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The emissivity of W coatings deposited on carbon materials for fusion applications

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**See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

Tungsten coatings deposited on carbon materials such as carbon fibre composite (CFC) or fine grain graphite (FGG) are currently used in fusion devices as armour for plasma facing components (PFC). More than 4000 carbon tiles were W-coated by Combined Magnetron Sputtering and Ion Implantation (CMSII) technology for the ITER-like Wall at JET, ASDEX Upgrade and WEST tokamaks.

The emissivity of W coatings is a key parameter required by protection systems of the W-coated PFC and also by the diagnostic tools in order to get correct values of temperature and heat loading. The emissivity of tungsten is rather well known, but the literature data refer to bulk tungsten or tungsten foils and not to coatings deposited on carbon materials. The emissivity was measured at the wavelengths of 1.064 μm , 1.75 μm , 3.75 μm and 4.0 μm .

It was found that the structure of the substrate, particularly in the case of porous CFC, has a significant influence on the emissivity values. The temperature dependence of the emissivity in the range of 400°C-1200°C and the influence of the viewing angle were investigated as well. The results are given in a table for W coatings and for other materials of interest for fusion such as bulk W and bulk Be.

Keywords: Emissivity, Tungsten coatings, Carbon fibre composite (CFC), ITER-like wall

1. Introduction

Tungsten coatings deposited on carbon materials such as carbon fibre composite (CFC) or fine grain graphite (FGG) are currently used in fusion devices as armour for plasma facing components (PFC). More than 4000 carbon tiles were W-coated by Combined Magnetron Sputtering and Ion Implantation (CMSII) technology for JET, ASDEX Upgrade and WEST tokamaks [1]. The emissivity of W coatings is a key parameter required by protection systems of the W-coated PFC and also by diagnostic tools in order to get correct values of temperature and heat loading of PFC. The emissivity of tungsten is rather well known, but the literature data refer to bulk tungsten or tungsten foils [2, 3]. Extensive research on the spectral emissivity and optical properties of tungsten was performed by L. D. Larrabee [4], but mainly at the wavelengths of 0.3-0.8 μm . More recently the emissivity of W material for ITER divertor was investigated at 4.0 μm at CEA, Cadarache [5].

To the best of our knowledge there is no literature data concerning the emissivity of W coatings deposited on carbon materials. The first investigations were carried out at the wavelength of 1.064 μm and the data are used for the protection system of the ITER-like Wall (ILW) at JET. Since the scientific cameras at JET work on 4.0 μm and the wavelengths of 1.75 μm and 3.75 μm are of interest for WEST tokamak the research on emissivity of W coatings was extended for these wavelengths too. The results are presented in this paper.

2. Method and experimental setup for measuring the emissivity

The emissivity is defined as the ratio between the radiation intensity emitted by the surface of interest (I_{coat}) and the radiation intensity produced by a black body (I_{bb}) at the same temperature and wavelength after subtracting the background (I_0) that is measured near to the heated zone. $\varepsilon = (I_{\text{coat}} - I_0) / (I_{\text{bb}} - I_0)$ (1).

The W coating with a thickness of 10 μm or 20 μm was applied on tubes ($\Phi 16 \times 0.8 \times 85$ mm) made of Dunlop DMS 780 CFC, N11 CFC or SGL fine grain graphite R6710 (FGG). A hole of $\Phi 2.0$ mm was drilled in the middle of the tube to play the role of black body. A K type thermocouple was introduced into the tube through an end and the welding was in contact with the wall (Fig.1a). The W coated tube was heated by electric conduction using a high current power supply ($I_{\text{max}}=300$ A, $U_{\text{max}}=6$ V) up to 1200 °C. The tube temperature was monitored by an IR pyrometer as well.

For measurements at 1.064 μm a Hitachi video camera type KP-M1AP, identical with those from the protection system of the ILW at JET, was used. Since an IR camera was not available for higher wavelengths a new technique was developed and applied. Instead of taking simultaneously the image of the entire W-coated component, a single pixel IR detector together with the IR optics (chopper, lens and filters) was moved in X and Y directions for distances of 20x20 mm using an X-Y motorized stage. The step was 0.125 mm.

For 1.75 μm an InGaAs IR detector type PDA20H (1.5 – 4.8 μm , 0.2 mm^2) was used. An IR TE-cooled detector type PDA10JT HgCdTe amplified with TEC, 2.0 - 5.4 μm , 1.0x1.0 mm, AC-Coupled Amplifier, with a detectivity of 10^{10} $\text{cm}\cdot\text{Hz}^{1/2}/\text{W}$ at -30°C was used for measurements at 3.75 μm and 4 μm . The noise equivalent power was $2.0\cdot 10^{-11}$ $\text{W}\cdot\text{Hz}^{1/2}$. Using an aperture of 0.2 mm just below the detector the space resolution of the system was about 0.2 mm. Both detectors were supplied by Thorlabs. The IR measuring system and the diagnostics were installed on the top lid of the vacuum chamber. A sapphire window ensured the vacuum sealing below the IR optics. The FWHM of the bandpass filters were 50 nm for 1.064 μm and 250 nm for the other wavelengths.

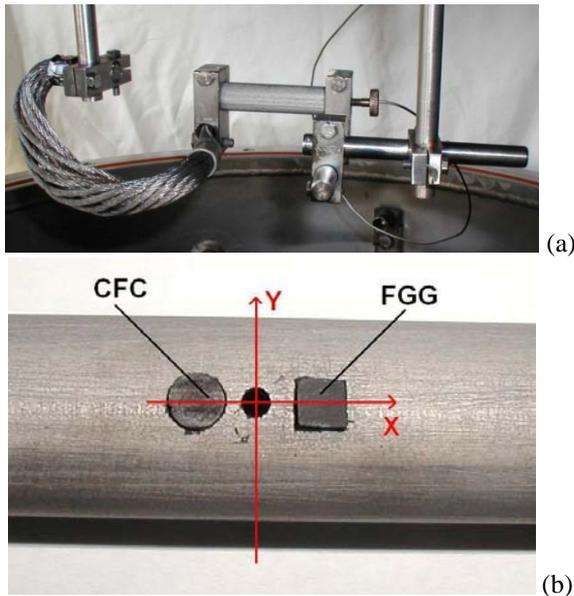


Fig.1 The W-coated CFC tube with the supports and thermocouple (a) and the black body (central hole) and two CFC and FGG pins (b)

3. Experimental results and discussion

3.1. Measurement of emissivity at 1.064 μm

A typical IR image of the W-coated tube taken at the temperature of 1172 $^\circ\text{C}$, ($\lambda = 1.064$ μm) and the temperature dependence of the emissivities for a few regions of interest (A, B, C, etc.) are shown in Fig.2.

A strong influence of the CFC structure particularly of the porosity can be seen. The pores have the tendency to act as black bodies. This leads to a relatively large spread of the emissivity values (0.63 ± 0.07).

The influence of the viewing angle on the emissivity of 10 μm W coating deposited on FGG measured at 800 $^\circ\text{C}$ is shown in Fig. 3.

3.2. Measurement of emissivity at 1.75 μm , 3.75 μm and 4.0 μm

The emissivity of W coating deposited on CFC calculated from the IR signal measured at 800 $^\circ\text{C}$ ($\lambda = 4.0$ μm) on Y axis (see Fig. 1b) is shown in Fig. 4a. The plateau corresponding to the black body (2 mm central hole) and the dispersion of the emissivity due to the porosity and irregularities of the CFC can be clearly seen. With FGG the curve is much smoother (Fig. 4b).

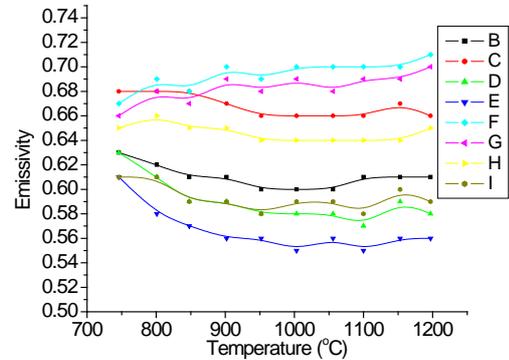
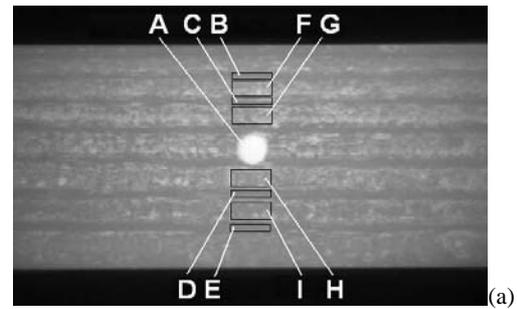


Fig. 2 IR image at 1.064 μm ($T=1172$ $^\circ\text{C}$) (a) and the emissivities for the regions of interest (b)

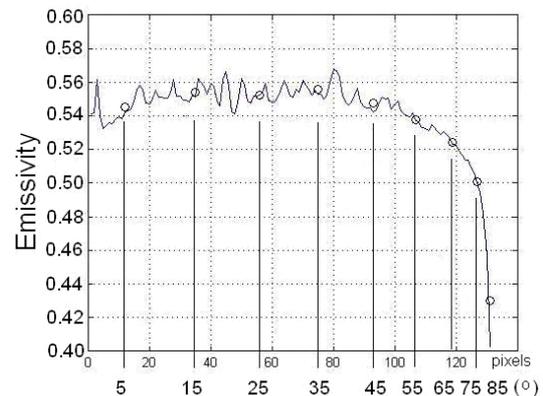
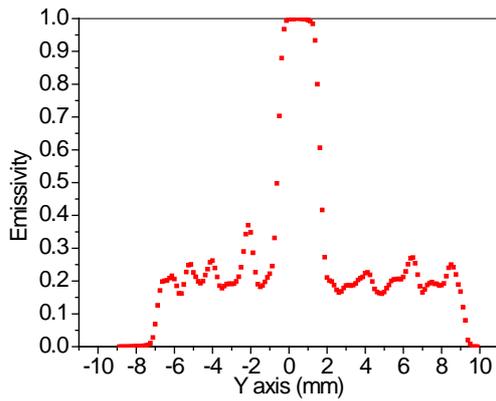
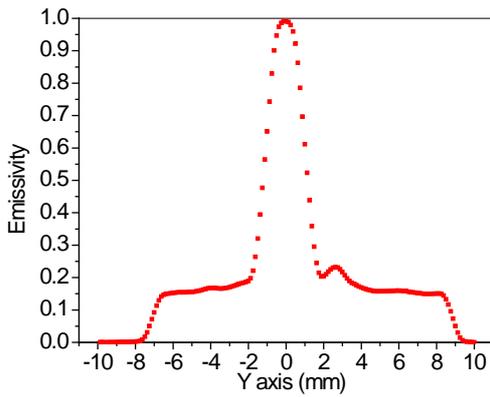


Fig. 3 Influence of the viewing angle on the emissivity of 10 μm W coating on FGG

On both sides of the central hole drilled in the W-coated tube there are two more holes where pins of different materials can be introduced (see Fig. 1b). By moving the IR detector and the optics along the X axis the emissivity of those materials can be determined. The background value is taken from experiments performed on Y axis. In this way the emissivities of the W coatings deposited on Tiles 3, 4 and 7 exposed to JET plasma in 2011-2012 campaign as well as the emissivities of bulk W and bulk Be were measured. In Fig. 5 the emissivity curve measured at 4 μm (800 $^\circ\text{C}$) on two samples ($\Phi 5 \times 10$ mm) cored from Tiles 4 and 7 after plasma exposure is shown. The variation of the emissivity in the central area of the samples is due to the CFC structure, but the high values of 0.7-0.85 are produced by the broken edges of the samples where W coating was removed during coring from the big tiles. Here the emissivity of uncoated CFC is measured. The values are close to 0.8. A comparison with the emissivity of the W coating before plasma exposure is shown in Fig. 6.



(a)



(b)

Fig. 4 The emissivity at 4.0 μm ($T=800\text{ }^\circ\text{C}$) for 10 μm W coating deposited on Dunlop DMS 780 CFC substrate (a) and R6710 FGG (b)

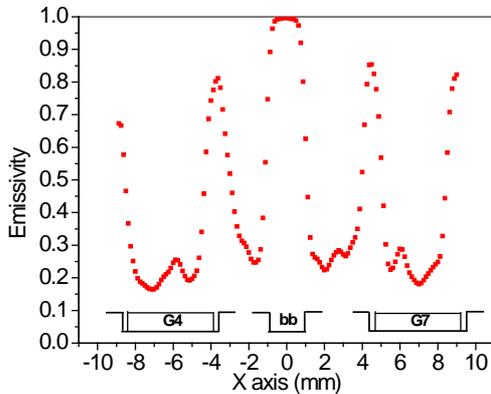


Fig. 5 The emissivity at 4.0 μm for two pins (G4 and G7) cored from Tiles 4 and 7 exposed to JET in 2011-2012

It can be seen that there is no a significant change of emissivity after one year of ILW exploitation. The emissivity on Tile 3 is a little bit lower than that of non-exposed W-coated tile, but this can be due to the fact that the outermost layer on that particular Tile 3 was Mo not W. On the other hand most of the discharges in this campaign had one strike point on Tile 3. This might affect a little bit the emissivity, but the change is about 10 % and it is in the error limits. A small increase of emissivity appears to occur on Tiles 4 and 7, but this is also within the error limits.

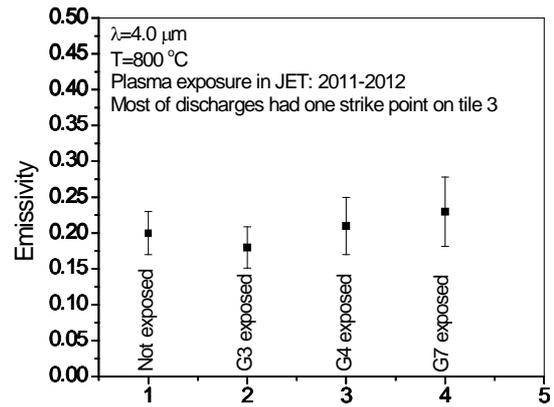


Fig. 6 The influence of plasma exposure in JET on the emissivity of Tiles 3, 4 and 7

Using the same technique the emissivity was measured on W-coated N11 CFC and FGG at the wavelengths of $1.75\pm 0.25\text{ }\mu\text{m}$ and $3.75\pm 0.25\text{ }\mu\text{m}$.

In addition to the W-coated materials the emissivity was measured for bulk W and bulk Be up to $900\text{ }^\circ\text{C}$. Their surface was polished to a roughness of about $3\text{ }\mu\text{m}$. For each wavelength and type of material the emissivity was measured at different temperatures in the range $400\text{--}1200\text{ }^\circ\text{C}$. In this way the temperature dependence of the emissivity was determined as well. The results are shown in Table 1 that contains the emissivity values for various fusion materials at different temperatures and wavelengths.

4. Conclusions

- An experimental method to determine the emissivities at different wavelength ($1.0\text{--}4.0\text{ }\mu\text{m}$) in the temperature range $400\text{--}1200\text{ }^\circ\text{C}$ was developed and applied for W coatings deposited on CFC and FGG substrates. The emissivities of bulk W and bulk Be were determined as well.
- The emissivity of the W coatings depends essentially on the structure of the substrate. A relative large dispersion of the values appears for porous CFC material, while for FGG the spread of the emissivity values is much lower.
- No significant change of the emissivity after plasma exposure in JET (2011-2012) was detected for Tiles 3, 4 and 7.
- No significant influence of the temperature on the emissivity was detected at $1.064\text{ }\mu\text{m}$. However at higher wavelengths the emissivity increases with the temperature.
- No significant influence of the viewing angle on the emissivity was observed in the range of $0^\circ\text{--}55^\circ$. At 85° the emissivity drops by about 22%.
- With increasing the investigating wavelength from $1\text{ }\mu\text{m}$ to $4\text{ }\mu\text{m}$ the emissivity measured on the same material decreases significantly.

Table 1 The emissivity of W coatings and other materials for fusion applications

Material	Temperature								
	400°C	500°C	600°C	700°C	800°C	900°C	1000°C	1100°C	1200°C
$\lambda=1.064 \mu\text{m}$									
10 μm W-coated Dunlop CFC				0.63± 0.07	0.63± 0.07	0.63± 0.07	0.63± 0.07	0.63± 0.07	0.63± 0.07
20 μm W-coated Dunlop CFC				0.59± 0.06	0.59± 0.06	0.59± 0.06	0.59± 0.06	0.59± 0.06	0.59± 0.06
10 μm W-coated R6710 FGG				0.56± 0.03	0.56± 0.03	0.56± 0.03	0.56± 0.03	0.56± 0.03	0.56± 0.03
Bulk W				0.45± 0.03	0.45± 0.03	0.45± 0.03	0.45± 0.03	0.45± 0.03	0.45± 0.03
$\lambda=1.75 \mu\text{m}$									
12 μm W-coated R6710 FGG		0.40± 0.02	0.42± 0.03	0.42± 0.03	0.43± 0.03	0.43± 0.03	0.43± 0.03	0.44± 0.013	0.45± 0.03
12 μm W-coated N11 CFC	0.38± 0.03	0.39± 0.04	0.40± 0.04	0.41± 0.04	0.42± 0.04	0.45± 0.04	0.±49 0.04	0.51± 0.04	0.54± 0.04
Bulk W	0.32± 0.01	0.33± 0.01	0.33± 0.01	0.34± 0.01	0.35± 0.01	0.35± 0.01			
$\lambda=3.75 \mu\text{m}$									
12 μm W-coated R6710 FGG		0.147± 0.007	0.150± 0.007	0.158± 0.008	0.165± 0.008	0.172± 0.009	0.180± 0.009	0.190± 0.009	0.20± 0.01
12 μm W-coated N11 CFC	0.20± 0.05	0.20± 0.05	0.21± 0.05	0.22± 0.05	0.23± 0.05	0.23± 0.05	0.23± 0.05	0.23± 0.05	0.24± 0.05
Bulk W	0.095± 0.005	0.10± 0.005	0.11± 0.005	0.115± 0.005	0.12± 0.005	0.125± 0.005			
$\lambda=4.0 \mu\text{m}$									
10 μm W-coated R6710 FGG		0.13± 0.01	0.14± 0.01	0.15± 0.01	0.16± 0.01	0.17± 0.01	0.18± 0.01	0.19± 0.01	0.20± 0.01
10 μm W-coated Dunlop CFC	0.18± 0.05	0.19± 0.05	0.20± 0.05	0.21± 0.05	0.23± 0.06	0.24± 0.07	0.25± 0.07	0.26± 0.07	0.27± 0.08
20 μm W-coated Dunlop CFC	0.18± 0.03	0.19± 0.03	0.20± 0.04	0.21± 0.05	0.22± 0.05	0.24± 0.06			
Bulk W	0.09± 0.01	0.09± 0.01	0.10± 0.01	0.10± 0.01	0.11± 0.01	0.12± 0.01			
Bulk Be	0.24± 0.02	0.26± 0.02	0.27± 0.02	0.28± 0.03	0.29± 0.03	0.30± 0.03			
G3 W-coated exposed in JET	0.16± 0.03	0.17± 0.02	0.18± 0.02	0.18± 0.02	0.18± 0.03	0.19± 0.03			
G4 W-coated exposed in JET	0.20± 0.04	0.19± 0.04	0.20± 0.04	0.20± 0.04	0.21± 0.04	0.21± 0.04			
G7 W-coated exposed in JET	0.20± 0.04	0.21± 0.05	0.22± 0.05	0.22± 0.05	0.23± 0.05	0.25± 0.06			
Uncoated FGG					0.79± 0.01				
Uncoated Dunlop CFC					0.78± 0.03				

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