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Optical emission diagnostic of thermionic vacuum arc plasma during beryllium film formation

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Abstract

Beryllium is a candidate plasma-facing material for the main chamber wall in ITER. It will also be at JET during the ITER-Like Wall (ILW) Project aiming at tokamak operation with a full metal wall. Special marker tiles will be used in order to assess the beryllium erosion. These will be solid beryllium tiles coated first with a thin high-Z metal film (acting as an interlayer) and then with a layer of deposited beryllium. The aim of this contribution is to report on the development of a production method for thin beryllium coatings relevant for this application.

I. Beryllium deposition

The Be marker layer must be adherent to the substrate and compact to resemble bulk beryllium.

Two methods of Be deposition have been used to produce test coupons: standard evaporation and Thermionic Vacuum Arc (TVA) technique [1]. The latter one has been selected to prepare 8 μm thick films. TVA is based on the electron-induced evaporation. The experimental set-up is shown in Fig.1. A cathode filament surrounded by a Whenelt cylinder is heated by an external low voltage-high current. Thermo-electrons emitted from the tungsten filament are accelerated towards the anode. High evaporation rate of the anode material leads to high vapour density in front of the anode. The space density of these particles is high enough to lower the ionization mean free path making it smaller than the cathode – anode distance. As a result, plasma is ignited in that region while the surrounding space is evacuated to below 10^{-3}Pa. Under these conditions high purity films of the anode material can be deposited onto substrates. High-energy ion bombardment of the growing layer leads to the formation of pure and a compact layers.

As shown in Fig. 1, the rotating support of the TVA electron gun allows the vertical displacement of the gun toward the anode during the deposition when the beryllium rod (20

mm in diameter) was consumed by evaporation. The rod is fixed on a stainless steel blade settled on the electrically insulated feed-through.

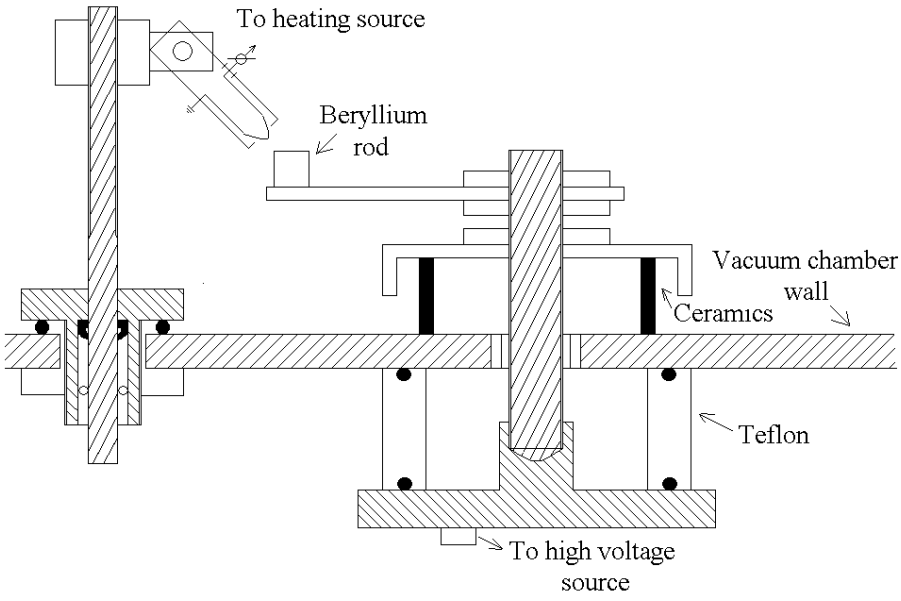


Fig.1 Experimental set-up of the thermionic vacuum arc method for beryllium film formation.

The stainless steel supporting blade remained at a temperature at which vapour pressure of steel components was very low, thus not influencing the purity of the deposited Be layer. The anode structure (Be rod) and beryllium plasma are presented in Fig. 2. The high voltage source could furnish 5 kV at maximum 1000 mA while the necessary heating filament current value was of 45 A. After heating up the cathode filament, the anode positive potential was gradually applied from the high voltage source up to 1.5 kV. The beryllium rod begun locally to melt and evaporate and finally bluish plasma appeared around the anode and expanded towards the substrates.

Fig. 2 TVA gun and Be plasma

In order to estimate the plasma temperature of the arc discharge in pure beryllium vapours, an assumption of partial local thermodinamic equilibrium (PLTE) was made. In this state temperatures of electron, ion and neutral atoms tend to be equal. For atoms (ions) of the same kind, the relative intensities of spectral lines emitted by the plasma depend only on the plasma temperature [2]. The electron temperature in plasma was estimated by monitoring the emission lines from plasma produced in pure beryllium vapours. The heating current of the cathode filament and the voltage applied on the cathode-anode gap controlled the feeding with excited beryllium atoms.

Fig. 3 shows the optical emission spectrum acquired during the plasma process. Three main lines were observed: Be I 440.79nm, 2*s*2*p* - 2*s*4*s*, Be I 457.26nm, 2*s*2*p* - 2*s*3*d* and Be I 825.40 nm, 2*s*2*p* - 2*s*3*s*. The intensity of the observed spectral lines emitted by the plasma is proportional to the population of the upper level, to the transition probability and to the energy of the quantum [3].

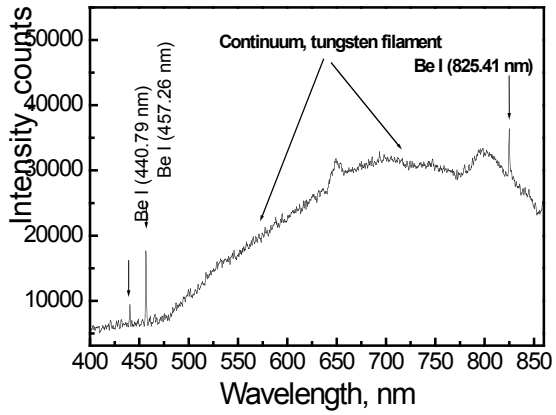


Fig.3 Optical emission spectrum of Be plasma.

$$I_{ul} \propto \frac{1}{4\pi} A_{ul} \cdot N_{e,u} \cdot h \cdot \lambda_{ul} \qquad (1)$$

where: h is the Plank constant, $N_{e,u}$ – the electron population in the excited stated u, $\lambda_{u,l}$ the wavelength of the transition from the upper excited level "u" to the lower level "l", A_{ul} the corresponding transition probability per unit time. For the considered species (electrons), Boltzmann's distribution connects the excited states with a given electron temperature (T_e):

$$I_{ul} \cdot \alpha \cdot \frac{1}{4\pi} \cdot A_{ul} \cdot h \cdot \lambda_{ul} \cdot \frac{N_e}{Z_e} \cdot g_{e,u} \cdot \exp\left(-\frac{E_{e,u}}{kT_e}\right) \qquad (2)$$

where: I_{ul} is the intensity of the emission line, $E_{e,u}$ - the energy of the upper excited state of electron, N_e – the concentration of the electrons calculated at the T_e, Z_e – the partition function of electron calculated at T_e, $g_{e,u}$ – the statistical weight of the upper excited state of the electron and k- the Boltzmann's constant. Assuming the PLTE and provided that $kT_e \ll E_u$, the following equation can be applied for estimation of plasma electron temperature [3-5]:

$$T_e = \frac{E_1 - E_2}{k} \left\{ \ln \left[\frac{I_2 \cdot A_1 \cdot g_1 \cdot \lambda_2}{I_1 \cdot A_2 \cdot g_2 \cdot \lambda_1} \cdot \left(\frac{E_2}{E_1} \right)^{1/2} \right] \right\}^{-1} \qquad (3)$$

where indexes 1, 2 refer to the two spectral lines; $E_1$and E_2 are the upper level energies of the considered transitions; g_1 and g_2, statistical weights of the optical transitions under consideration with the transition probability A_1 and A_2, respectively, λ_1 and λ_2 are the spectral lines wavelengths, I_1 and I_2 the measured lines intensities. Chosen lines were Be I 457.2665 nm and Be I 825.2665 nm. The two lines were recorded simultaneously using an SM-242

CCD Spectrometer (Spectral Products-USA). Parameters of the optical transitions and the energies of the excited energy levels have been taken from ref. [6] and presented in Table 1. Electron temperature was found in the range of 6620 - 7900 K increasing with the anode-cathode potential and decreasing with the discharge current.

Table 1. Parameters used for plasma electron temperature estimation.

Wavelength (nm)	Transition probability (s^{-1})	Statistical weight	Energy of the upper level (eV)	Measured intensity (counts)	T_e
λ_1 = 457.2665	A_1 = 7.9 E+7	g_1 = 5	E_1 = 7.988095	I_1 = 14086 I_1' = 10379	T_e = 7960K T_e' = 6620K
λ_2 = 825.4067	A_2 = 3.8 E+7	g_2 = 1	E_2 = 6.788095	I_2 = 7257 I_2' = 3502	T_e = 0.686 eV T_e' = 0.571 eV

II. Film structure

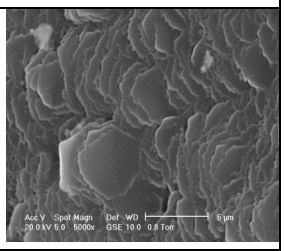
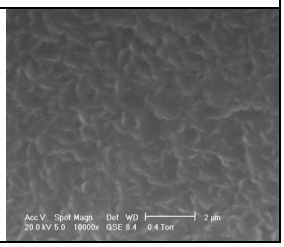
Substrate/ Method	SEM image 10000x
Inconel/ Thermal	
St. steel/ TVA	

Fig.4. SEM images of Be films produced by TVA and thermal evaporation methods.

Images in Figure 4 shows the structure of beryllium layers deposited by two techniques: standard evaporation and TVA. Evaporated films were prepared using the facilities at the Nuclear Fuel Factory in Pitesti, Romania. It is noticed that films obtained by TVA are much smoother than evaporated layers. X-ray diffraction studies have also proven highly ordered crystalline structure of TVA-produced films.

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References

[1] C. P. Lungu, I. Mustata, G. Musa, A. M. Lungu, V. Zaroschi, K. Iwasaki, R. Tanaka, Y. Matsumura, I. Iwanaga, H. Tanaka, T. Oi, K. Fujita: Surf. and Coat. Techn. 2005, **200**, 399.
[2] K. Albinski, K. Musiol, A. Miernikiewicz, S. Labuz, and M. Malota, Plasma Sources Sci. Technol. 1996, **5**, 736.
[3] H. R. Griem, *Plasma Spectroscopy*, McGrawHill Book Company, N.Y., 1964
[4] R. H. Huddlestone and S. L. Leonard, *Plasma Diagnostic Techniques*, New York: Academic Press, 1965, p. 204.
[5] P. Frugier, C. Girold, S. Megy, C. Vandesteendam, E. A. Ershov-Pavlov and J.-M. Baronet, Plasma Chemistry and Plasma Processing, 2000, **20**, 65.
[6] NIST Atomic Spectra Database, http://physics.nist.gov/PhysRefData/ASD1.