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UNDERSTANDING PLASMA SPRAYING PROCESS AND CHARACTERISTICS OF DC-ARC PLASMA GUN (PJ-100)

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Abstract

The thermal spray processes are a group of coating processes used to apply metallic or non-metallic coatings. In these processes energy sources are used to heat the coating material (in the form of powder, wire, or rod form) to a molten or semi-molten state and accelerated towards a prepared surface by either carrier gases or atomization jets. In plasma spraying process, the spraying material is generally in the form of powder and requires a carrier gas to feed the powder into the plasma jet, which is passing between the hot cathode and the cylindrical nozzle-shaped anode. The design of DC plasma gun (PJ - 100) is designed and manufactured in Serbia. Plasma spaying process, the powder injection with the heat, momentum and mass transfers between particles and plasma jet, and the latest developments related to the production of DC plasma gun are described in this article.

Key words: plasma, plasma spaying process, DC-arc plasma gun, PJ-100.

Introduction

One of the first inventions of the Thermal spray process was patented in 1882 by M. U. Schoop (Zurich, Switzerland), when he tried to modify oxy – acetylene welding torch. Later torches were modified to accept powdered materials [1]. Another patent was in 1908, also developed by Schoop, electric arc spray, which enabled spraying different kinds of metals. Many improvements in these processes have been made since then, but the basic operating principles remain unchanged. Equipment for thermal spray processes has started to develop after the Second World War, especially in the period between the 1960 and 1990 when its wide application in various industries began [1, 2].

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Thermal spray processes are mostly used to obtain metallic and non-metallic coatings, and include four major groups of processes: spray combustion processes, electric arc spray process, cold spray and the plasma spray process. Obtained energy is used to heat the material to the desired molten or semi-molten state and to accelerate the particles, with the purpose to form coatings. The type of thermal spray process which will be selected and used depends on the kind of processed material, the required characteristics of the coating, cost-effectiveness of the process and the size, portability and flexibility of the apparatus [2]. A major advantage of thermal spray processes is the extremely wide variety of materials that can be used to produce coatings. Almost any metal, composite, ceramic or plastic material can be thermal sprayed. The spray rates range from 1.4 – 27 kg/hr depending on the material and the spray system. Typical rates for material application are 0.23 – 0.91 kg/hr of material per m^2 per 0.0254 mm thickness.

The first idea of a plasma spray process was patented in 1909 in Germany, and the first structural plasma installation appeared in the 1960's, as the product of two American companies Plasmadyne and Union Carbide [2]. In the middle of the 70's, in Switzerland, the company Plasma-Technik AG was founded, and about 20 years later this company merged with U.S. company Metco and formed new company named Sulzer Metco, which is today one of the leading companies in the production of equipment for plasma installation. DC plasma jet has began to develop intensively together with the development of cosmic technology, Actually, it has been shown that this technique is the only technically feasible method of implementation and maintenance of a continuous temperature in order of 20 000 K, in some cases up to 50 000K. In the past ten years the focus of research has been directed to one important type of application of this technology, the application of plasma in a plasma spray process.

The most of commercial plasma installations and the concept of plasma guns are based on the formation of arc plasma. These types of guns form plasma inside the walls of the limited space of cylindrical nozzle in which the cathode is placed; the cylindrical nozzle is in the same time the anode [2]. This kind of construction is called plasma torch, and it works when the carrier gas (argon and nitrogen as the primary, hydrogen and helium gases as secondary gases) introduces between the cathode and the anode [2, 3]. After establishment of conditions for initial plasma there will be formed "arc path" between the cathode and the anode, which performs electric conductance used for heating gas [4]. Plasma formed by the passage of current (generally DC) is ejected from the nozzle in the form of the plasma jet [2]. Main Temperatures of obtained plasma jets are in range of 5000-8000 K for the diatomic gases, and in 10000-20000 K for monatomic gases (Ar, He). [3]

Construction of plasma torch which has the cathode and anode nozzle placed at a short distance to each other, around 1 mm, is called "conventional" solution [2]. Today, in the commercial market two plasma constructions running in a gas stabilized arc may be found. One is the so-called "high power plasma gun", which appeared in the 90's, while the other construction is called "triplex" because it uses three cathodes. [2]

Understanding the interaction between plasma and particles is essential in controlling the plasma spray process, its reliability and reproducibility. It is a very complex problem that includes the size (5 - 140 μm), speed (50 - 500 m/s) and temperatures (1200 - 4500 K) of the particles [3].

Plasma

The term "plasma" was first used by Langmuir in the 1928, when he tried to describe the gas condition in the positive column of a gas discharge at low pressure [3]. Plasma is a partly or fully ionized gas in the condition of quasi - neutrality [3]. If the main kinetic energy of the particles is associated to aggregate state, then the state of the plasma can reasonably be termed as the "fourth" state of aggregation. The average value of the particle's kinetic energy ε (eV) changes approximately by order of magnitude when crossing from one to another aggregate state, starting with the solid state of aggregation, through the liquid, gas and plasma aggregate state, to the state of high-temperature plasma characterized by plasma temperatures in order of 10^6 K [2, 3]. These changes are shown in Table 1.

Table 1. The order of magnitude of the main value of kinetic energy of particle, ε (eV), and the temperature T (K) of aggregate state [2].

Aggregate state	ε (eV)	T (K)
Solid	0.01	100
Liquid	0.10	1 000
Gas	1.00	10 000
Plasma	10.0	100 000
High-temperature plasma	100	1 000 000

Mean kinetic energy of the particle ε (eV) and temperature T (K) are directly related to the molecular-kinetic theory with equation:

$$\varepsilon = \frac{3}{2} kT \tag{1}$$

where *k* - Boltzmann constant [3].

According to the usual convention in the kinetic theory of energy of particles measured in electron-volts (eV), where 1 eV is the energy of the electron which is accelerated in an electric field with potential difference of 1 V, and using equation (1), it can be obtained a very useful equivalence for plasma physics:

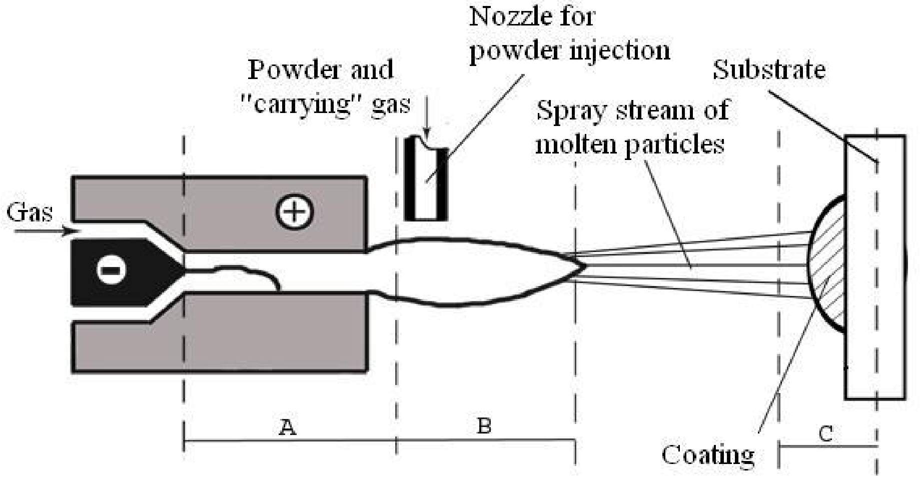
$$1 \text{ eV} = 11\,600 \text{ K} \tag{2}$$

State of ionized gas (plasma) is possible when the mean kinetic energy of plasma particles is of the order of magnitude of the ionization energy, W_j. [3]

Plasma spraying process

The plasma spray process is shown on the Figure 1. When the plasma jet is formed, a powder through nozzles carried by the "carrier" gas is injected into it [5]. Accelerated and melted powder particles leave the plasma jet in the form of molten particle stream. The molten particles bombard the substrate surface where they cool forming a coating. Also particles may be cooled and collected in the form of spheres [4]. Every molten particle has a high thrust which leads to high bond strength of the coat [6]. The temperature of the substrate remains below 100 ˚C. Thickness of the coat varies between 0.3 and 1 mm, but it may be also up to 5 mm [2].

The basic function of the plasma jet is to heat the powder particles to the melting point and to accelerate them to the highest possible speed. The whole spraying process of the formation of a coating can be divided into three sub processes A, B, C (Figure 1) [6]



A) The formation of the plasma jet and its interaction with the environment
B) The entry powder into the plasma and powder interaction with plasma
C) The process of forming a coating.

Figure 1. Schematic diagram of plasma spray process for forming a coating [2].

The plasma spray process is mostly used in normal atmospheric conditions (air or atmospheric plasma spray - APS). It also has the ability to operate in an inert atmosphere using method of Low Preasure Plasma Spraying (LPPS) or Vacuum Plasma Spraying (VPS). This enables deposition of materials sensitive to oxidation (Ti, Mg). [1]

Interaction of plasma and powder

The material usually enters into the plasma jet in the form of powder, but also it can be used the form of wire. If the grain size of powder is very small, the particles are injected in the form of suspension (a mixture of powder and liquid), because the entry of such small particles into the plasma is practically impossible. At this stage the transport phenomena of the momentum transfer and heat transfer are occurring, and for these processes importance of the following parameters is crucial [2]:

1. Construction of powder feeder – mass input is in the range from a couple of pounds per hour up to several tens of kilograms per hour, the feeder has to

provide a uniform, reproductive input for powders with very different characteristics (which provides the "fluidity" of powders). The feeder must be able to be quickly and easily remounted for cleaning and powder changing.

2. Powder injector – it must have a good permeability for the powder and as small as possible exit hole because its it needs to provide the small angle of injection (resulting from the refusal the powder particles of the nozzle walls). Injector nozzle diameters are in the range from 1.2 to 2 mm.
3. Environment for spraying – when plasma exits nozzle the heat loss occurs due to radiation and redistribution of heat from the plasma to entered material substrate. Cooling of the plasma leads to a reduction of plasma viscosity, but increasing the turbulence (also the Reynolds number increases). There may be an interference of ambient gas and plasma. In the case of APS process, a significant amount of air that can lead to oxidation of particles is injected into the plasma. If oxidation has to be reduced to a minimum the process can be carried out in an inert atmosphere or in a vacuum (VPS). By switching to VPS mode plasmatron parameters are changed (plasma temperature decreases, the ratio of voltage and current changes, the speed of plasma increases and plasma is significantly elongated geometrically), therefore plasmatron power used in the VPS process must be much higher than in the APS process.
   a) Powder characteristics –several factors that may were identified [7]. These factors that may have a strong impact on properties of both particles and coatings are as follows: specific characteristics of the powder considering its technological process by which the powder is obtained, powder fluidity, bulk density of powder, particle size and shape (spherical particles improve the fluidity, "polyhedral" leads to unequal heating of the particles), range of particle size is aiming for a larger interval in which are the particles of a given powder (for example, within the narrow interval of 22-45 μm, where the difference in powder size is only twice, the difference in masses can be up to 8 times) [8]. It is very important to establish a compromise, because the large narrowing of particle size interval is neither technologically nor economically beneficial.

Momentum transfer

A particle with mass (*m*) carried by carrier gas is entering the plasma from the injector nozzle at an angle of 90^0. Schematic diagram of the process of particle injection into the plasma is shown on Figure 2. Thus, the variety trajectories of particles within the plasma depends on material properties of powder particles, particle sizes and different flow rates of the carrier gas (v_o) which determines the size of injector nozzles [2]. Possible marginal cases are rejection of particles from the plasma flow (case A, Figure 2a), or breaking through the jet (case C, Figure 2a). The ideal case would be the injecting of the particles to occupy "central" trajectory, (case B, Figure 2a) with a dispersion angle α. Trajectories A and C are unfavorable for plasma spraying because they lead to losing a part of the powder, which reduces the efficiency of the process. Detailed view of exit of powder from the nozzle is shown in Figure 2b. Initial velocity of the particle is defined by the flow rate of the carrier gas and nozzle diameter (*d*), suggesting that it is defined by ~~its~~ impulse (mv_o). [2]

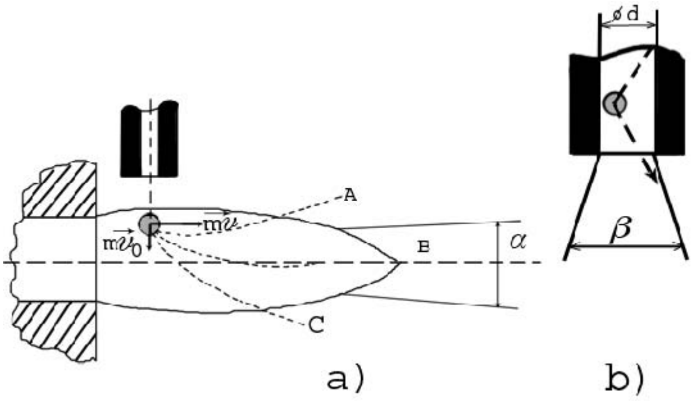


Figure 2. The process of particle injection into the plasma (a), and exit of powder from the nozzle (b) [2].

When the particle enters the plasma, it is influenced by several forces that are included in the most general equation of movement called the "BBO equation" (according to authors Basset, Boussinesq and Oseen),

$$m\frac{dv}{dt} = \Sigma F_i \tag{3}$$

where m – mass of particle [2].

Forces that are included in the BBO equation are: 1. viscous (friction) force: 2. force due to the acceleration of fluid flow, the consequence of plasma impulse and buoyancy; 3. “added” mass – describes the acceleration of the fluid around the particle, because fluid tends to slow down the particle; 4. effect of the "history" of the particles movement; and 5. the force of gravity. [2]

Increased particle diameter reduces the proportion of viscous frictional force, but it is still the dominant force, since the acceleration of the fluid affects about 5% of the particle diameter of 100 μm [9]. However, the decrease in the plasma temperature, occurring with cooling of the jet on its way, decreases the viscosity and increases the density of the jet [8]. Thus, for the plasma temperature of 3000 K, percent of power "fluid acceleration" will reach about 40% of the "viscous force" for the particle size of 100 μm. Hence, the predominant force, influencing the particle feeding into the plasma flow, is viscous friction force and it is generally considered responsible for particle acceleration. The shape of trajectories of the particles in plasma, as well as the total time of particles in the plasma zone, depend on different parameters $\rho\frac{d_p^{\,2}}{\mu}$, which indicates a complex interaction of particles; where (density – ρ and particle diameter – d_p) with characteristics of the plasma (dynamic viscosity – μ). Since this expression has the dimension of time, it is called a "reference time" [10].

Heat transfer

Equation for the energy balance (4) shows the temperature of the particles, which could heat powder particles injected into the plasma [2, 3].

$$mCp\frac{dT_c}{d\tau} = h_t A(T_{pl} - T_c) - A\sigma_{SB}(T_c - T_\alpha)^4 \tag{4}$$

where: Cp – heat capacity of the materials particles: T_c – temperature of particles; h_t – the total heat transfer coefficient (W/m^2 K); T_p–T_c – temperature difference of plasma and particles; A – particle surface; σ_{SB} – Stefan–Boltzmann constant; ε_p – emissivity of particle surface; T_a – room temperature, it can be disregarded because of $T_c >> T_a$.

This equation implies that the total power delivered to particle of mass (*m)*, the left side of equation (4), is equal to the power that is transferred from plasma to particle (first member on the right side of the equation), and simultaneously decreased by extracted radiation of particles [2]. Heat transfer from the plasma to the particle is given through the total heat transfer coefficient (h_t) without taking into a consideration the dominant mechanism of heat transfer (convection and conduction) [11].

Based on the heat balance equation (4), it is possible to estimate which part of the loaded weight of powder (*dGp/G*) at given moment was brought to the melting stage (equation 5), neglecting the emission of heated particles [2].

$$\frac{dGp}{Gp} = \frac{Q_t}{mL_t} \tag{5}$$

where: Q_t – the total thermal flux transferred to the particle; mL_t – energy needed for completely melting of loaded powder mass (m); L_t – latent melting heat of material (kJ/kg).

The total heat flux transferred to the particle depends on the particle residence time in the plasma (t_s)**:**

$$Q_t = \int_0^{t_s} h_f A(Tp - Tc)dt \tag{6}$$

Application of this equation is fundamental because it introduces the crucial parameters of the process of heat transfer, such as the total heat transfer coefficient (h_t), which indicates the nature of the plasma enviroment and residence time (t_s) of particles in the plasma zone, which is of the essential importance core for processes in the sistem plasma-particles. Also, it is very difficult to calculate the heat flux, as it requires estimation of these two parameters [12].

Comparison performances of arc plasma guns

Two best known manufacturers of the spraying plasma jet installation are Sulzer-METCO and Praxair's TAFA. The first and only Serbian plasma jet installation is PJ-100 [13]. The PJ-100 plasma torch (patented) was developed and manufactured by Plasma Jet Co (Serbian company). It was developed to meet the need for a faster, lengthier and temperature homogeneous plasma jet [13]. In the case of PJ-100 gun is physically totally defined in contrast to Sulzer-METCO and Praxair's TAFA guns, and the arc length and applied solution of PJ-100 gun provides a co-linear gas flow with the arc path [14]. Performances of these DC plasma guns were shown in Table 2. DC arc plasma guns, designed by Sulzer-METCO and Praxair's TAFA, have hyperbolic Voltage/Amperage working regime, while PJ-100 has simple Ohmic working regime.

Table 2. Overview of working parameters of DC plasma guns [14].

DC-arc plasma gun designs	Working parameters				
	Gas flow rate, l/min		Voltage, V	Amperage, A	Power, kW
Sulzer-METCO	Argon	54	60 - 70	500	80
	Hydrogen	7.5			
PJ-100	Argon	80	180 – 185	460 – 500	85 – 100
	Hydrogen	30 – 40			
Praxair's TAFA	Nitrogen	236 – 330	330 - 440	450 – 500	165 – 220
	Hydrogen	94 – 151			
PJ-100	Nitrogen	55 – 65	190 – 210	450 – 600	85 – 120
	Hydrogen	0 – 5			

The final result of the originally designed PJ-100 gun is that the much longer plasma plume exits the anode opening, twice longer than in conventional SulzerMetco design, mainly as a result of the higher exiting plasma speed (Figure 3) [14, 15].

The comparison of plasma plumes exiting the cylindrical (d = 8 mm) and conical nozzles (7 mm/6) shows that the plasma exiting the cylindrical nozzle has a more homogeneous radial temperature distribution, with a fully laminar flow in the first half of its length. [15,16]

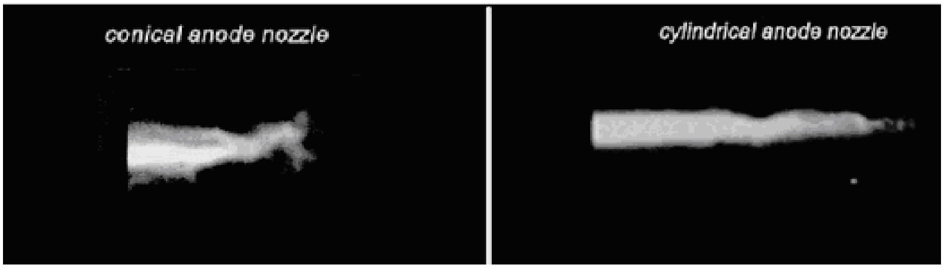


Figure 3. Shape and texture of the plasma plume exiting the conical (SulzerMetco) and cylindrical (PJ-100) anode nozzles. [15]

The plasma plume exiting the conical nozzle has a notable radial distribution of brightness, suggesting a significant radial distribution of the temperature and velocity. The cylindrical nozzle generated a faster plasma (v ≈1800ms−1) when compared with the conical nozzle (v ≈1450ms−1). The same trend was obtained with a measured effective exhaust thrust velocity, giving ve ≈ 1600ms−1 for the cylindrical and ve ≈ 1100ms−1 for the conical nozzles [15].

Conclusions

The Plasma Spray Process is basically the spraying of the molten or heat softened material onto a surface to provide a coating. Until now, it was determined that the greatest advantage of thermal spray process is the extremely wide variety of materials that are suitable for the formation of coatings (any material that melts without changing its characteristics can be used). The next advantage is that these materials with a high melting point can easily form a coating without transferring large amount of heat and without damaging the characteristics of the substrate. In the case if restoration of a damaged or a used coating is needed, it can be easily done without changing the characteristics and dimensions of the already formed coating. The disadvantage of the thermal spray processes is a size limit of the cavities, because the coating can be applied only on cavities in which guns or torches can enter.

System plasma – particles is very complex, and the great attention must be given to transport phenomena. Momentum and heat transfer are generally the function of two important parameters, plasma gas composition and residence time of particles in the plasma.

Nowadays, plasma spray technology has a widespread application. For example, in industrial overhauls applying adequate coating for surface protection or reparation of a machine part significantly enhances the functionality and increases the service life. For that purpose, coatings resistant to wear, abrasion, corrosion, thermal barrier, etc. adequate coatings have been developed and applied. Also, plasma spray processes offer the possibility of synthesis and modification of powders (spheroidization of particles with sharp edges, densification of porous particles, and the formation of nanopowders).

Top world producers of the spraying plasma jet installation are Sulzer-METCO and Praxair’s TAFA. Also, there is a new design of DC-arc plasma gun, the PJ-100 plasma torch, which was developed and manufactured by Plasma Jet Co (Serbian company). Compared with Sulzer-METCO and Praxair’s TAFA guns, the PJ-100 exhibits better performances: faster, lengthier and temperature homogeneous plasma jet.

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