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# Injection of Hot Particles in the Plasma Flame

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**This study deals with experimental and theoretical investigations of preheating of the particles injected into a flame during the process of atmospheric plasma spraying (APS). Prior to the injection in the flame, the particles, delivered from the powder feeder, were heated in a carrier gas. The experimental devices to preheat the carrier gas, based on a principle of *linear, superficial,* and *volume* heating are discussed. The particle velocity and temperature in the pipeline connected to a preheating device were estimated theoretically using a simple analytical model. Two types of preheating devices were submitted to preliminary tests. The temperature of the carrier gas was measured using a thermocouple for a *volumetric* device working with a gliding arc discharge. The microstructure and properties of chromium oxide coatings plasma sprayed with the aid of a superficial preheating device are also presented and discussed.**

**Keywords** preheating, prespray treatment, powder injection

## 1. Introduction

The quality of thermal spray coatings, processed with low velocity, high-temperature flames typical for the atmospheric plasma spraying process,[1] depends on molten particles being deposited on the substrate. Upon impact, the molten particles are deformed plastically and adapt themselves to the irregularities of the substrate or previously deposited coating.[2,3] The partly melted or solid particles are loosely bound to the substrate. Consequently, the mechanical properties of coatings sprayed with a large fraction of unmelted particles are poor. Their adhesion strength, elastic modulus, and toughness are considerably worse than those of coatings sprayed under optimized conditions.

The degree of particle melting results from two main factors:[4] (1) the shape and temperature of the plasma flame and (2) the trajectory of particles inside this flame. The shape and properties of an arc flame are determined by the plasma torch operational parameters[5] and the surrounding medium. The particle trajectory depends on the injection conditions into the flame. Assuming one port injection, this trajectory depends on the initial velocity of the particles. After injection, the particles travel in the flame and their temperature upon impact with the substrate would be, a rough approximation, higher if their trajectory was closer to the flame centerline. On the other hand, this temperature would increase if the initial temperature were higher. The impact temperature is related to the initial temperature of the particles, and to achieve an increase of this temperature, it is necessary to design a powder preheating device. Two types of such devices were experimentally tested in the present study: (1) superficial, being an electrically heated metallic tube; and (2) volumetric, being a plasma reactor working with a gliding arc discharge (also called *Glidarc*[6]).

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## 2. Experimental Procedures

### 2.1 Powder Particles Preheating

The feed stock powder is delivered from a powder feeder, which has a rotating or a vibrating plate control for the feed rate. The fed portion is injected to a pipeline as a suspension in a carrier gas. In order to achieve stable powder transport, the carrier gas flow rate must be greater than a certain value, which depends on the geometry of the pipeline, powder, and gas properties.[7] The carrier gas could be heated inside the powder feeder or in a reactor between the feeder and the plasma torch. A simple solution is heating with electric energy using a Joule effect or by an electric discharge in the gas (Fig. 1). The hot carrier gas transfers energy to the powder particles.

In a *linear* device (Fig. 1a), the electric energy is dissipated by an electric wire, which is set along the centerline of the pipeline. However, the particles could stick to this hot wire and modify the geometry of the pipeline and disturb the powder feeding. This effect is also possible, but to a lesser degree, for a *superficial* device (Fig. 2b). This type of device was used in the experiments of plasma spraying. It was designed with a stainless steel tube of 3 m length, 6 mm OD, and 4 mm ID.[8] An auto transformer supplied the electric energy.

The temperature of a carrier gas was tested for the volumetric preheater (Fig. 2). The set up included a Castolin Eutectic (Lausanne, Switzerland) powder feeder and a homemade Glidarc reactor of 117 mm ID and 210 mm length with 6 electrodes (3 pairs). Each pair was powered from a three-phase electric generator. The reactor was powered with 2 kW. The heated carrier gas with the particles was delivered to an alumina pipe of $l_1$ = 920 mm length and a diameter of $d_1$ = 8 mm (ID). The temperatures of the carrier gas were determined with Ni-NiCr thermocouples at the inlet and outlet of this tube ($T_{in}$ measured with thermocouple 1, and $T_{out}$ measured with thermocouple 2).

Air was used as a carrier gas. The alumina powder of size –125 + 63 $\mu$m (AMIL 6010.090) from Amil (Würselen, Germany) with different powder feed rates was used throughout all experiments.

The Glidarc is a powerful and highly active nonthermal plasma source, particularly adapted to processing of gases, vapors, dispersed liquids, or solids.[6] The Glidarc has at least two diverging knife-shaped electrodes. These electrodes are immersed in a fast gas flow. The progress of an arc discharge is depicted in Fig. 3. A high voltage and relatively low current discharge is generated across a gas flow between the electrodes. The discharge forms at the closest point, spreads as it glides along the electrodes, and disappears. Another discharge immediately reforms at the initial spot. The geometry of the electrodes, flow conditions, and characteristics of the power supply determine the path of the arc. The discharge performs its own maintenance on the electrodes, preventing chemical corrosion and erosion. The electrodes do not need to be cooled so the electrical energy is directly and totally transferred to the processed gas. The voltage can be as high as 20 kV for currents up to 50 A per discharge.

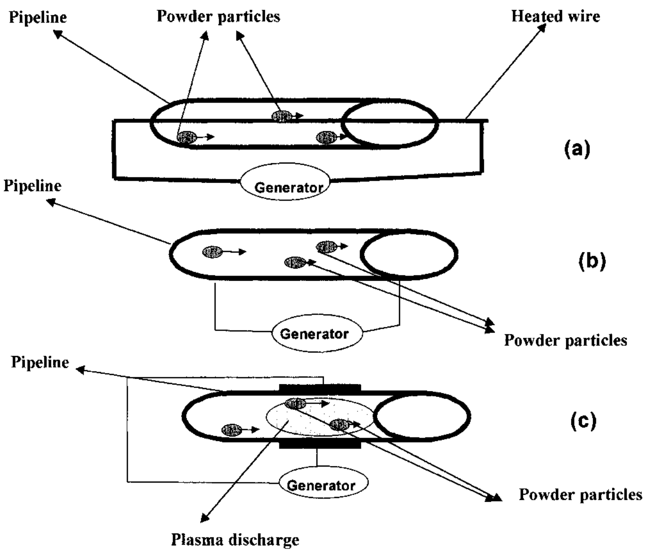



**Fig. 1** Possible configurations of powder preheating devices working with electric heating of a carrier gas: (**a**) linear, (**b**) superficial, and (**c**) volumetric

### 2.2 Plasma Spraying

The tube of the *superficial* preheating device was connected to a conventional Metco (Westbury, NY) 3MB plasma torch. The Eutectic Castolin (Lausanne, Switzerland) unit was used to feed the powder. The standard processing parameters were used (Table 1). The coatings were sprayed on a mild steel cylinder of 27 mm OD. The cylinder was sand blasted using a corundum sand of F60 grade (particle mean size: about 250 $\mu$m). The cylinder rotated at 300 rpm with the torch at a linear speed of 36 cm/s.

Four coatings were sprayed, two each, with or without powder preheating. The coating thickness was equal to about the following: (1) 150 $\mu$m, sprayed using 6 torch passes; and (2) 550 $\mu$m, sprayed using 15 torch passes. The coating microstructure was characterized using an Olympus (Tokyo, Japan) optical mi-

**Table 1 Plasma spray parameters**

| Parameter | Value |
|---|---|
| Working gas | $Ar + H_2$ |
| Stand off, mm | 65 |
| Electric power, kW | 30[2] |
| Carrier gas | Ar |
| Carrier gas flow rate, graduations | 20 |
| Powder | $Cr_2O_3$ (Amperit 740.1) |
| Powder particles size, $\mu$m | $-45 + 22.5$ |

[2] Voltage 60 V, current 500 A

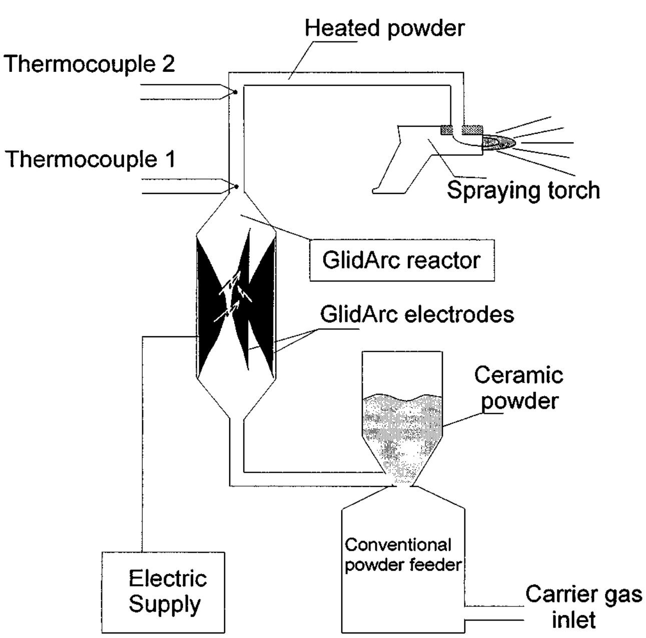



**Fig. 2** Sketch of a set up to determine the temperature of carrier gas heated by a volumetric preheating device working with a homemade Glidarc reactor

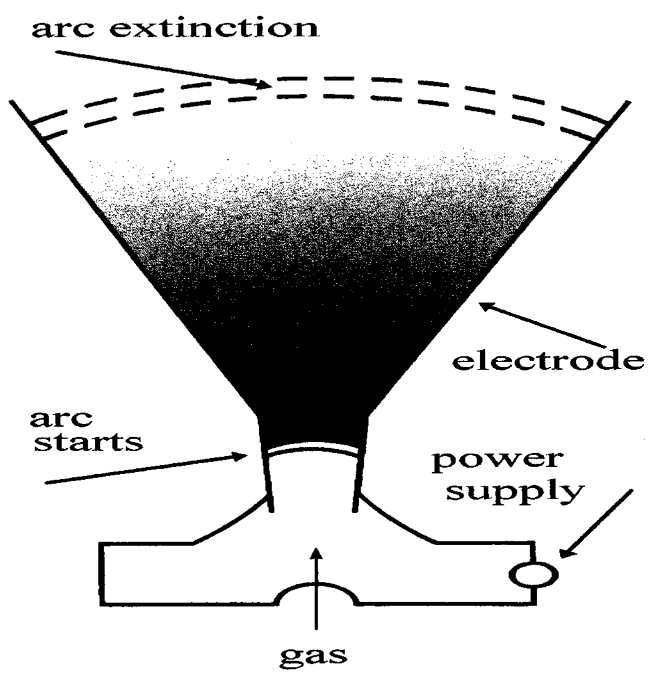



**Fig. 3** Principle of *Glidarc*

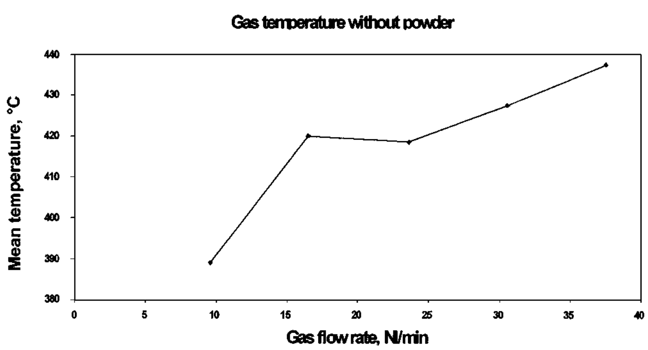
croscope type Optiphot 100S. The microscope, coupled with an image analyzer SONY (Tokyo, Japan) type UP 1200 working with a commercial software MARS version 3.010 of Buehler (Lake Bluff, IL), enabled estimation of the porosity of the deposits. Finally, the microhardness of the coatings was determined using a Shimadzu (Tokyo, Japan) type M set up with a load of 300 g.

## 3. Results and Discussion

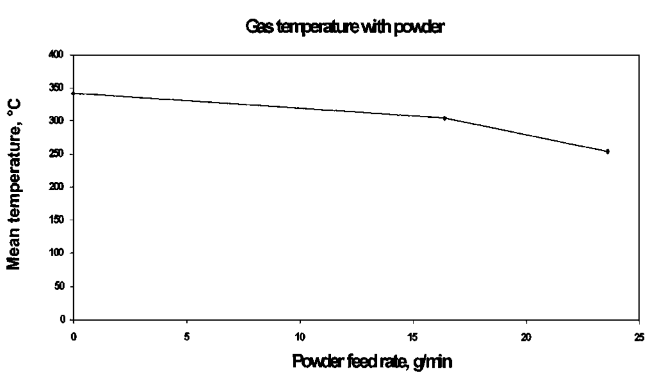
### 3.1. Carrier Gas Temperature and Velocity

The preheating device heats a carrier gas. As the gas flows in a pipeline, an increase in the temperature is accompanied by its thermal expansion and by an increase of the flow velocity. The temperature of a flowing carrier gas (air) was tested with the use of a *volumetric* preheating device. The setup presented in Fig. 2 was used. The results are shown in Fig. 4. The mean temperature of the carrier gas, *i.e.*, $(T_{in} + T_{out})/2$, in the pipeline joined to the preheating device, is depicted. This temperature depends on the carrier gas flow rate when testing without powder.

The results indicate that the mean temperature increases with the gas flow rate. This can be explained by the 1 m length of the pipeline. The carrier gas of low flow rate could easily cool down when it reached the end of the pipeline (where one of the thermocouples was located). The cooling was less efficient, with an increase of the gas flow rate corresponding also to an increase of gas velocity. Under this condition, the contact of the gas with the walls of the pipeline is shorter and it maintains a higher temperature on the end of the pipeline. On the other hand, this temperature depends also on the powder feed rate at a constant gas flow rate (being equal to 20 NL/min).




**(a)**




**(b)**

**Fig. 4.** Mean temperatures of the carrier gas (air) in the pipeline joined to the volumetric preheating device depending on the (**a**) gas flow rate and (**b**) the powder flow rate

The Glidarc reactor was powered in all the experiments with 1.3 to 1.7 kW. The carrier gas temperature measured without powder at the inlet of the alumina pipeline was about 600 °C and was independent of the gas flow rate. The temperature at the outlet ranged from 160 °C (at 9.6 Nl/min gas flow rate) to 265 °C (at 37.5 Nl/min gas flow rate). The preheating device loaded with the powder heats the carrier gas less efficiently (Fig. 4 b), and the temperature of carrier gas on the inlet of the pipeline decreases from 535 °C to 370 °C as the powder feed rate increases. The temperature at the outlet is less dependent on the powder feed rate and ranges from 150 to 130 °C.

The decrease of the temperature with the powder feed rate can be related to a "charging effect." This effect results mainly from the lower capacity of heating the carrier gas inside the device due to the powder. The presence of the powder between the electrodes of the gliding arc reactor electrodes disturbs development of the discharge. This phenomenon could be overcome by injecting powder into the pipeline joined to the reactor and not to the reactor itself. This solution is discussed later.

A simple analytical model was adopted to characterize the temperature and the velocity of the powder particles at the end of the pipeline. The simplifications of this model are as follows: (1) heat and momentum transfer between the carrier gas and the particles takes place only in the pipeline, (2) the temperature of the particle's surface is equal to the gas temperature in the pipeline, (3) the carrier gas temperature and velocity are constant in the pipeline, and (4) powder particles do not interact with the pipeline or with other particles.

The velocity $u_1$ of the carrier gas of a flow rate $q$ in the pipeline of a diameter $d_1$ is equal to

$$u_1 = \frac{4q}{\pi d_1} \qquad \text{(Eq 1)}$$

The carrier gas flow rate was corrected by taking into account its thermal expansion. The perfect gas approximation was used. The dwell time $t$ of a powder particle having diameter $d_z$ and a density $\rho_z$ in the pipeline of a length $l_1$ is equal to[8]

$$t = \sqrt{\frac{2l_1}{ku_1}} \qquad \text{(Eq 2)}$$

where $k$ is a constant, depending on a the carrier gas dynamic viscosity $\eta_g$ and on the properties of the powder particles:

$$k = \frac{18\eta_g}{\rho_z d_z^2}$$

The velocity of a powder particle $v$ at the end of the pipeline is equal to

$$v = u_1[1 - \exp(-kt)] \qquad \text{(Eq 3)}$$

The temperature at the center of a powder particle $T_c$, having initially temperature $T_0$ and a thermal diffusivity $a$ at the end of the pipeline with a gas having temperature $T_g$, is given by the following expression:[9]

$$T_c - T_0 = \frac{d_z T_g}{2\sqrt{\pi a t}} \sum_{n=0}^{\infty} \exp\left[\frac{-(2n+1)^2 d_z^2}{16at}\right] \qquad \text{(Eq 4)}$$

The numerical calculations made for a gas flow rate of $q$ = 16.5 Nl/min and a gas temperature of $T_g$ = 400 °C established a gas velocity of $u_1$ = 14.8 m/s. The dynamic viscosity of air at this temperature is about $3.18 \times 10^{-5}$ kg/(ms),[10] the density of powder $\rho_z$ = 4000 kg/m$^3$, and a mean particle diameter of $d_z$ = 95 $\mu$m made it possible to find a constant $k$ = 15.8 l/(ms) and, subsequently, the dwell time of the particle in the pipeline, $t$ = 88.5 ms. The velocity of the particle on leaving the pipeline is $v$ = 11.2 m/s, and the temperature at its center, assuming the thermal diffusivity[8] of $a = 2.1 \times 10^{-6}$ m$^2$/s, is equal to the temperature of the carrier gas $T_c$ = 400 °C.

Taking into account that in industrial practice the length of the pipeline is often greater than that of $l_1$ = 0.92 m used in this study (*e.g.,* to spray long rolls), the value of the particle temperature could indeed be as high as that of the carrier gas. A practical limitation of the maximum preheat temperature seems to be the nature of the pipeline material. It should be flexible, and, at the same time, it should preserve its properties at a temperature as high as 400 to 600 °C. An alternative design would allow preheating of the carrier gas without powder in the reactor and then the heating of the powder particles inside the pipeline.

### *3.2. Coatings Sprayed Using a Preheated $Cr_2O_3$ Powder*

The porosity and the microhardness of the chromia coatings sprayed using a superficial preheater are shown in Table 2.

The porosity appears less when the preheating device is applied to spray the coatings. The porosity of thin coatings drops from 2.5% to 0.9% as a result of powder preheating, and, for the thick coatings, this difference is even more pronounced, *i.e.,* from 4.8% to 0.6%. The microstructure of the coatings sprayed with the preheated powder exhibits good contacts between grains (Fig. 5a).

The favorable aspects of the microstructure formed from preheated powder become clearer on comparison to coatings sprayed with a powder that was not preheated. The contact between grains is much easier to distinguish. These contacts seem to depend on the temperature of the particles impinging onto the substrate or previously deposited coating such that better contacts are achieved if the particles have higher temperature. Improvements in the grain contact usually results in better thermophysical (thermal diffusivity) and mechanical (elastic modulus) properties (see, among many others, Ref 1), and such studies will be the objective of future work.

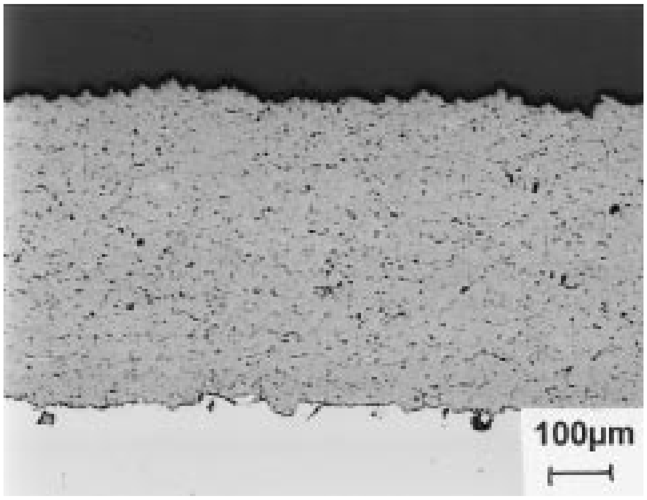
## 4. Conclusions

Throughout this study, two types of preheating devices were used to heat the powder particles: (1) volumetric with a gliding arc reactor and (2) superficial with an electrically heated tube. The volumetric device enabled heating of the powder carrier gas up to more that 600 °C with less than 2 kW of electric power. A simple analytical model made it possible to estimate the temperature of the powder particles. This temperature, calculated in the center of an alumina particle of 95 $\mu$m diameter, reached the temperature of a carrier gas at the end of the pipeline of a length of about 1 m.

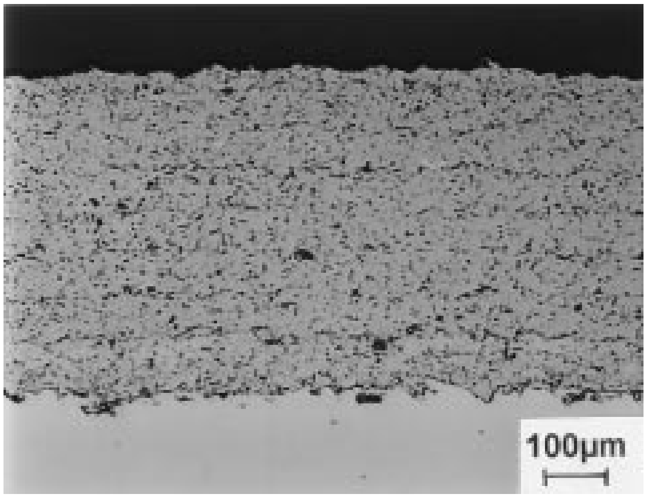
Another preheater, based on the superficial design, was applied to spray chromia coatings using a powder of $-45 + 22.5$ $\mu$m particle size. The porosity of the deposits sprayed with the preheater was lower than the porosity of those deposits without the

**Table 2 Properties of coatings plasma sprayed using preheated $Cr_2O_3$ powder**

| Number | Thickness, $\mu$m | Preheater, yes/no | Porosity, % | Microhardness, HV 0.3 |
|---|---|---|---|---|
| 1 | 150 | No | 2.5 | . . . |
| 2 | 150 | Yes | 0.9 | 1390 (Fig. 5a) |
| 3 | 550 | No | 4.8 | (Fig. 5b) |
| 4 | 550 | Yes | 0.6 | 1200 |




(a)




(b)

**Fig. 5** Microstructure of a chromium oxide coating (**a**) sprayed using a preheated powder and (**b**) without preheating

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preheater (Table 2). The preheated powder coatings appear to exhibit enhanced contact between grains.

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