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A novel structure of YSZ coatings by atmospheric laminar plasma spraying technology

Sen-Hui Liu [a], Cheng-Xin Li [a,*], Hui-Yu Zhang [a], Shan-Lin Zhang [a], Lu Li [b], Pan Xu [b], Guan-Jun Yang [a], Chang-Jiu Li [a]

[a] State Key Laboratory for Mechanical Behavior of Materials, School of Materials Science and Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China
[b] Zhenhuo Plasma Technology Company, Chengdu, Sichuan 610065, China

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ABSTRACT

A novel structure of yttria stabilized zirconia coatings was developed in this study by a newly laminar plasma spraying technology in atmospheric environment. The unique microstructures of coatings showed the multi-island protrusions feature at the top surface, quasi-columnar structures along the cross-section distributed as a certain interval and hybrid droplet/vapor deposited structures at the fracture surface. The distributions of particle velocity and surface temperature along the axial direction of long laminar plasma jet were investigated and compared with other plasma spraying methods. The effects of different microstructures to thermal conductivities comparing with other current plasma spray methods were also demonstrated.

Plasma sprayed thermal barrier coatings (TBC) of low-thermal conductivity have been extensive used to provide thermal insulation for metallic components in gas turbine engines [1–3]. A typical thermal barrier coating system on the surface of superalloy substrate consists of an oxidation-resistant metallic bond coating and a ceramic top coating [4,5]. Yttria stabilized zirconia (YSZ) of low thermal conductivity, high toughness and melt temperature has been widely used as the top coatings materials [2]. The YSZ top coating is deposited by either electron-beam physical-vapor deposition (EB-PVD) method [6] or plasma-spray deposition (APS, SPS, PS-PVD) methods [7,10]. The EB-PVD coating with columnar microstructures performed high thermal cyclic lifetime and also high thermal conductivity (usually 1.5–2.0 W m^{-1} K^{-1}) [8,9]. The typically atmospheric plasma sprayed YSZ coatings with lamellar structure possessed low adhesive strength and low thermal conductivity (usually 0.8–1.8 W m^{-1} K^{-1}) [10,11,32].

Technically, current plasma spray methods (APS, SPS and PS-PVD) are using the direct current non-transferred arc plasma torch with linear channel structures for thermal spray process, like the commercial Sulzer serials 9 M torches, Sulzer F4VB torch, Sulzer Triplex serials torches or Praxair serials SG-100 Guns. The arc is operated across a flow of argon, hydrogen, helium, nitrogen or mixtures between a cathode (Sulzer Triplex serials torches with three cathodes [12]) and a nozzle-shaped water-cooled anode where the plasma gas is induced along the cylindrical channel and injected into the surrounding environment [13]. The lengths of these plasma jets that generated by the conventional non-transferred arc plasma torches cannot exceed 200 mm in atmospheric environment at a minimum gas flow rate of 30 splm [10], the spraying distance in atmospheric environment usually is in the range of 80 mm~200 mm [14]. Except for the PS-PVD process, it can obtain an expansion flow of plasma jet in a length from 1000 mm to 2000 mm and a diameter from 200 mm to 400 mm only when the plasma torch is in a closed-chamber at a low-pressure condition [15].

In atmospheric plasma spraying YSZ coating process, the working power and total gas flow rate for atmospheric plasma spraying YSZ coatings usually exceed 30 kW and 40 slpm, respectively [4,5,16]. The ceramic powders that suspended in carrier gas are injected into the thermal plasma plume in radial or axial direction, where solid powders are accelerated and heated to molten or semi-molten state. Finally, these particles continuously impinge on the prepared substrate to form coatings of numerous overlapped splats. The microstructure of coatings features the lamellar structure consisted of overlapped splats and this process cannot obtain abundant vapor-deposited coatings in atmospheric environment.

In addition, for the PS-PVD process, these systems usually work at input power ranging from 65 kW to 150 kW and total gas flow rate ranging from 80 slpm to 200 slpm [7,15,19,21]. At these conditions, the injected YSZ powder can be vaporized sufficiently and obtained

Abbreviations: APS, atmospheric plasma spray; ALPS, atmospheric laminar plasma spray; EB-PVD, electron-beam physical-vapor deposition; PS-PVD, plasma sprayed-physical vapor deposition; SEM, scanning electron microscopy; SPS, suspension plasma spray; TBC, thermal barrier coating; YSZ, yttria stabilized zirconia.

* Corresponding author.
E-mail address: licx@mail.xjtu.edu.cn (C.-X. Li).

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Table 1
Laminar plasma spraying parameters.

Parameters	Value
Input power/ kW	25–26
Torch move velocity/ m/s	0.6
Torch move interval/ mm	4
Spraying distance/ mm	250
Plasma gas N_2/Ar	7:3 (by volume)
Total gas flow rate/ slpm	14
Feed powder	YSZ (Metco6700)
Powder feed rate/ g/min	4 (no carrier gas)

lamellar, hybrid, quasi-columnar, EB-PVD-liked columnar type or column type YSZ coatings in different spraying distances. The results show low thermal conductivity (usually 0.5–1.2 $Wm^{-1}K^{-1}$) and excellent thermal cycling performances than the conventional atmospheric plasma spray method (APS) [17–19]. It also provides a method in higher deposition rate and lower investment costs than EB-PVD process [20,21].

Therefore, a mass of vapor deposited YSZ coatings can only be obtained under the low-pressure conditions, liked PS-PVD or EB-PVD process. Conventional atmospheric plasma spray technology cannot obtain abundant vapor-deposited YSZ coatings that consisted of column-type or quasi-column features.

In this work, a novel long laminar plasma jet that generated by a newly type of non-transferred arc plasma torch was used in atmospheric thermal spray process. The lengths of plasma jet can be changed range from 200 mm to 700 mm in atmospheric environment at different working conditions [22]. This method can also obtain quasi-columnar structure YSZ coatings with abundant vapor-phases at the input power of 25–26 kW (I = 160 A) and total gas flow rate of 14 slpm by 70% nitrogen and 30% argon in atmospheric condition.

7%~8% yttria stabilized zirconia spheroidal powder (Metco 6700, −30 μm ~ +1 μm, d_{50} = 10 μm, Oerlikon Metco, Westbury, USA) was used as the feedstock material, which was a fine and agglomerated powder specifically designed for Plasma Sprayed Physical Vapor Deposition (PS-PVD) coating process [23]. The particles injection in this work was through a specific gravity-vibration device in the radial direction of torch nozzle and did not use the conventional powder supply by the way of auxiliary gas [24]. The initial injecting velocity was less than 3 m/s at the mass flow rate of 4 g/min. The substrate used in coating deposition was 304 stainless steel, which was prepared after grit-blasting, with a NiCoCrAlY bond coating having a thickness of 40 μm deposited by a low-pressure plasma spraying (LPPS) system (Ni23Co20Cr8.5Al4.0Ta0.6Y, Amdry 997, −37 μm ~ +9 μm, Sulzer Metco, Westbury, NY) [25]. The details of laminar plasma spray process were shown in Table 1.

The thermal conductivity is calculated by Eq. (1):

$$\lambda = \alpha \cdot C_p \cdot \rho \tag{1}$$

where α is the thermal diffusivity in m^2/s, C_p is the specific heat capacity in J/(kg K), ρ is the density in kg/m^3, and λ is the thermal conductivity in W/(m K) [26]. The thermal diffusivities (α) of the YSZ coatings were measured using a laser-flash apparatus (Netzsch, LFA-427, Germany).

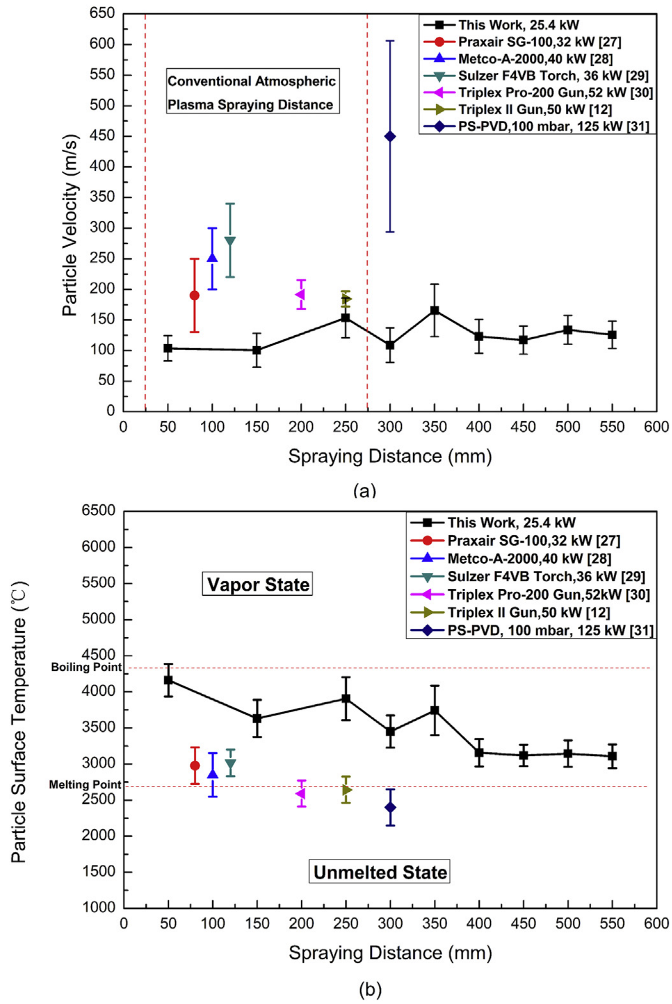

Fig. 2. Particle velocity (a) and particle surface temperature (b) in laminar plasma jet at different positions from the nozzle exit and comparison with the results from other plasma spray methods.

The diameter of the specimens was designed as 12.7 mm~13 mm. The surfaces of the specimens were coated with a thin film of graphite for thermal absorption of laser pulses at the beginning. Each sample was measured three times at one selected temperature. The value of the heat capacity of the coatings was determined with differential scanning calorimeters (Netzsch-404, Germany).

As Fig. 1-a showed the photo of long laminar plasma jet in atmospheric environment. The YSZ powders that injected at the radial direction of nozzle exit were accelerating and heating in laminar plasma jet (Fig. 1-b). The in-situ experimental measurement results of particle velocity and surface temperature as a function of spraying distances were plotted in Fig. 2-a and Fig. 2-b, respectively. Moreover, other results in Fig. 2 were from the APS methods by five typically commercial plasma torches [12,27–30], which used spherical hollow 7–8% YSZ particles as

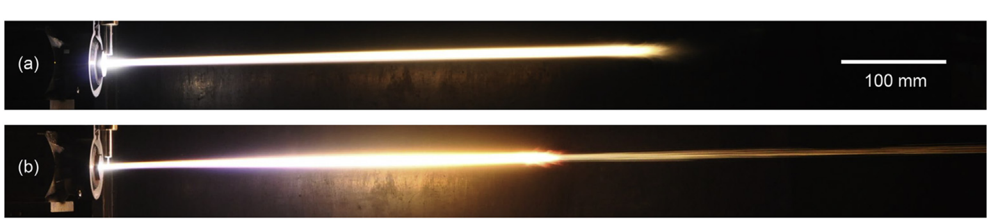

Fig. 1. Photos of the laminar plasma jet in atmospheric air (a) and with YSZ particles heating and accelerating of (b).