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Title:

THE STRUCTURE AND THERMAL PROPERTIES OF PLASMA-SPRAYED BERYLLIUM FOR THE INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER)

Author(s):

Richard G. Castro, MST-6
Andrew Bartlett, MST-6
Keith E. Elliott, MST-6
Kendall J. Hollis, MST-6

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Abstract

Plasma spraying is under investigation as a method for *in-situ* repair of damaged beryllium and tungsten plasma facing surfaces for the International Thermonuclear Experimental Reactor (ITER), the next generation magnetic fusion energy device, and is also being considered as a potential fabrication method for beryllium and tungsten plasma-facing components for the first wall of ITER. Investigators at the Los Alamos National Laboratory's Beryllium Atomization and Thermal Spray Facility have concentrated on investigating the structure-property relationship between the as-deposited microstructures of plasma sprayed beryllium coatings and the resulting thermal properties of the coatings. In this study, the effect of the initial substrate temperature on the resulting thermal diffusivity of the beryllium coatings and the thermal diffusivity at the coating/beryllium substrate interface (i.e. interface thermal resistance) was investigated. Results have shown that initial beryllium substrate temperatures greater than 600°C can improve the thermal diffusivity of the beryllium coatings and minimize any thermal resistance at the interface between the beryllium coating and beryllium substrate.

FABRICATION AND MAINTENANCE OF PLASMA FACING SURFACES that are directly exposed to the plasma in magnetic fusion energy devices will present challenging problems in the development and design of the International Thermonuclear Experimental Reactor (ITER). Plasma spraying is currently being considered as the primary technology for in-situ repair of damaged beryllium and tungsten plasma-facing surfaces which will be subjected to severe environmental conditions as a result of either normal or off-normal operating conditions. Plasma spraying is also being considered as a potential fabrication method for producing first wall beryllium and tungsten armor on curved plasma facing components which will be present on the first wall, dome, divertor, baffle and limiter regions of ITER.

In order to qualify beryllium plasma spray technology for ITER applications research investigations have focused on the following critical areas:

- Optimizing the thermal conductivity of beryllium plasma sprayed coatings to maximize heat transfer through the thickness of the coating
- Evaluating the adherence between the beryllium plasma sprayed coatings and the underlying surfaces which include beryllium surfaces for in-situ repair applications and copper heat sink surfaces for initial fabrication applications
- Methods of preparing the surface of beryllium prior to *in-situ* plasma spray repair operations
- Evaluating the structure, properties, and performance of the beryllium plasma sprayed coatings under non-irradiated and irradiated conditions which will be typically experienced in ITER
- Evaluating remote maintenance operating schemes inside of the ITER reactor and developing procedures for *in-situ* repair operations
- Real time inspection and process control of the plasma spray operation and the resulting beryllium coatings

In this paper, experimental results will be presented on the effect of the initial beryllium substrate temperature on the resulting thermal diffusivity of the beryllium plasma sprayed coatings. Information will also be presented on the thermal diffusivity at the interface between the beryllium coating and the underlying beryllium substrate. The bond strength between the beryllium coatings and the underlying beryllium surface will also be discussed.

Experimental Procedure

Vacuum plasma spraying (VPS) of beryllium was performed at the Los Alamos National Laboratory's (LANL) Beryllium Atomization and Thermal Spray (BATS) facility. The VPS system at LANL contains a commercial SG-100 Plasmadyne torch which is mounted on a 173K EPI two-axis X-Y manipulator. Control of the processing gases for plasma spraying is accomplished using an MKS 147 multi-gas flow controller. Details of the BATS facility and VPS system at LANL can be found in reference (1). Operating parameters used for plasma spraying beryllium are given in Table I.

Table I. Operating parameters for plasma spraying beryllium

Parameters	Settings
Current (A)	400
Voltage (V)	35
Primary gas (Ar)	40 slm
Secondary gas (H)	1 slm
Powder gas (Ar)	1 slm
Chamber pressure (torr)	400-450
Feed rate (g/min)	7.5
Spray distance (cm)	10.2
Torch translation (mm/sec)	34
Anode/cathode	730/129
Gas injector	112

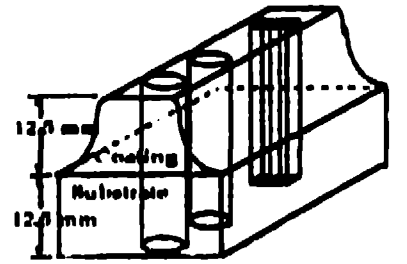
Beryllium plasma sprayed deposits were produced from -38μm +10μm spherical atomized beryllium powder purchased from Brush Wellman Inc. A typical chemistry of the beryllium powder used in this investigation is given in Table II.

Table II. Chemical analysis of -38μm +10μm spherical atomized beryllium powder

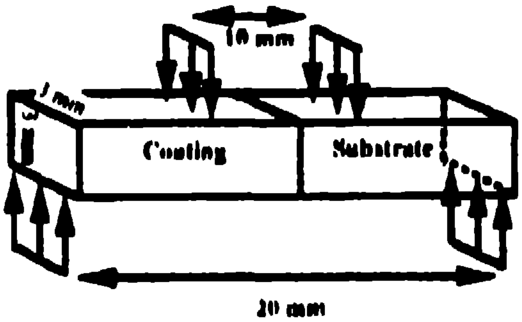
Be	balance	Ag*	<3
BeO wt.%	.36	Ti*	75
C wt.%	.089	Co*	9
Fe*	985	Pb*	<20
Al*	605	Ca*	20
Si*	420	W*	<100
Mg*	130	U*	125
Zn*	<10	Mo*	<20
Ni*	105	Cr*	110
Mn*	85	N*	170
Sc*	<5	Cu*	40

*ppm

Thick beryllium coatings 12 mm thick x 25.4 mm wide were deposited on four beryllium substrates which were 25.4 mm wide x 12 mm thick x 63 mm long. Negative transferred-arc cleaning was used to prepare and preheat the beryllium substrates prior to depositing beryllium. Information on the use of negative transferred-arc cleaning of beryllium surfaces can be found in reference (2). The beryllium substrates were preheated to 500, 600, 700 and 800°C prior to depositing beryllium onto the substrate surfaces. A type "K" thermocouple was placed 5 mm below the beryllium substrate surface in order to monitor the initial substrate temperature. Following the deposition of beryllium on the (4) beryllium samples, thermal diffusivity specimens 3 mm thick x 12.7 mm in diameter were machined from the beryllium coating, the interfacial region (which contained 1.5 mm of the beryllium substrate and 1.5 mm of the coating), and the beryllium substrate. Four-point bend tests samples 3 mm wide x 3 mm thick x 20 mm long were also machined from the thick beryllium coatings and beryllium substrates in order to evaluate the interfacial bond strength between the coating and the substrate. A schematic illustrating the location and specimen dimensions for the thermal diffusivity and 4-point bend samples are given in Figure 1.



a)



b)

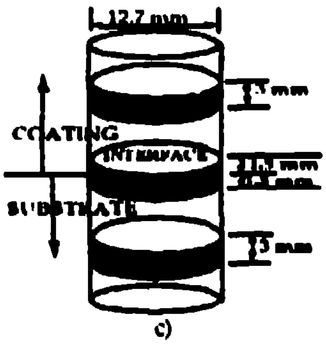


Fig. 1 Schematic illustrating a) the location, and specimen dimensions for the b) 4-point bend and c) thermal diffusivity samples.

Thermal diffusivity measurements from room temperature to 600 °C were performed at Virginia Polytechnic Institute, Thermophysical Research Laboratory, Blacksburg, Virginia, using laser flash diffusivity. Four-point bend testing of the plasma sprayed beryllium coatings on the beryllium substrates were performed at room temperature at a strain rate of ~ 10^{-4} /sec. Loading of the test samples was applied parallel to the direction of the beryllium coating/substrate interface as illustrated in Figure 1b. As-deposited densities were measured using a water immersion technique (Archimedes principal). Density measurements and microstructural characterization using polarized light microscopy and scanning electron microscopy (SEM) were made on the beryllium coatings, coating/substrate interface, and the beryllium substrate.

Results and Discussion

The results of the thermal diffusivity measurements for the plasma sprayed beryllium coatings and the coating/substrate interface samples at the different initial substrate temperatures are given in Figures 2a, b, c, and d. For the beryllium coating which was deposited on an initial substrate temperature of 500 °C (Figure 2a), the measured thermal diffusivity of the coating was approximately 75% of the thermal diffusivity of the beryllium substrate over the room temperature to 600 °C temperature range. The thermal diffusivity for the coating/substrate interface which contained 1.5 mm of the beryllium coating and 1.5 mm of the beryllium substrate had thermal diffusivity values which were between the beryllium coating and the beryllium substrate. The thermal diffusivity for the coating/substrate interface ranged from 80% to 90% of the beryllium substrate thermal diffusivity.

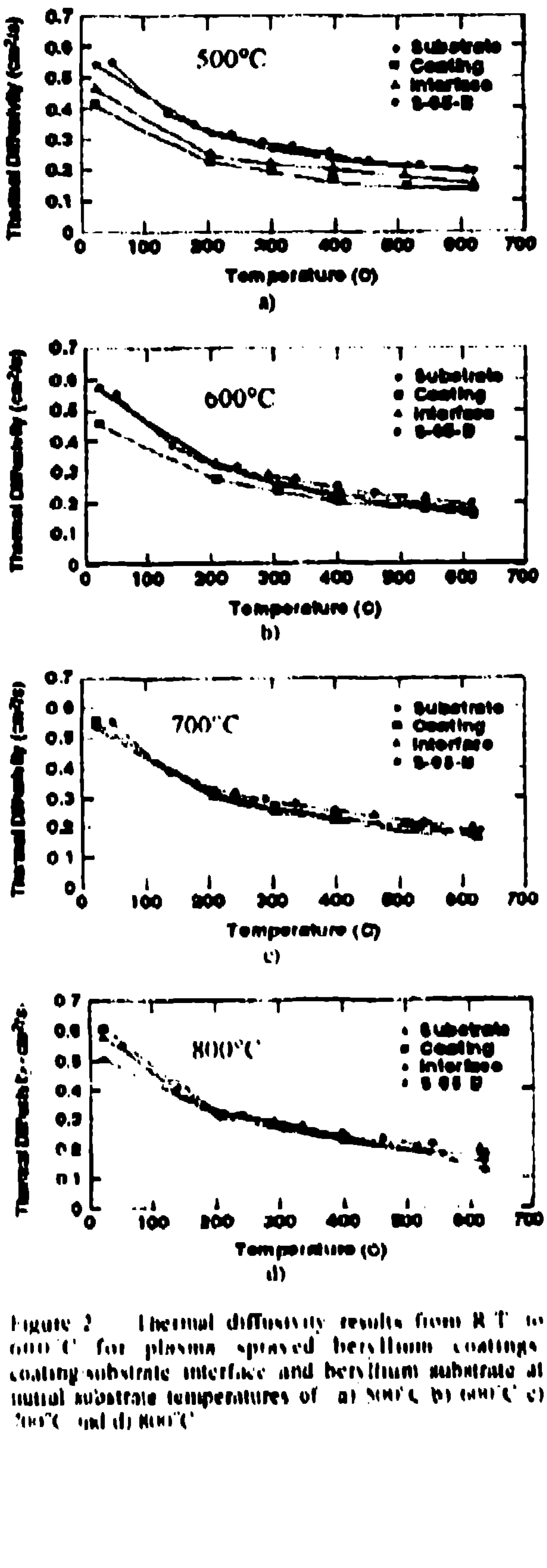


Figure 2. Thermal diffusivity results from R.T. to 600 °C for plasma sprayed beryllium coatings, coating/substrate interface and beryllium substrate at initial substrate temperatures of a) 500°C, b) 600°C, c) 700°C and d) 800°C.

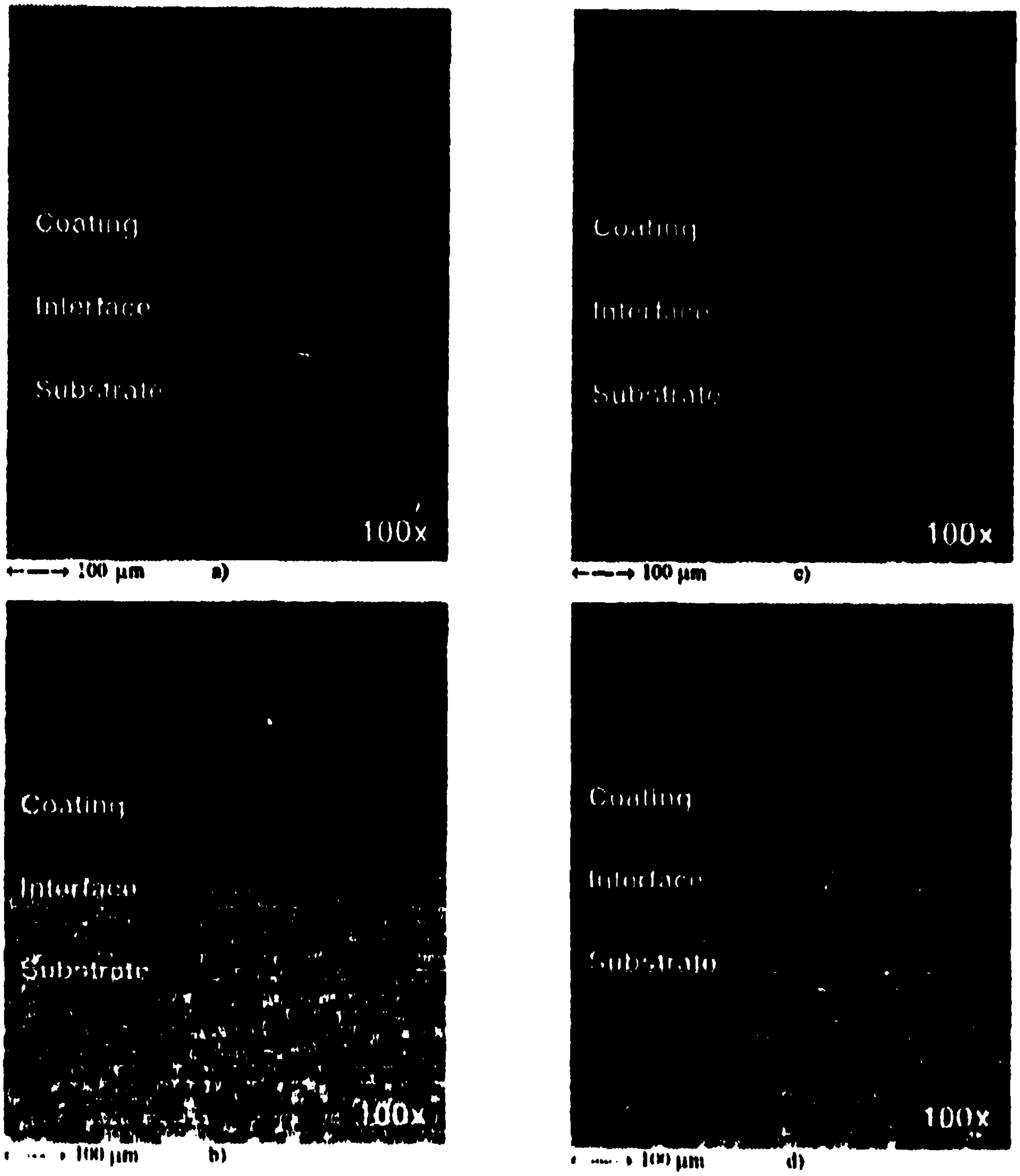


Figure [illegible] As-deposited microstructure of the beryllium coating, interface and beryllium substrate at initial substrate temperatures of a) 500°C b) 600°C c) 700°C and d) 800°C

For the beryllium coating which was deposited on a beryllium substrate which had an initial temperature of 600°C (Figure 2b), the thermal diffusivity of the beryllium coating increased to approximately 90-95% of the thermal diffusivity values reported for the beryllium substrate. The thermal diffusivity of the coating/substrate interface in this case approached the reported thermal diffusivity values for the beryllium substrate. As the temperature of the beryllium substrate was increased to 700 and 800°C (Figures 2c and 2d) the thermal diffusivity of the beryllium coating and the coating/substrate interface increased to the measured values for the beryllium substrate over the RT to 600°C temperature range. For all cases, the reported thermal diffusivity values for the coating, coating/substrate interface and substrate showed very good agreement with a commercial grade of S-65-B beryllium.

The as-deposited microstructure of the beryllium coating, interface, and beryllium substrate at the different substrate temperatures are given in Figures 3a, b, c, and d. The beryllium coatings which were deposited on the beryllium substrates which had initial temperatures of 500°C and 600°C had as-deposited densities on the order of 90% (1.67 g/cc) of the theoretical density for beryllium (1.85 g/cc). The beryllium coatings which were deposited on the beryllium substrates with initial temperatures of 700 °C and 800 °C had as-deposited densities of approximately 98% of theoretical (1.82 g/cc). It was observed that as the temperature of the substrates increased from 500°C to 800°C the grains became more elongated in the sprayed direction.

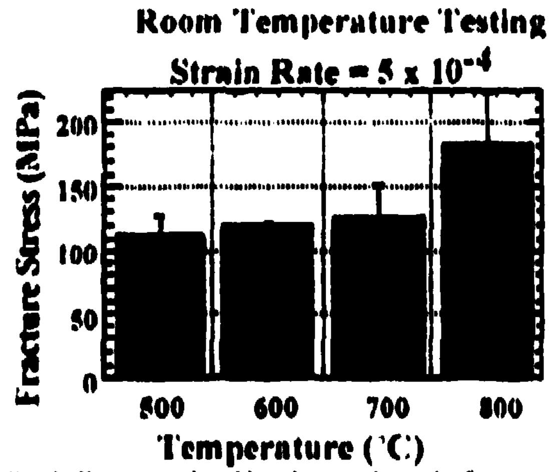


Fig 4. Four-point bend bond strength results for beryllium coatings on beryllium substrates with initial temperatures of 500°C, 600°C, 700°C and 800°C.

Results of the 4-point bend tests to determine the bond strength between the beryllium coating and the beryllium substrates are given in Figure 4. The bond strength ranged from approximately 100 MPa for the beryllium coating deposited on an initial substrate temperature of 500°C to a bond strength of 175 to 200 MPa for the beryllium coating deposited on a substrate with an initial temperature of 800°C.

Conclusion

- Increasing the initial substrate temperature of the beryllium from 500°C to 800°C resulted in an increase in the thermal diffusivity of the beryllium plasma sprayed coatings and the thermal diffusivity of the coating/substrate interfaces.
- Increasing the beryllium substrate temperature above 600°C resulted in thermal diffusivity values for both the coating and coating/substrate interface similar to that reported for the beryllium substrate and a commercial S-65-B beryllium grade material.
- By increasing the initial beryllium substrate temperature from 500°C to 800°C, a more elongated microstructure was observed in the beryllium coatings. This elongated microstructure has been shown to substantially improve the through thickness thermal conductivity of plasma sprayed beryllium coatings (2).
- Increasing the beryllium substrate temperature from 500°C to 800°C also showed an increase in the bond strength between the plasma sprayed beryllium coatings and the underlying beryllium substrate. Four-point bend bond strengths of the coating/substrate interface ranged from 100 MPa to 200 MPa.

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