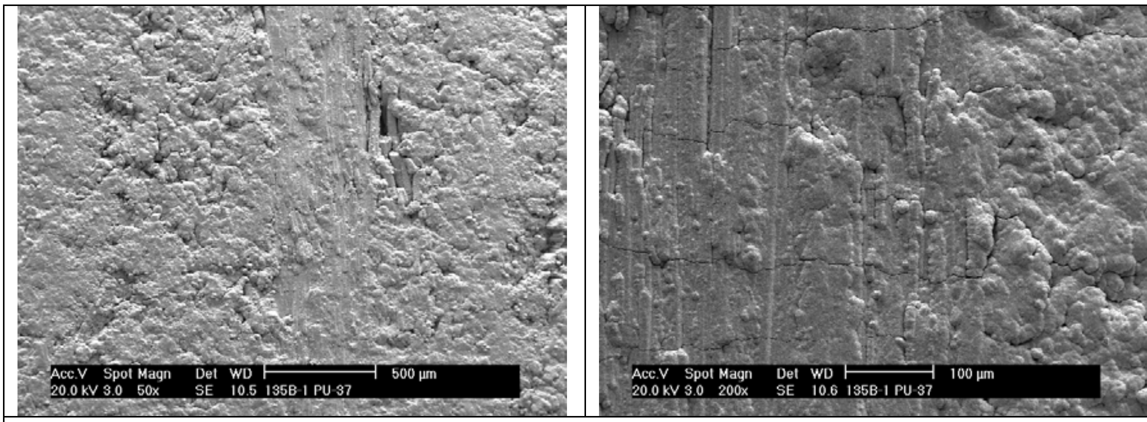
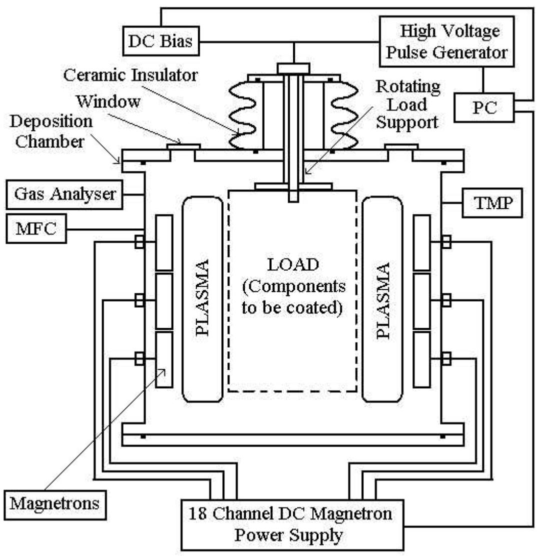


Figure 1. SEM images of the W coatings after HHF tests

3.2. Design and manufacturing of the New Coating Facility (NCF)

Schematic representation and the general view of the coating equipment are shown in Fig.2. The deposition chamber, made of stainless steel with double wall for water cooling, has an inner diameter of 800 mm and a height of 750 mm. Twenty-four magnetrons are positioned inside the chamber in 8 columns of 3 magnetrons each. By this way a usable volume Φ 420 x 360 mm is provided. On the top lid of the chamber there is a ceramic insulator designed to sustain 100 kV. On this insulator a double axes rotating load support is installed. Four widows allow the visual inspection of the load during the coating process. Mass flow controllers (MFC) are used to introduce argon and reactive gases (if necessary) into the deposition chamber. A turbomolecular pump (TMP) of 1,000 l/s ensures the evacuation of the chamber. A gas analyzer with a quadrupole mass spectrometer is connected to the chamber in order to monitor the composition of the deposition atmosphere. The magnetrons are energized by an 18 channel DC power supply with a total power of 25 kW, which was designed and manufactured in the framework of this project. The current intensity for each channel is stabilized (±1%) and can be adjusted independently in the range of 0.3 – 2.5 A. Arc suppression devices are installed to each channel.



(a)

(b)

Figure 2. CMSII coating equipment: schematic representation (a) and general view (b)

The High Voltage Pulse Generator provides pulses up to 50 kV with a width of ~ 20 µs, a frequency of 12.5 - 50 Hz and a maximum current intensity of ~ 40 A.

The coating facility was commissioned by 31.12.2008.

Figure 3. W coated tiles during the HHF test

The first lot of samples coated with the NCF was successfully tested at IPP Garching in hydrogen beam GLADIS machine at power densities up to 23.5 MW/m^2 for 1.5 s and cycling loading at 16.5 MW/m^2 for 2s. No blisters or delamination have been detected after HHF tests. The surface of the W coating looked like that shown in Fig.1. A picture of the tiles during the thermal screening is shown in Fig. 3.

3.3. Qualification of the GDOES method for quality control of the W coatings.

Glow Discharge Optical Emission Spectrometry (GDOES) is currently used for measurement of the coating thickness and impurities as a quality control technique for industrial production. The equipment used for this purpose is GDA – 750 HP machine supplied by SPECTRUMA GmbH, Germany (Fig.4). In each coating run, four witness titanium samples are introduced at different locations including areas where the coating thickness exhibits maximum and minimum values. This solution has been chosen because CFC is porous and it can not be used directly for GDOES analysis. After coating, Ti witness samples are analyzed. Typical depth profiles of W, Mo, C, O and Ti are shown in Fig.5. As it can be seen the C and O concentrations within the W coating are negligible. The thickness measured by GDOES was compared with the thickness measured on the same sample by optical microscopy with a precision of 0.2 µm. The values correspond within an error range of ± 1 µm.

Figure 4. GDOES equipment

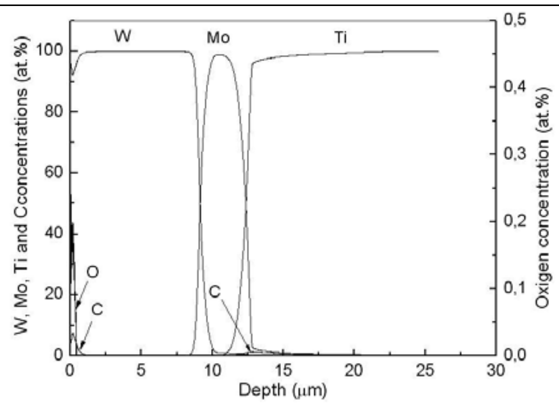


Figure 5. Typical GDOES depth profiles of W, Mo, C and O for a W coating deposited on Ti substrate

3.4. Development of a suitable technique for removal of W coating from CFC tiles

The CFC tiles are very expensive. In order to recover these tiles in case of failure of the coating process, a device and a method were developed for removing the W coating from the CFC surface. The method involves mechanical removal with a diamond tool (Φ15 x 15 mm). A small electric motor rotates a cylindrical diamond tool which easily removes the W coating. By means of a micrometric screw, the depth of the removed layer can be adjusted in the range of 50 – 500 µm. After W removal, the tile is U/S cleaned and dried.

4. Conclusions

All the tasks of the MEdC Association for 2007, in the framework of the Task Agreement JW6-TA-EP2-ILC-01 were fulfilled. Industrial coating equipment based on CMSII deposition method was designed, manufactured and commissioned. The HHF tests carried out at IPP Garching in GLADIS machine proved that the CMSII method can be successfully applied at industrial scale.

5. Collaborative actions

A close cooperation with IPP Garching and JET is established. In April 2007 two specialists from MEdC (C.Ruset and E.Grigore) participated in HHF tests at IPP Garching. Technical aspects concerning the HHF test parameters and their correlation with the W coating characteristics have been discussed. C.Ruset attended the two Project Board and the associated technical meetings at JET.

6. Activities to be performed in 2008

In 2008 the CMSII technology for W coating of CFC substrates will be qualified and CFC tiles from JET first wall will be coated. Quality control documents will be issued for each coating run.

7. Publications

[1] **C. Ruset, E. Grigore, H. Maier, R. Neu, X. Li, H. Dong, R. Mitteau, X. Courtois and JET EFDA contributors**, *"W Coatings Deposited on CFC Tiles by Combined Magnetron Sputtering and Ion Implantation Technique"*, Phys. Scr. T128, 2007, 171 – 174.

[2] **H. Maier, R. Neu, H. Greuner, Ch. Hopf, G.F. Matthews, G. Piazza, T. Hirai, G. Counsell, X. Courtois, R. Mitteau, E. Gauthier, J. Likonen, G. Maddaluno, V. Philipps, B. Riccardi, C. Ruset, EFDA-JET Team**, "*Tungsten Coatings for the JET ITER-like Wall Project*", Journal of Nuclear Materials, Vol. 363-365, 2007, p 1246-1250.

[3] **H. Maier, T. Hirai, M. Rubel, R. Neu, Ph. Mertens, H. Greuner, Ch. Hopf, G. F. Matthews, O. Neubauer, G. Piazza, E. Gauthier, J. Likonen, R. Mitteau, G. Maddaluno, B. Riccardi, V. Philipps, C. Ruset, C.P. Lungu, I. Uytdenhouwen and JET EFDA contributors**, "*Tungsten and Beryllium Armour Development for the JET ITER-like Wall Project*", Nucl. Fusion, Vol. 47, 2007, pp. 222-227.

[4] **R.Neu, H. Maier, E. Gauthier, H. Greuner, T. Hirai, Ch. Hopf, J. Likonen, G. Maddaluno, G. F. Matthews, R. Mitteau, V. Philipps, G. Piazza, C. Ruset, JET EFDA contributors**, *"Investigation of Tungsten Coatings on Graphite and CFC"*, Phys. Scr. T128, 2007, 150 – 156.

[5] **G. F. Matthews, P. Edwards, T.Hirai, M. Kear, A. Lioure, P. Lomas, A. Loving, C. Lungu, H. Maier, P. Martens, D. Neilson, R. Neu, J. Pamela, V. Philipps, G. Piazza, V. Riccardo, M. Rubel, C. Ruset, E. Villedieu and M. Way**, *"Overview of the ITER-like wall project"*, Phys. Scr. T128, 2007, 137 – 143.

[6] **T. Hirai, H. Maier, M. Rubel, Ph. Mertens, R. Neu, E. Gauthier, J. Likonen, C. Lungu, G. Maddaluno, G. F. Matthews, R. Mitteau, O. Neubauer, G. Piazza, V.Philipps, B. Riccardi, C. Ruset, I. Uytdenhouwen and JET EFDA contributors**, *"R&D on full tungsten*

divertor and beryllium wall for JET ITER-like Wall Project", Fusion Engineering and Design, Vol. 82, Issues 15-24, Oct. 2007, pp 1839-1845.

[7] **R.Mitteau, JM. Missiaen, P. Brustolin, O. Ozer, A. Durocher, C. Ruset, C.P. Lungu, X. Courtois, C. Dominicy, H. Maier, C. Grisolia, G. Piazza, P Chappuis**, *"Recent Developments Toward the Use of Tungsten as Armour Material in Plasma Facing Components"*, Fusion Engineering and Design, Vol. 82, Issues 15-24 Oct. 2007, pp 1700-1705.