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Feasibility of suspension spraying of yttria-stabilized zirconia with water-stabilized plasma torch

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ABSTRACT

Thermal spraying of suspensions allows preparation of coatings from submicron-sized powders but demands a source of heat with a high enthalpy in order to provide an appropriate thermal treatment of the liquid feedstock during the in-flight stage so that the solvent may be evaporated, dispersed particles melted and accelerated towards the substrate to form a coating. Water-stabilized plasma (WSP) torch developed at the Institute of Plasma Physics AS CR, v.v.i. provides such a heat source with high enthalpy, high velocity of the plasma and, when compared to high-enthalpy gas-stabilized plasma (GSP) torches, relatively cheap operation. In this study, results of our experiments with suspension spraying of yttria-stabilized zirconia (YSZ) with WSP torch are presented and demonstrate that coating deposition with a high feed rate is possible with WSP technology. Formation of both columnar "cauliflower" microstructure and segmentation cracks was achieved. Variation of the deposition conditions was observed to modify coating microstructure in terms of splat morphology, porosity and thickness per pass, which is promising for further coating development.

1. Introduction

One of the ways to improve functional properties of conventional thermal spray coatings is to use finer powders. In this way, e.g. microstructure, porosity, thermal conductivity, etc., of the coating may be tailored for a considered application. However, with a decrease of the particle size below about 5 μm, flowability of the powders in a gas carrier rapidly decreases resulting in clogging of the feeding lines which makes spraying of very fine powders practically impossible. Moreover, due to the low momentum of light particles, ability of their proper penetration into the plasma core is limited. Both of these problems may be solved by injection of suspensions — fine particles dispersed in appropriate liquid. Moreover, suspension plasma spraying enables preparation of coatings with novel microstructural features (such as nanometric pores or vertical cracks) and interesting properties (such as low thermal conductivity, high porosity, enhanced thermal shock tolerance, etc.) [1–9]. However, the liquid carrier must be evaporated prior to the melting of the particles and impact of the molten droplets on the substrate, so that the coating may be formed. Due to a relatively high content of solvent in the suspension (concentrations about 30 wt.% of solid phase are commonly sprayed) and the high amount of energy needed to heat up and evaporate the liquid phase, spraying of suspensions has been in recent years one of the main driving forces for the development of high-power plasma torches, introduction of multiple cathodes or axial injection, which should allow for high feed rates of 100 ml/min or more [10].

Alternative to modification of traditional gas-stabilized plasma (GSP) torches may be employment of water-stabilized plasma torch which seems to be very promising for deposition of suspension coatings as it has very high plasma enthalpy (up to 272 MJ/kg compared to 25 MJ/kg for GSP [11]). This provides for conventional plasma spraying of powders very high feed rates (tens of kilograms of powders per hour) and high throughput ability is expected also for spraying of suspensions. WSP torch provides a plasma density lower than GSP plasma (0.0027 kg/m^3 compared to 0.0292 kg/m^3) but significantly higher velocity (5 to 7 km/s compared to 1 to 2 km/s) [3,11,12]. As the plasma momentum and Weber number governing acceleration of the droplets and their fragmentation are a function of plasma density and square of plasma velocity, WSP torch is very promising to provide plasma parameters not achievable with GSP torches. Moreover, chemistry of the water plasma can also promote other effects of using different plasma medium, such as substantially increased thermal conductivity of water plasma when compared to argon-based plasma of GSP torches [13–15]. Last but not least, no argon is needed for operation of WSP torch, which makes its operation more economical as large volumes of argon are usually needed for GSP operation at high power levels.

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The aim of this study was to confirm, whether it is possible to exploit the benefits of high enthalpy content of WSP torch for suspension spraying and attempt to deposit coatings with a selected model material. Suspension of yttria-stabilized zirconia (YSZ) was chosen as a typical material deposited by suspension plasma spraying and widely used for thermal barrier coatings [16].

2. Materials and methods

Commercially available stabilized suspension of 8 wt.% YSZ dispersed in ethanol (25 wt.% solids) produced by Treibacher Industrie AG (A) was used for deposition. Manufacturer guaranteed mean particle size about 40 nm, which was confirmed by direct observation of dried suspension by scanning electron microscope.

Water-stabilized plasma torch WSP®500 (Institute of Plasma Physics AS CR, v.v.i., CZ) with radial injection was used for spraying of suspension on static AISI 304 steel substrates (thickness 4 mm) attached to the cooling fixture.

Prior to the deposition, substrates were grit-blasted by alumina grit ($Ra = 6.28 \pm 0.43$ μm). Rear sides of the substrates were cooled either by air or water. Spray pass design, preheating, number of spraying cycles, cooling intensity, etc., were varied in order to achieve different deposition conditions, namely spraying distance and sample deposition temperature, which was expected to influence the coating build-up and microstructure [6,17].

Within this study, 15 deposition experiments with different spraying conditions were carried out. Results obtained for 4 depositions with the most distinctive microstructures are presented in this paper. Further optimization of the deposition conditions for specific applications is anticipated.

Sample cooling system and shape of samples had to be redesigned for the higher deposition temperatures (samples C and D) in order to prevent local overheating of the samples and sample holder. Trajectory of the robot had to be slightly adapted accordingly. Obtained results (namely thickness per pass) should be therefore primarily compared within two groups of deposition conditions — samples A and B or C and D.

A custom-made pneumatic feeding system with separate purging liquid (ethanol) and suspension tanks with ultrasonic agitation was used for liquid feeding through sapphire nozzle with circular orifice (diameter 0.35 mm) providing a laminar liquid stream. SprayCam system (Control Vision Inc., USA) was used for adjustment of the suspension injection and visualization of the liquid stream break-up in the plasma jet. Sample temperature was evaluated during deposition by K-type thermocouple attached to the rear side of the substrate and by thermocamera TIM 160 (Micro-Epsilon, D) surveying the frontal side.

Materialographic samples were prepared on automatic polishing system Tegramin-25 (Struers, DK) to assure identical preparation conditions for all samples. Polished cross-sections and free-surfaces were observed using EVO MA 15 scanning electron microscope (Carl Zeiss SMT, D). Powder X-ray diffractometer D8 Discover (Bruker, D) equipped with 1D detector and a copper anode tube was used for phase composition evaluation employing standard Bragg–Brentano geometry. After phase identification, all the diffraction patterns were processed in TOPAS 4.2 software for Rietveld refinement.

3. Results and discussion

Based on preliminary trials and geometry of the WSP torch, injector angle was set to 25° and feeding distance to 25 mm. Standard spraying distance was set to 100 mm with exception for coating B, where it was set to 150 mm (Table 1). Pressure of 2.5 bars in the feeding system provided a feed rate of about 5.3 l of suspension per hour and was optimized with the SprayCam system so that the liquid stream penetrated into the core of the plasma jet and effective fragmentation of the stream was achieved (see Fig. 1A).

Table 1
Spraying setup and characteristics of the deposited coatings.

Sample	A	B	C	D
Spraying distance [mm]	100	150	100	100
Nozzle diameter [mm]	0.35	0.35	0.35	0.35
Feed rate [ml/min]	92	92	86	86
Robot speed [mm/s]	500	500	300	300
Sample shape	Rectangular	Rectangular	Circular	Circular
Cooling medium	Water	Water	Water	Air
Cooling intensity	High	High	Medium	Low
Spray pass design (cycles × passes)	20 × 2	20 × 2	6 × 6	6 × 6
Total number of spray passes	40	40	36	36
Preheating	No	No	Yes	Yes
ST after preheating [°C]	26	21	100	260
Mean ST before spray cycle [°C][a]	35	23	220	361
Coating thickness [μm]	132.7 ± 14.5	135.8 ± 14.5	177.8 ± 11.2	109.2 ± 12.6
Thickness per pass [μm/pass]	3.32 ± 0.36	3.40 ± 0.36	4.94 ± 0.31	3.03 ± 0.35
Coating porosity [%]	36.2 ± 3.3	43.3 ± 1.0	16.7 ± 1.4	15.5 ± 1.9
XRD crystallite size [nm]	416 ± 15	264 ± 7	252 ± 8	300 ± 14

Note: ST = Sample temperature as measured from the thermocamera.
[a] Target temperature for the start of the second to the final spraying cycle. For the first spraying cycle see ST after preheating.

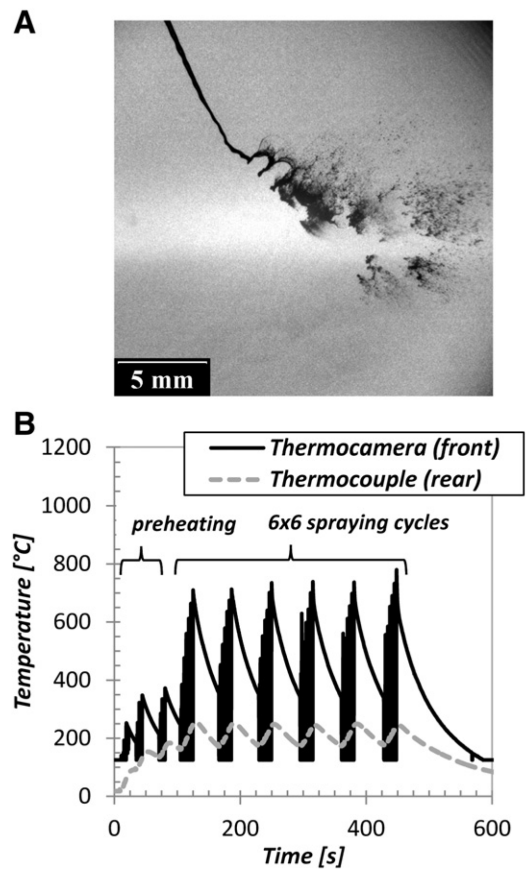

Fig. 1. A) Break-up of the liquid stream in the WSP jet (bright area). B) Temperature history for sample D. Drops of the thermocamera reading during deposition are due to obscuration of the sample by plasma torch.