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Study of the particle behavior in a pulsed arc

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ABSTRACT

This paper details a spray technique, named as "sparkjet", which generates high-speed particles and a high temperature gas jet. It aims to demonstrate the feasibility of the process and the physical mechanisms, the influence of the process parameters on the characteristics of the flyer particles, and the quality of interfaces and coating structures. The coupling efficiency between the powder injector and the arc generator and the measurements of the process parameters were successively estimated. Tests proved the feasibility of this new process as well as its automated energy efficiency, which can offer a real potential application for developing metallic and ceramic coatings.

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1. Introduction

Thermal spray techniques are widely used in industrial areas requiring high additional value, such as the aeronautics, energy and automotive fields. They are considered a part of the surface treatment technology that are able to produce different coatings (from ceramic to metallic powder) and different coating thicknesses (from 10s–100s microns typically) on varied substrates (metals, ceramics, glass, plastic, etc) [1–3]. Generally, these coatings are developed for specific applications such as protection against corrosion, wear or high temperatures; also they are used to provide desirable and functional properties and special requirements such as catalysis or bioactivity [4].

Thermal spray applications are highly varied, ranging from simple galvanization for metal infrastructures (bridges), to high technology applications such as aircraft jet engines with the development of abradable materials (i.e. very friable materials used to reduce heat leakage by adapting the dimensions during commissioning) [5]. These materials are also applied in the fields of electrical engineering, medicine (coatings for prostheses), energy in gas turbines, the automotive industry with molybdenum coatings of synchronizing rings for example, and nuclear energy [6].

Each thermal spray process consists of using the heat and kinetic energies present in the jet to melt and accelerate a powder material toward a substrate. After their impact onto the substrate, the powder particles are spread and solidified within a very high quenching rate ($>10^6 K \cdot S^{-1}$) [7]. Pass after pass, they form a successive stack deposition. They are conventionally classified depending on their heat source: Flame or HVOF, Plasma, Arc wire, and more recently cold spray.

Even if the principle of the thermal spray processes is quite similar, each spraying method has its own strong and weak points. If we try to summarize the advantages and disadvantages in terms of speed and temperature, the following points can be noted:

- Current detonation spraying has some unique advantages due to its extremely high particle velocity. However, the temperature is not high enough to achieve the melting of typical ceramics for example, which have a high melting point, or to obtain a deposit of high quality [2,8].
- Plasma spraying has a very high temperature, but the velocity is limited and cannot be easily increased, since increasing the velocity implies increasing the gas flow ratio, which may cause sudden turbulent motion of the electric arc at the anode, leading to plasma extinction [9]. Kitamura et al. [10] succeeded in improving thermal spray technology using electromagnetically accelerated plasma spraying to deposit refractory powder: the source materials are accelerated about 2 km/s, the actual shot cycle of this system is about 15–20 shots/day. Ichiki et al. [11] treated a steel surface using pulsed-arc nitrogen plasma under atmospheric pressure with a low-frequency voltage pulse (4–5 kV and 21 kHz), considering that the plume temperature is lower than DC arc discharge because of pulse excitation. These cases do not show instantaneous explosion, so it should not have an attractive rate and temperature.
- Flame spraying has a maximum temperature of 3000 °C [12].

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So far, tests carried out on detonation spraying have investigated metallic and cermet particles, and some ceramics such as Al_2O_3. For ceramics with a high melting point, the detonation technique is unsuitable and there is currently no process that can obtain both high temperature and high speed [13].

Fig. 1 displays the working area of each process with respect to the particle velocity and gas temperature.

As shown in Fig. 1, no process simultaneously offers properties including high temperature and high velocity. As a result, this process was studied at a higher velocity compared to the detonation process, and at a higher temperature compared to plasma spraying. Hence, the deposit characteristics are enhanced.

In this preliminary study, the parameters of the electric arc device were firstly studied by implementing different controllers, analysis of the impact of the powder was then performed in order to ascertain the feasibility of this technique.

Ideally this process generates a short time and powerful electric arc in a tube, with a high temperature, ranging from 6000 to 7000 °C, then the volume of gas will be expanded and it can generate a high velocity. The particles can be molten and accelerated to a high velocity.

The device presents an axis-symmetry between the cathode and anode. In the configuration, the cross section of the plasma discharge in the discharge gap is not uniform; its electrical state is unstable also. According to the brightness of the spark channel and its energy, the gas temperature during the spark phenomena can reach 7×10^3 K and the electron avalanche propagation velocity is about 1.25×10^5 m/s. From a spectrometry point of view, a large number of ionized particles is generated in the vicinity of the anode near the spark discharge, which greatly exceeds the ionization extent of the ionization electron avalanche. The formation of this highly ionized area and the rapid spread of features called streamer, leads to an expansion that may reach 10^6 m/s during the spark phenomena. Because of the pulses of about 10^7–10^8 m/s leading to gas ionizations, the acceleration of powders passing through such a spark system is obviously obtained as is observed in the detonation gun spraying.

2. Experimental materials

For the preliminary study, to prove the feasibility of the considered process, different powders were selected depending upon their melting temperature especially. Hence, we did not focus on the applications but only on the potentiality of this process to manufacture coatings. Powder selection was then based on their differences in melting point and mechanical properties.

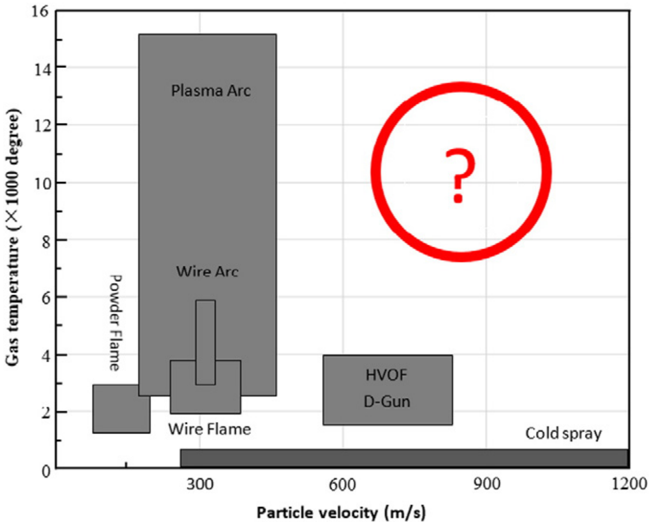


Fig. 1. Temperature and particle velocity in the thermal spray [14,15].

Commercially available NiCrBSi powder (HOGANAS 1-40 SP 379), NiCoCrAlY powder (Sulzer-Metco AMDRY 9951) and $Al_2O_3 + 3\%TiO_2$ powder (STARCK AMPERIT 742.3) were used as feedstock. The morphologies of the powders were observed by scanning electron microscopy (SEM) (JEOL, JSM-5800LV), the respective particle size distribution was determined by laser light scattering (Coulter LS130R particle size analyzer equipped with a dry powder module), indicating respective mean values of about 40.44 μm, 27.07 μm and 30.39 μm as illustrated in Table 1.

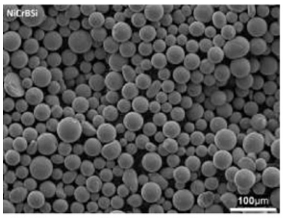
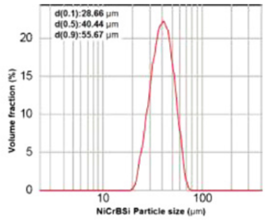
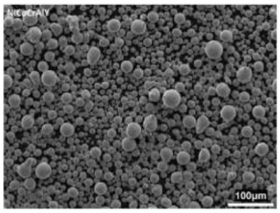
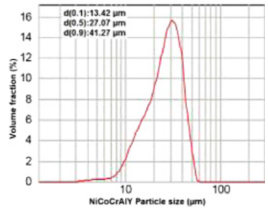
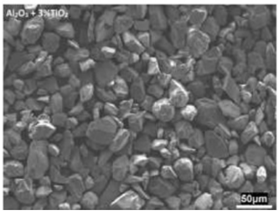
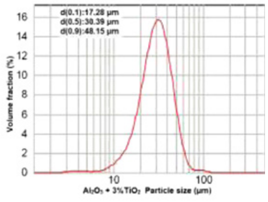
The splashing process was observed using SEM and the coatings were observed via OM.

3. Experimental device

A basic experimental setup was used for this preliminary study. The pulsed arc was generated in a cylindrical cavity of 8 mm in diameter and 60 mm in deep. The cylinder was made in acrylic enabling the side-on observation of the light produced by the arc and powder injection as described in Section 4. The following figure illustrates this tube and also the electrical circuit for the process.

Two face-to-face electrodes in tungsten were implemented inside the cylindrical cavity at a distance of 50 mm to the opening, they were perpendicularly to the symmetrical axis of the tube as shown in Fig. 2. The pulse arc is generated by a capacitor discharge between the two electrodes whose distance was adjustable. The electric circuit is composed of a high voltage power supply and a capacitor shown also in Fig. 2. The 2.6 μF capacitor has been charged to a high voltage in range of 10–15 kV. A device is implemented to detect the end of the charge and to deliver a signal at the end of the charge. This signal was used to switch-on a spark-gap leading to the electrical discharge in the tube of the energy stored in the capacitor. Typically, the total duration of the discharge was about 80 μs as shown in the Fig. 4. Note that this duration may be adjusted by changing the value of the inductance coil integrated in the discharge system. The voltage of the capacitor was monitored thanks to a high voltage probe (Tektronix P6015A, 75 MHz) and the

Table 1
SEM image of powders and powder size distribution.

Powder	Morphology	Size distribution
NiCrBSi		
NiCoCrAlY		
Al_2O_3 + 3%TiO_2		

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