ELSEVIER

Journal of Nuclear Materials 283–287 (2000) 1081–1084

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Infrared characterization and high heat flux testing of plasma sprayed layers

Ph. Chappuis [a,*], F. Escourbiac [b], M. Chantant [a], M. Febvre [c], M. Grattarola [d], M. Bet [d], M. Merola [e], B. Riccardi [f]

[a] *Association Euratom CEA, DRFC, 13108, St Paul lez Durance, France*
[b] *ATEM, rue de grand pré, 13009 Marseille, France*
[c] *Framatome, Centre Technique, porte Magenta, 71160 Le Creusot, France*
[d] *Ansaldo Recerche, 16161 Genova, Italy*
[e] *EFDA Team, Max Planck IPP, 85748 Garching, Deutschland*
[f] *ENEA, via Enrico Fermi 27, Frascati, 00044 Rome, Italy*

Abstract

Four series of plasma sprayed actively cooled mock-ups have been evaluated by infrared measurements and heat flux testing. Infrared characterization showed heat transfer capability of the plasma sprayed layer bonded to the substrate. Even if the thermal conductivity of the B_4C plasma sprayed coating is only 5% of the bulk material, the coating can easily survive 1000 cycles at 7.5 MW/m^2 if the thickness is less than 150 μm. Thick tungsten coatings (3–5 mm) were more fragile, depending on the plasma spray technology. The highest heat flux acceptable for 1000 cycles is 4 MW/m^2 with a vacuum plasma spray coating and a Ni–Al–Si–W precoating, accounting for a reduction in the thermal conductivity by a factor of 3. © 2000 Elsevier Science B.V. All rights reserved.

---

1. Introduction

For the next step fusion machine, the plasma facing area of the in-vessel components will increase in size and complexity. They will certainly be composed of an actively cooled heat sink covered by a high or low Z plasma facing material with various thicknesses depending on the design. The mean heat fluxes will be in the range of 1–10 MW/m^2 for the convective part, 0.1–1 for the radiative and charge exchange part and up to 20 MW/m^2 for some off-normal events on localized and identified areas [1].

The shape of plasma facing components (PFCs) is selected to reduce the heat flux by minimizing the incident particle trajectory angle. In other cases complex vented PFCs structures are designed to allow pumping of a dense neutral cloud. The plasma facing material and the bonding technology have to be compatible with the heat sink material and geometrical complexity.

Plasma spray is a promising technology for covering large in-vessel areas which have curved shape [2]. Also it has great potential for in situ repair of eroded parts on PFCs. Industrial plasma spray experience on refractory materials exists for B_4C and W layers which are good examples of low and high Z plasma facing elements, respectively.

This paper summarizes the high heat flux test results of four series of different mock-ups covered with plasma sprayed layers and developed either for Tore-Supra or for the international thermonuclear experimental reactor (ITER) divertor.

2. High heat flux testing

All mock-ups were high heat flux tested in the FE200 test facility operated jointly by Framatome and the Commissariat a l'Energie Atomique (CEA) located in Le Creusot, France. This facility includes a large vacuum

---

[*] Corresponding author. Tel.: +33-4 42 25 46 62; fax: +33-4 42 25 49 90.
E-mail address: chappuis@drfc.cad.cea.fr (P. Chappuis).

0022-3115/00/$ - see front matter © 2000 Elsevier Science B.V. All rights reserved.
PII: S 0 0 2 2 - 3 1 1 5 (0 0) 0 0 2 4 6 - 4

vessel ($1.2 \times 1.2 \times 2.5$ m^3), a sweeping (800×200 mm^2) 200 kW electron beam, a controlled pressurized water cooling loop with a flow capacity up to 6 kg/s and a temperature range from 50°C to 200°C [3]. The main diagnostics are calorimetric measurements on the water loop and optical diagnostics for the surface temperatures. Testing campaigns generally begin with a ramp up in heat flux up to the maximum value for surface temperature characterization. This is followed by a fatigue test for 1000 cycles where the pulse length and dwell time are equal or less than the structure time constant. Finally the heat flux is ramped up again to characterize the eventual damage.

2.1. Plasma sprayed divertor neutralizers

These high heat flux elements are composed of hollow square bars, 500 mm long and made of CuCrZr. Due to their curved shape and the reduced space, the only plasma facing armor compatible with this was a plasma sprayed layer. B_4C was chosen because:

1. the Tore-Supra PFCs are low *Z* (graphite and carbon fiber composite);
2. that boronisation is regularly done in the vessel;
3. this technology had already been used on other components with satisfactory results [4].

Plasma spraying was done in a vacuum vessel with an Ar partial pressure and cryogenic cooling. The total layer thickness was 150–200 μm with a 50 μm precoating of a mixture of Cu and B_4C, and the remaining thickness of pure B_4C. Fabrication process was controlled with spot samples which were tested for thermal conductivity and adherence strength.

An evaluation of the design limits and fatigue behavior of these elements was done on one element (120 μm B_4C) in a preliminary test. Testing was done with the Tore-Supra nominal cooling parameters (150°C, 3.5 MPa, 7 m/s) and an incident heat flux of 7.5 MW/m^2. The element survived 1000 cycles at 5 MW/m^2 plus 1000 cycles at 7.5 MW/m^2 with a rather constant surface temperature of 700°C (Fig. 1). No indication of surface damage was visible.

A second set of tests was done with four elements assembled on a mock-up to characterize the thermal properties of the deposited layer more precisely and to characterize the maximum admissible heat flux.

A screening test was done up to 14 MW/m^2 simultaneously on the four elements, with cooling parameters identical to the previous test. To show the effect of electron penetration on the thermal behavior of the thin layer of low *Z* material, the same heat flux was produced with two different accelerations (100 and 140 kV). Surface temperatures were monitored by pyrometers and an infrared camera either on the line mode (0.1 mS) for the time constant measurement or on frame mode for the slower transient (25 mS).

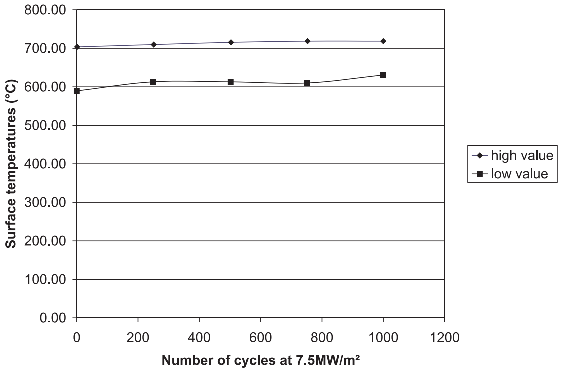

Fig. 1. Surface temperature change on B_4C during fatigue testing.

Finite element calculations of heat transfer in the structure were done to evaluate the thermal conductivity of the layer by matching the transient surface temperature behavior. Fig. 2 shows that good agreement was obtained for a thermal conductivity of 1.5 W/m K on the element with the 180 μm layer. This value of conductivity is only 5% of the bulk B_4C conductivity (with a coated density reaching 90% of the bulk density!).

The steady-state surface temperature is given in Fig. 3 with the finite element calculated values for two different gun voltage resulting in different electron penetration depth in the B_4C layer. The projection for the Tore-Supra behavior is also given (assuming ion heat flux with zero penetration). Experimentally, a maximum heat flux of 14 MW/m^2 was obtained with slight local B_4C melting and no cracking of the layer.

2.2. ITER divertor elements

Tungsten plasma spray technology was developed for the ITER divertor components [5]. The first four and

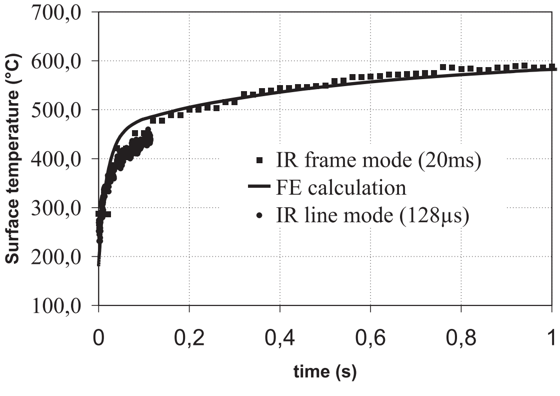

Fig. 2. Transient surface temperature behavior of a B_4C layer ($\lambda = 1.5$ W m K). Shot 2091, heat flux = 3.9 MW/m^2 and θ cooling = 180°C.

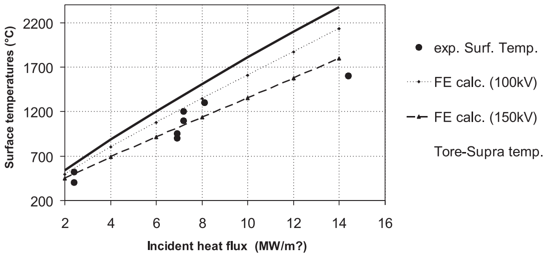

Fig. 3. Calculated and measured steady state surface temperature for a B_4C layer on neutralizing elements.

tested elements had a 50 mm diameter CuCrZr tubular heat sink with lengths of 200 mm for EN 21 and EN 22 and 50 mm for EN 23a and EN23b. The other five elements tested had a hollow square CuCrZr heat sink 22 mm wide and 100 mm long. The four sides were covered with W. These elements were representative of a solution for the ITER divertor wing [7]. Table 1 gives the main plasma spraying parameters for all elements.

The heights of these elements were high heat flux testing in the FE 200 facility following a similar procedure as described above.

Element EN21 failed after 100 cycles at 0.5 MW/m^2 with a circumferential crack. Strong outgassing was also detected, from the beginning, by the vacuum vessel pressure gauge indicating the presence of trapped gas (argon?) in the layers.

Element EN22 did not outgas under heat flux and was satisfactorily fatigue tested up to 2 MW/m^2 (1000 cycles). Even though the mean surface temperature was close to 1200°C at 4 MW/m^2, some W melting occurred on some locations where the layer was poorly attached to the surface.

Elements EN23a and EN23b were alternately loaded at 2.6 and 4.4 MW/m^2 for 1000 cycles. A hot spot appeared on EN23a during ramp-up at 4.4 MW/m^2 but showed no visible cracking. At 6.1 MW/m^2 the surface temperature reached 2200°C on EN23a and 1470 on EN23b. This heat flux characterization clearly demonstrated the better performance of the vacuum plasma spray coating with the Ni–Al–Si–W interlayers. New elements (to be tested in the future) have consequently been manufactured with this technology [6].

The second batch (WPS3) of five elements was manufactured with a different plasma spray process [7] requiring nonbonding layer. An infrared technique [8]

Table 1
Parameters for W plasma spray elements

Mock-up identification	Plasma spray atmosphere	Bonding layer composition and thickness	Interlayer composition and thickness	Tungsten thickness (μm)
EN 21	Ar	Al & Si, 200 μm	Ni + Al + W, 800 μm	3
EN 22	Vac	Al & Si, 200 μm	Ni + Al + W, 800 μm	5
EN 23a	Ar	Al & Si, 200 μm	Ni + Al + Si + W, 800 μm	4
EN 23b	Vac	Al & Si, 200 μm	Ni + Al + Si + W, 800 μm	4
WPS3 2669	Ar	Non	Ni + Al*, 2000 μm	3
WPS3 2671	Ar	Non	Ni + Al*, 2000 μm	3
WPS3 2678	Ar	Non	Ni + Al*, 2000 μm	4.4
WPS3 2681	Ar	Non	Ni + Al*, 2000 μm	4.7
WPS3 2682	Ar	Non	Ni + Al*, 2000 μm	4.2

* Various processing temperature.

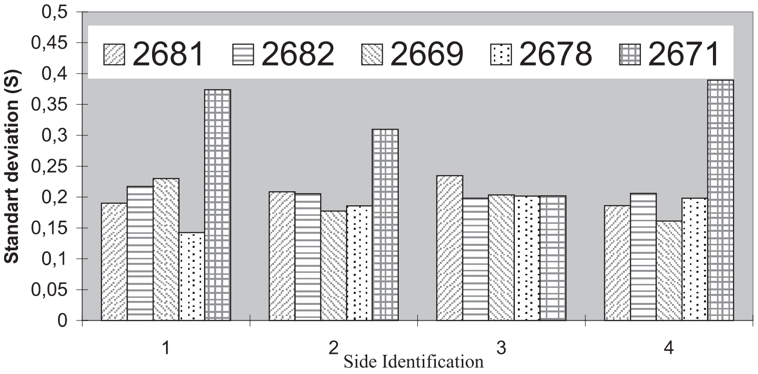

Fig. 4. Time constant standard deviations per faces on WPS3.

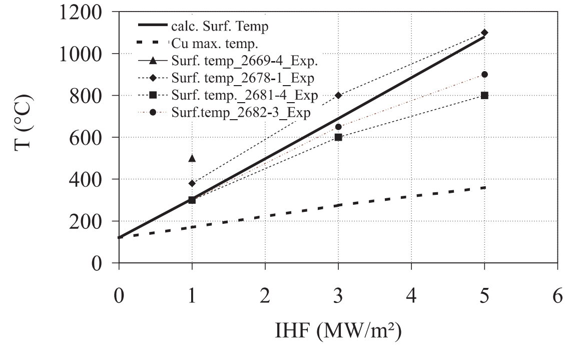

Fig. 5. Calculated and measured surface temperature on WPS3.

allowing to evaluate the thermal time constant of the coating under a transient thermal load was applied to selected four best elements and the best face of each element. The selection was done choosing the most homogeneous faces with the lowest time constant. As shown in Fig. 4, the element WPS3 2671 was less homogeneous than the others and therefore not selected.

During the first heat flux ramp-up to a maximum of 3 MW/m^2, element WPS3 2669 showed a higher surface temperature, indicating of a low bond quality. Elements WPS3 2681 and 2682 survived 1000 cycles at 3 MW/m^2 without damage but failed during the first few cycles at 5 MW/m^2. Element WPS3 2678 was not cycled at 3 MW/m^2 but failed during the first cycles at 5 MW/m^2, indicating that the 3 MW/m^2 fatigue cycling did not affect the higher flux testing. Finite element calculation (shown in Fig. 5) of the surface temperature fit the experimental measurements when the W thermal conductivity (20°C) was lowered from 150 to 40 W/m K (factor 3).

3. Summary

Four series of plasma sprayed actively cooled mock-ups have been evaluated by high heat flux testing and one was characterized by infrared test.

The infrared characterization gives an indication on the of the plasma layer bonding to the substrate.

The high heat flux testing showed that even if the heat conductivity of the B_4C plasma sprayed coating is only 5% of that of the bulk material, the coating can easily survive 1000 cycles at 7.5 MW/m^2 if the thickness is less than 150 μm.

Thick tungsten coatings (3–5 mm) are more fragile depending on the plasma sprayed technology. The highest heat flux acceptable for 1000 cycles is 4 MW/m^2 with a vacuum plasma spray and a Ni–Al–Si–W pre-coating.

References

[1] R.R. Parker, Fus. Eng. Des. 36 (1997) 33.

[2] G. Cai, M. Grattarola, G.B. Ottonello, F. Zacchia, in: Proceedings of the 19th SOFT, Lisbon, Fus. Technol. (1996).

[3] M. Diotalevi, M. Febvre, P. Chappuis, in: Proceedings of the 19th SOFT, Lisbon, Fus. Technol. (1996).

[4] M. Lipa, E. Gauthier, Fus. Technol. (1994) 455.

[5] B. Riccardi, A. Pizzuto, L. Bertamini, M. Diotalevi, G. Vieder, in: Proceedings of the 16th IEEE/NPSS 1997 SOFE, San Diego.

[6] B. Riccardi, A. Pizzuto, A. Orsini, S. Libera, L. Bertamini, F. Casadei, E. Severini, R. Montanari, R. Vesprini, P. Varone, G. Filacchioni, N. Litunovski in: Proceedings of the 20th SOFT, Marseille, Fus. Technol. (1998).

[7] M. Grattarola, M. Bet, M. Merola, G.B. Ottonello, L. Plöchl, B. Riccardi, A. Salito, G. Vieder, F. Zacchia, in: Proceedings of the 20th SOFT, Marseille, Fus. Technol. (1998).

[8] A. Durocher, P. Chappuis, R. Mitteau, L. Moncel, in: Proceedings of the 20th SOFT, Marseille, Fus. Technol. (1998).