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Low power consumption suspension plasma spray system for ceramic coating deposition

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ABSTRACT

Suspension plasma spraying (SPS) is a modification of conventional plasma spray techniques that has been developed to overcome the challenge of using nano-sized particles in plasma spray processes. The novel feature of using nano-sized particles in the form of a suspension makes the SPS process promising for several applications and for improving the performance of plasma spray coatings. The focus of this study is to develop a new SPS system that consumed low power and gas to deposit ceramic coatings.

Several ceramic coatings, such as titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), yttrium oxide (Y_2O_3), and yttria-stabilized zirconia (8YSZ), were successfully fabricated using only Ar as the plasma gas at a low power of 27 kW with the new SPS system. The new system is characterized by lower power and gas consumption (only Ar as plasma gas) and axial injection. It is a unique SPS system based on a twin-cathode-type plasma spray gun. The gun has three plasma torches, the main one is called a P-torch (anode) and the two sub-torches are called N-torches (cathodes). The main plasma torch has a reversed polarity (with a cathode nozzle and an anode electrode). The two sub-torches have normal polarity (with an anode nozzle and a cathode electrode). During operation, electric power is supplied between the anode of the P-torch and the two cathodes of the N-torches, so that the so called hairpin-shape of the plasma jet can be maintained. The system requires only argon as the plasma gas (without using any other gases). The voltage (enthalpy of the plasma jet) with Ar is high enough (150 V) for melting ceramic powders, which results in a gas consumption SPS system compared to the other available SPS systems. Furthermore, the electrode of the main torch (P-torch) is a hollowed anode, so that axial feeding of spraying materials could be carried out in this system, which is the best method for spraying. In this configuration, the particles are injected into the center of the plasma jet along the axis of its flow. Therefore, the feedstock suspension would be fully entrapped and melted within the plasma before deposition on the substrate surface.

1. Introduction

Plasma spraying is a well-established and widely used technology for surface coatings engineering with high application speed, high deposition rates, and relatively low cost [1,2]. The process is based on supplying the feedstock powder material into a very high temperature plasma jet, where it is rapidly heated and accelerated with its high velocity flow. The molten or semi-molten particles collide on the substrate surface and rapidly solidify, forming a coating.

Feedstock powder is one of the key factors for controlling and adjusting the plasma spray process, coating microstructure, and layer properties [2–5]. The feedstock powder should have good flowability during injection into the plasma stream to make the spray process consistent and reproducible [2,5]. Generally, the feedstock powder is micron-sized, with size ranging between 20 and 100 μm. This leads to certain limitations of the resulting splat size and, therefore, the achievable microstructure. The fabricated coatings present mainly micrometer-sized features with highly porous structures and complex microstructures of large "splat" boundaries/cracks, being full of defects like pores and microcracks.

One of the most promising approaches to overcome the above challenges and improve the performance of plasma sprayed coatings is the spraying of nano-sized powders. This leads to the formation of small splats during deposition, which will reduce the residual stress, internal cracks and pore size. Therefore, it assists the precise control of the coating built-up microstructure. However, it is difficult to spray the nano-sized feedstock powder in a conventional plasma spray system.

One of the major obstacles of using nano-sized powder in plasma spray is the difficulty of injecting the particles into the core of the

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plasma plume. Another drawback of spraying the nano-sized powder is the particle easy agglomeration and, therefore, the rapid clogging of the flow path towards the injecting point. This is caused by the poor rheological properties of the fine particles, which lead to non-uniform powder transport from the feeder to the plasma plume [6].

Suspension plasma spraying (SPS) process has been developed to overcome such drawbacks and to enable the feeding of nano-sized powder into the plasma plume [6–9]. This process is based on suspending the nano-sized particles in a water or alcohol carrier liquid to the plasma plume. Generally, the feedstock particle size is between 30 and 100 nm, which provides unique and novel characteristics for the coatings compared to the conventional spraying techniques. The SPS technique has attracted much attention, since it opens up a series of new research opportunities and challenges in the thermal spray field, including the suspension particle size and preparation, suspension handling and stability, suspension storage, injection system, flow ability and stability of suspension injection, suspension and plasma interaction, liquid processing, coating build up mechanism, heat flux and mass flux to the substrate, microstructure control, and spraying system. This study focuses on developing a new suspension plasma spray system with low power and gas consumption to deposit the ceramic coatings.

2. Experimental procedures

2.1. Suspension plasma spray (SPS) system

A twin-cathode type plasma spray gun (Aeroplasma Corporation, Japan) was used to develop the new SPS system. The gun consisted of three plasma torches: a main torch (P-torch) and two sub-torches (N-torches). The system is based on modifying a conventional plasma spray gun. The conventional systems are based on using normal polarity (with an anode nozzle and a cathode), and the plasma goes from cathode to anode, as schematically shown in Fig. 1. The conventional system depends on using two plasma gases (Ar, H_2, He, N_2), and a radial feeding system.

The newly developed suspension plasma spray system is schematically shown in Fig. 2. The system is based on using a twin-cathode spray gun, which consists of:

- The main torch in the center with reversed polarity (with a cathode nozzle and an anode electrode), named P-torch (+).
- Two sub-torches on the sides of the main torch with normal polarity (with an anode nozzle and a cathode), named N-torches (−).

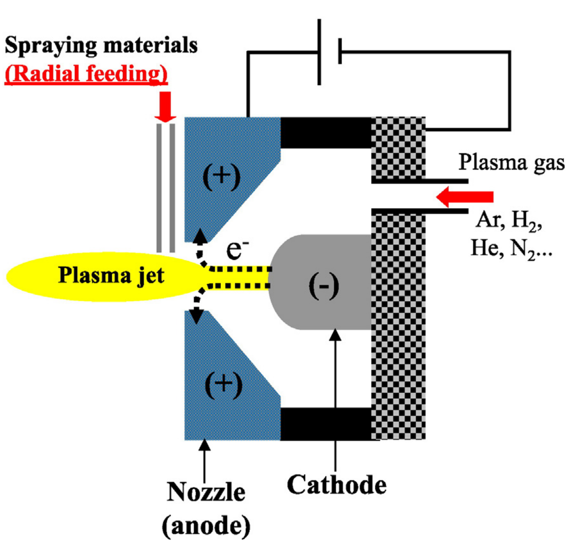

Fig. 1. The conventional plasma spray gun system.

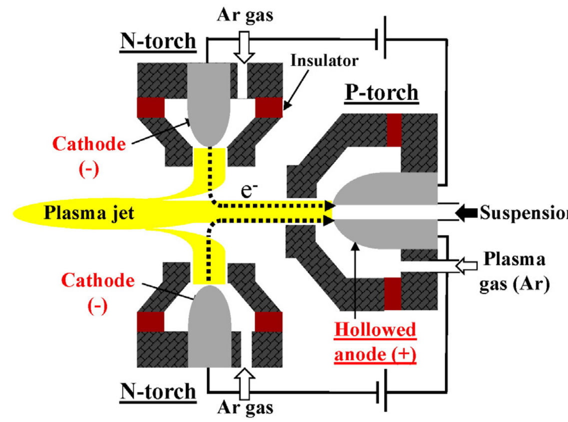

Fig. 2. Schematic diagram of the newly developed twin-cathode plasma spray gun.

Fig. 3 shows the actual modified twin-cathode plasma spray gun and the shape of the plasma jet. During operation, the plasma generated between the anode of the P-torch and the two cathodes of the N-torches, shown in Fig. 2, is developed so that the plasma jet can be maintained. Therefore, the system had two equivalent circuits, and the power of the system was controlled and calculated from the voltage and the current of these circuits. After the complete generation of the plasma, the hairpin-shape was formed, as shown in Fig. 3(e). The new system requires only argon (Ar) gas as plasma gas, without any other gases. The typical spray parameters are illustrated in Table 1.

2.2. Suspension injection system

Axial injection of the feedstock suspension was used in the new system. Thus, the P-torch had a hollowed electrode (anode), as shown in Fig. 2. A commercial dual tube nozzle, HM-6L (Fuso Seiki Co., Ltd.), was inserted into the hollowed anode of the main torch to supply the mist of suspension into the plasma jet. The schematic views of the dual tube nozzle are shown in Fig. 4. The dual tube nozzle consists of two tubes:

- An inner tube with 0.2 mm inner and 0.4 mm outer diameters. This inner tube is for suspension feeding to the plasma jet.
- An outer tube with 0.7 mm inner and 1 mm outer diameters. This tube is used for the atomizing gas (Ar gas) around the suspension.

The complete plasma spray system is summarized in Fig. 5. After the plasma generation and setting the required spraying conditions, only ethanol was injected in the plasma. Then, the suspension was injected in the plasma plume using a pneumatic system (Ar gas).

2.3. Feedstock materials and characterization

Several commercial ceramic materials have been used for the SPS system investigation. The materials used as feedstock spray material were TiO_2 powder (anatase, Tipaque W-10: Ishihara Sangyo Kaisha Ltd., with a particle size of 0.15 μm), Y_2O_3 powder (C.I. Kasei Co., Ltd., with a particle size of 0.4 μm), Al_2O_3 powder (Taimei Chemicals Co., Ltd., with a particle size of 0.1 μm), and yttria stabilized zirconia (8YSZ: Tosoh Corporation, Yamaguchi, Japan, with a particle size of 0.05–0.09 μm). The feedstock suspensions were prepared through mixing nano-sized powder with ethanol as the solvent and Poly-

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