Study of the in-Flight Characteristics of Particles for Different Configurations of the Debye™ - Larmor™ Cascade Plasma Torches

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Abstract

The cascade plasma torches should gradually replace the standard F4 type torches consisting of two electrodes without neutrodes. For industry, the advantages are a better lifespan of these electrodes but also a less expensive use of the process in terms of the type of gas to be used and of the power to be provided to the plasma, as well as a possible flowrate of injected powder increased. However, the configuration of a cascade torch is still poorly studied and notably the influence of the length of the body of the anode segmented by neutrodes. This work consists in studying the effect of the anode-cathode distance on the voltage fluctuations. The jet stability is clearly demonstrated with the cascaded torch. Indeed, the neutrodes can provide a longer and more stable jet compared to F4 plasma jet. That means that the length of the arc is much higher with the cascaded torch. The in-flight characteristics of alumina particles for different cascading lengths and operating parameters are studied. Particle velocities and temperatures are measured using diagnostic tools. Some alumina coatings are manufactured in order to address a correlation between the different configurations and the microstructure of the coating obtained. Good performances are obtained with microhardness of 1075HV0.3 for a porosity of 4.6 % but with a pure Ar plasma and a 350 A low amperage.

Introduction

Thermal spraying technology allows the production of coatings on technical surfaces or parts. Metals, ceramics, polymers or other alloys and composites, a very versatile range of materials can be applied to give the part a functional property that the base material does not possess [1]. This may be wear or corrosion protection, thermal or electrical insulation, bio-compatibility or virucide action. Thus, most industrial sectors such as transport, energy, biomedical, electronics, etc. are concerned. Compared to other processes (PVD, CVD, wet process, etc.), thermal spraying allows high deposition rates and adapts to the shape/size of the parts to be treated.

Any thermal spraying process consists of melting (thermal energy), accelerating (kinetic energy) and spraying (mechanical energy) a material in powder form at high speed onto a part to be coated, called substrate [2]. In the heat source, droplets of the material are formed. On impact, the particles spread out in the form of lamellae and solidify at very high quenching speeds (>10^6 $K.s^{-1}$). They form a deposit by successive stacking of these lamellae.

Among the various thermal spraying processes (flame, plasma or electric arc), plasma technology is one of the most widely used in industry. The range of materials that can be sprayed is very wide, including ceramics or metals with high melting points. It is a highly flexible technique efficient to adapt to pre-existing industrial environments. With a small footprint, the process generates a plasma jet of a few centimeter, which is easily manipulated on a robotic arm to treat large volume parts. In addition, the process can be considered relatively moderate in terms of cost compared to other techniques and environmentally friendly.

The principle of this technology is to create a high-energy plasma capable of melting the material and spraying it onto the surface to be modified. The plasma is created in a chamber inside the torch formed by a cathode and a concentric anode into which a gas (argon, hydrogen, etc.) is injected. The cold gas that passes through the chamber is ionized by the electric arc and forms the plasma. The hottest regions of the plasma at the exit of the anode can reach 15 000 K, and a speed of about 2000 m/s. A plasma jet consists of a main arc column, attached to the end of the cathode tip which is the source of the electrons, and a connecting column which terminates at the arc root on the inner surface of the anode.

Thus, regardless of the plasma spraying process, the basic tool is the plasma torch that produces the plasma jet. The geometrical design of a conventional plasma torch therefore consists of a cathode and an anode. The cathode is usually a cone-shaped tungsten tip and is associated with a hollow tubular copper anode concentric to it. For many years, this two-electrodes plasma torch geometry (i. e. type PTF4 from Oerlikon Metco) has been preferred in industry. Nevertheless, it is characterized by random and often unstable phenomena [3] [4]. The causes of these instabilities are numerous: instability of the electric arc in the nozzle [5] depending, in particular, on the wear of the anode [6] and the plasma forming gas mixture used, instability in the powder distribution, drifts of the electric current, random deviations of the particle trajectories due to a powder accumulation on the injector tip, etc. [7] [8].

When we focus on one of the most problematic instabilities of this technique, we notice that the root of the arc moves permanently onto the surface of the anode in a back and forth movement. A phase of elongation of the arc downstream of the anode is interrupted by a breakdown of the arc which re-bursts upstream or downstream of the previous foot of the arc. Then, the arc attachment is submitted to random displacement at the anode wall. It is clearly proved today that arc flow electrode interactions create special problems in the development of arc plasma devices. These variations in arc length induce a very significant variation in the operating voltage of the torch reducing the quality of coatings [9]. The use of diatomic secondary gases such as hydrogen increases the intensity of these voltage fluctuations [10], which inevitably results in variations in the heat treatment of the particles, ultimately influencing the quality of the coating.

The instability of the jet can be observed by different means [11]-[14]:
- deviation and dispersion of the trajectories of the particles due to the variation of the quantity of movement of the jet;
- widening of the local speed and temperature distributions of the particles. Indeed, the continuous variation of the enthalpy supplied to the gas results in fluctuations in the dimensions of the jet and its characteristics (velocity, temperature, composition);
- high speed camera.

Fluctuations in the arc root are caused by fluctuations in the arc voltage across the electrodes. Therefore, in order to precisely control the variations of this arc voltage, it would be necessary to try to strongly reduce or even eliminate these fluctuations, but this is not possible since it is inherent to the operation of the plasma torch. It is therefore necessary to find another solution to optimize this spray process.

Therefore, new generations of plasma torches have appeared in recent years [15]. Developments have focused on increasing the arc voltage as high as possible to allow high power levels while keeping the arc current as low as possible. These new so-called cascade torches are characterized by a reduced arc displacement due to the presence of neutrodes between the cathode and the anode. These torches use a cascade anode made up of a stacking of copper rings isolated from each other (the "neutrodes") and defined by a ring on which the arc is fixed. This design also stabilizes the arc as the movement of the arc is limited to the anode ring [16][17]. Another way explored is the possibility of controlling the movement of the arc in particular through the application of an external magnetic field to the torch [18]-[20].

The long length of the arc makes it possible to obtain a higher and above all more stable voltage. In addition, this new geometry allows the plasma to exist closer to the nozzle outlet (anode) which improves the efficiency of the torch (less heat loss during cooling) and increases the amount of energy available to treat the particles. The reproducibility of the coatings is then improved [21]. Lower power and secondary gas flow rates are required to melt materials and produce coatings [22], [23]. These new arc properties and plasma torch configuration even open the way to the use of materials that are unusual to the plasma process such as carbides [24]. These decompose due to the high temperature of the plasma with conventional F4MB torches and HVOF/HVAF processes are then preferred. This opens the door to a possible increase in the range of materials for the plasma. However, the characterization of these cascade torches is still very empirical, especially regarding neutrode configurations.

This study presents the preliminary results of the study of a cascade plasma torch that can be mounted in different configurations in terms of number of stacks/neutrodes. The following results concern the effect of plasma parameters, such as total flow gas rate, current intensity on the arc voltage evolution and particles characteristics during their flight in the jet. Preliminary alumina coatings are manufactured and characterized in terms of microstructure, phase composition and hardness measurements.

Materials and Processes

Feedstock
The powder used for investigations is a commercially available Al_2O_3 Amdry 6062 (Oerlikon Metco, Switzerland) with particle sizes distribution between 22 to 45 µm.

Spray Process and Related Operating Parameters
The design of the classical F4MB plasma torch (Oerlikon Metco, Switzerland) is employed with a 6 mm diameter anode and the corresponding results is considered as reference values.

Concerning the cascaded plasma torch, the development and analysis of different cascade torch configurations is acted by the development of a 3-stacks cascaded torch called Debye 1000™ and the development of up level stacks (6, 9, 12, 15 and 21) cascaded plasma torches called Larmor™. These plasma torches are manufactured and commercialized by Gulhfi AG (Switzerland) which is specialized in the design of advanced plasma processes (see Fig. 1).

The relationship between the number of stacks and the distance from the cathode to the anode is given in Table 1. Depending on the number and size of neutrodes that directly influences the length of the electric arc, it can be supposed that the voltage of the torch, the intensity and frequency of its fluctuations would be modified, thus the behavior of the plasma gases flowing between the electrodes leading to change in flight particles characteristics and coating properties finally.

Figure 1: Debye™ and Larmor™ cascade plasma torches.

The variations of operating parameters such as current intensity, total gas flowrate and H_2 flowrate are summarized in Table 2 for the cascaded torches and in Table 3 for conventional F4MB plasma torch. Due to the sanitary situation, the tests for the coatings manufacturing were obtained before the diagnosis of the in-flight particles taking into account the availability of the torch. That is why the parameters used are different. Coating are sprayed on stainless steel plates 60*20 mm with 2 mm thickness. Prior to the spray, they are grit-blasted with F36 corundum with a 2.5 bar pressure to obtain a surface topology of 3.5-4 µm (measured by a 3D profilometer (Altisurf 500, France).

Characterization Techniques

In order to study the different plasma torch configurations, different diagnostic means (digital oscilloscope, optical device) are used to observe the incidence of the number of neutrodes on the temporal voltage variations and in-flight characteristics in terms of velocity and surface temperature. Various torch operating parameters are tested in order to understand their influence on the change in voltage value and its fluctuation, and in particle properties. The data are collected with a 50 MHz Rigol DS1052E oscilloscope (Rigol, Germany). Each signal contains 512 points with a sampling rate of 1 MHz and can be real time processed. For each set of operating conditions, the same data are several times collected in order to obtain an average and a standard deviation of the characteristics of the plasma. This study is founded on the statistical analysis of time resolved recording the arc voltage for various working conditions of the multi-stack of cascade plasma torch. Excel software can conveniently perform fast Fourier Transforms in order to achieve the frequency behavior of the arc.

As this work focuses on the influences of process parameters on thermal and kinetic energy of powder in flight characteristics, the diagnostic system is used for measuring in-flight particle characteristics is the DPV 2000 (Tecnar, Canada). This system, already described in detail in other works [14] [25], is based on the detection of the thermal radiation emitted by a particle traveling through a measurement volume precisely localized into the plasma jet. Then, the particles detected are analyzed in terms of diameter, velocity and temperature. The measurements are performed at the centerline in the plume at the constant standoff distance of 110 mm from the nozzle exit to the substrate considering such distance as optimal distance for the coating manufacture. A statistical treatment allows determining an average value and a standard deviation deduced from all the particles measured. Velocity, temperature and diameter of the particles are determined in function of plasma properties depending on the cascade torch used.

Table 1: Cascaded plasma torch configurations.

Reference	Debye	Larmor			
stacks	3	6	9	12	15
cathode-anode distance [mm]	16.2	27.6	39.1	50.4	61.8

The microstructural analyses of the as-sprayed coatings are performed on the cross sections and the top surfaces using the field emission scanning electron microscopy (JSM-7800F, JEOL, Japan). Specimens for cross-section analysis are sectioned using a diamond cutting blade and mounted in resin. Samples are subsequently grinded with emery papers, polished with diamond paste, and cleaned with water and ethanol in an ultra-sonic bath. All observed samples are sputtered with a thin gold layer to allow the ceramic layers to be observed clearly. Chemical analyses are studied by EDS using a Brucker SDD X-Flash 6130 detector. An X-ray diffractometer (XRD, D8 Advance, Brucker AXS, Germany) with a CoK_{α} anti-cathode (λ_{Co} = 0.179 nm) is employed to determine the chemical composition of the coatings (scanning step: 0.02°). Microhardness measurements are carried out on the polished cross-sections of coatings using a Vickers hardness indenter (Leitz, RZD-DO, Germany) with a load of 300 g and a holding time of 15 s. Ten indentation measurements are taken randomly within different regions of each sample. The porosities are calculated by employing the software ImageJ. For each sample, five SEM images at a magnification of 200X are collected randomly across the entire cross-section in regions not close to the edges.

Table 3: Plasma spray operating parameters with F4 torch.

Designation	F4
powder [µm]	22-45
Ar/H_2 flow rate [SLPM]	40/12
arc current intensity [A]	650
arc voltage [V]	73
electrical power [kW]	47
net power [kW]	27
spraying distance [mm]	110

Table 2: Plasma spray operating parameters with cascaded plasma torch.

Designation	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
stacks	3					9		15
Ar/H_2 flow rate [SLPM]	60/0	50/1	60/3	40/3	35/3	40/0	40/2	40/0
arc current intensity [A]	500					400		350
arc voltage [V]	62	61	69	64	64	99	103	116
code for Figures	Stacks - Ar/H_2 – Arc current intensity ex for C1: 3-60/0-500							
electrical power [kW]	30	31	35	32	32	37	41	41
net power [kW]	17	18	21	18	16	21	23	22
spraying distance [mm]	110							

Results and Discussion

Voltage Fluctuations

Erosion is mainly due to the arc root attachment in the nozzle, which determines the instantaneous arc length and voltage. Thus, the study of the voltage variations can lead to a better understanding of the conditions which prevail at the arc root and which are responsible, on one hand for electrode erosion and on the other hand for the stability of the generated plasma flow. In the case of the cascaded torch, the stacking of neutrodes (stack of insulated electrical floating copper plates) forces the arc to hang at a longer distance and the arc root is located close to the terminal anode. The long arc and the small area of the anode limit the oscillations of the arc and increase the stability of the arc [26]. This condition helps to prevent overheating of the anode and prevents voltage drop occurring at higher input current levels than with the conventional torch.

Figure 2 gives the time resolved arc voltage fluctuations of the collected signals, which is obtained with two operating parameters: a current of 400 A and 50/2 L/min Ar/H_2 flowrates and a current of 450 A and 50 L/min Ar flowrates from the cascaded torch composed on 3, 6, 9, 12 or 15 stack of neutrodes (parameters that are different from those used for the realization of coatings). The mean arc voltages and max fluctuation value with various anodes are given in Table 4. These arc voltage fluctuations are measured as the indication for arc behavior inside the torch nozzle. It is clear shown that the plasma jet is affected by the anode geometry. For identical operating parameters, a fluctuation trend appears. For configurations between 3 and 9 stacks the fluctuation follows a stable evolution on more or less 2.5-3 V. The larger fluctuations obtained with the 3-stacks Debye torch are due to a slightly different electrode configuration compared to Larmor 6 to 15 stacks. Starting from a 12-stacks configuration, a convolution of two signals appears. The first one is identical to the previous one, i.e. an oscillation of ± 2.5-3 V. The second appears as a ripple of ± 11 V. This is comparable to the sum of two signals.

Table 4: Mean value of arc voltage vs the neutrodes of the cascaded torch for an Ar/H_2 (50/2) – 400 A plasma and for F4MB Ar/H_2 (40/12) – 650 A operating parameter.

Number of stacks	Arc voltage mean value (DC) (V)	Arc voltage fluctuation AC (V)	AC/DC (V)
3	71	±5	14.1%
6	89	±2.5	5.6%
9	106	±3	5.7%
12	124	±7	11.3%
15	139	±11	15.8%
F4MB	72	±35	97.2%

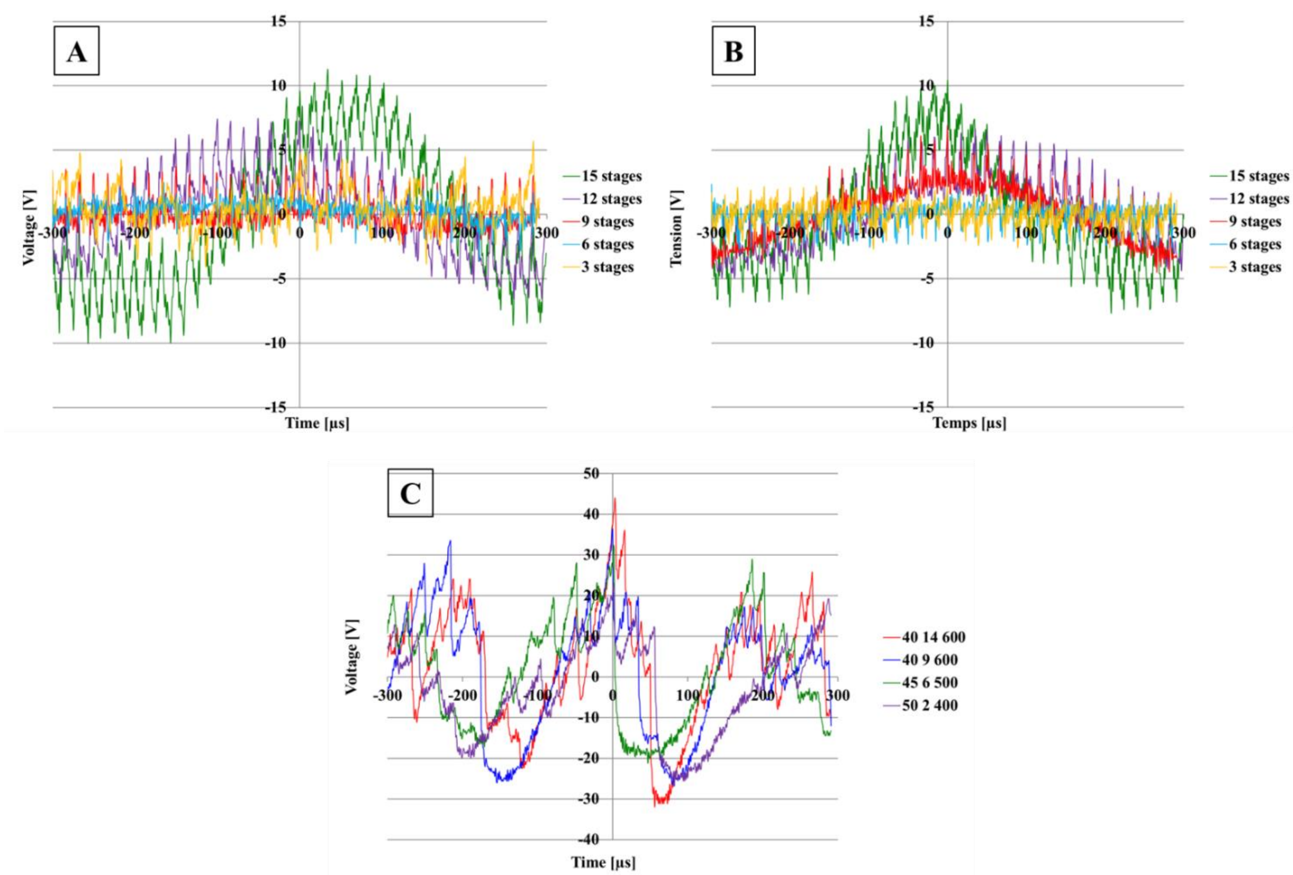

Figure 2: Time resolved measurements for arc voltage obtained with 3, 6, 9 ,12 and 15 stacks of neutrodes in a cascaded torch for: A) an Ar/H_2 (50/2) – 400 A plasma; B) an Ar/H_2 (50/0) – 450 A plasma; C) 4 operating parameters (Ar H_2 Arc current) F4MB torch.

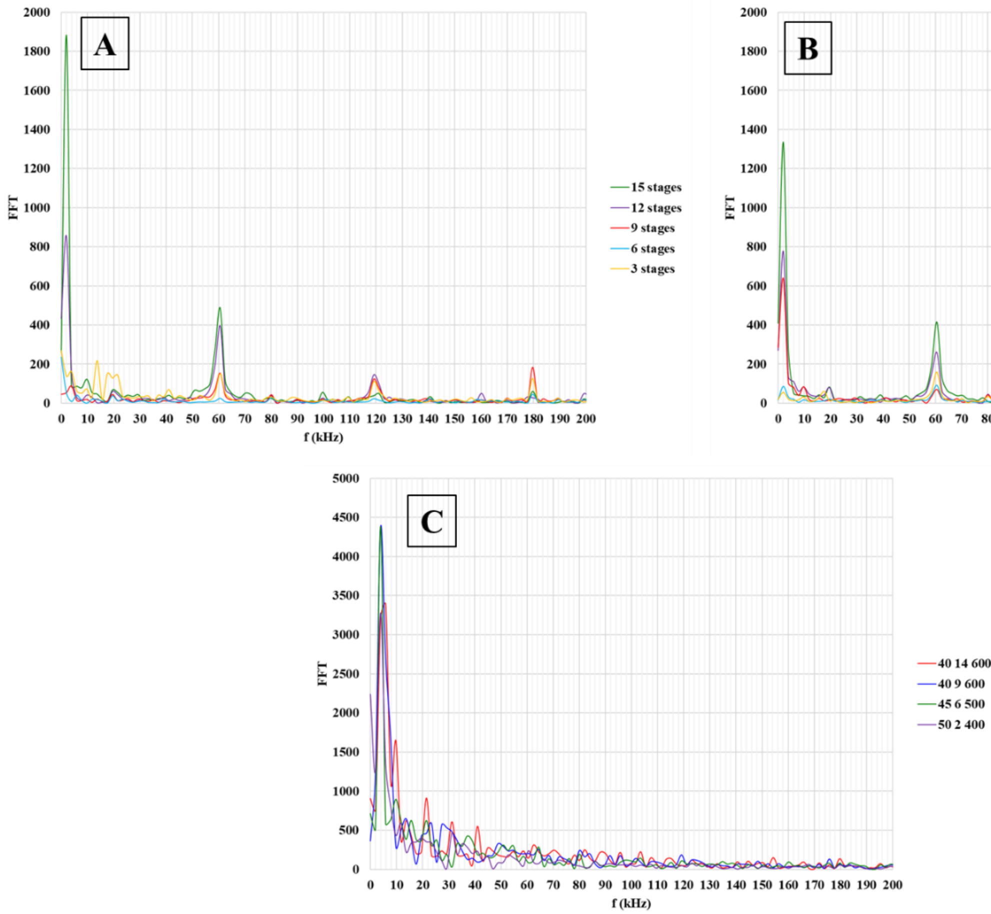

Figure 3: Power spectra of the arc voltage fluctuations obtained with 3, 6, 9 ,12 and 15 stacks of neutrodes in a cascaded torch for: A) an Ar/H_2 (50/2) – 400 A plasma; B) an Ar/H_2 (50/0) – 450 A plasma; C) 4 operating parameters (Ar H_2 Arc current) F4MB torch.

This plasma regime phenomenon is found for the two operating parameters used for each configuration and the root cause is today not explained. The restrike mode of the F4MB torch is associated with the appearance of a shrill noise when injecting hydrogen into the nozzle. The appearance of this ripple is also associated with a change in the noise emitted by the plasma. The shape of the time resolved measurements is influenced by the torch configuration. However, these fluctuations are much smaller than those encountered with the use of an F4MB torch, which are more irregular and range from ± 35 V. If the 3-stacks configuration and the F4 torch are compared with an almost identical arc voltage value, the voltage fluctuation is 7 times higher with the conventional plasma torch. This shows the overriding effect of using neutrode to stabilize the arc between the electrodes.

The increase in the number of stacks, and therefore the distance between the tip of the cathode and the last stack of the anode, induces not only an increase in the arc voltage but also a progressive increase in the fluctuations, but to a lesser extent than a conventional plasma torch. The observation of the increase in fluctuations but also the appearance of undulation with the increase in the number of stacks seems to indicate a limit in the design of cascade plasma torches. By increasing the distance between cathode and final anode, the average voltage is increased, of course, but on the other hand, instabilities appear in the plasma, which is to the detriment of what is expected for this type of torch. There is therefore an optimal configuration probably combining anode diameter, cathode to anode distance and probably the geometry of the different neutrodes used in the design of the torch.

Because it is very difficult to get a direct information from the time resolved signals, the power spectrum can give us a clear way to understand these signals. This way, from this time resolved signals, a frequency analysis determines the corresponding power spectrum. Figure 3 shows the respective power spectra of the arc voltage fluctuations shown in Fig. 2. Some very well defined peaks occur at the same frequency whatever the number of neutrodes. However, the intensity of the peak is progressively increased with the number of neutrodes. So sharper and higher peaks appear, and a dominant peak is present at the lowest frequency. Figure 3 also displays the corresponding power spectra obtained with a F4 plasma working under various conditions. This time, the power spectra measured with a F4MB plasma torch contains no well-defined peak frequency indicating a random displacement of the arc root leading therefore to less stability of the arc.

In-Flight Particle Characteristics

Evolutions of particles velocity and temperature are shown in Fig. 4. It can be seen well-marked tendencies in function of the used cascaded torch. Indeed, a constant increase in both velocity and temperature of detected particles (same measuring position) can be observed regarding the progressive upper stack levels of the cascaded torch (from 3 to 15 stacks). It can be noted the values in velocity and temperature are in the same range of evolution for Larmor design torches, but a real gap exists in particles properties with the Debye design generating much less energy. Whatever Debye or Larmor torch, 50 m/s and 150 °C increases in velocity and temperature, respectively, accordingly are systematically observed for the different cascaded plasma torch (3, 6, 9 15 stacks) versus current intensity. Using these new cascaded torch design, the highest velocity and temperature is then obtained with the 15 stacks reaching 410 ± 32 m/s and 2954 ± 70 °C with the set of 450 A, 50/2 L/min Ar/H_2 gas flowrate operating parameters. In order to achieve the same range of particle properties, the conventional F4MB plasma torch leads to 401 ± 32 m/s and 2890 ± 80 °C with a plasma composed of 650 A and 40/12 L/min Ar/H_2 forming gas flowrate for comparison. The significant amount of H_2 leads to a strong wear of the electrodes which also defines the limit of use of the F4MB plasma torch. So, precious information about the thermal and kinetic treatment of particles can be deduced in terms of current and gas consumption with the new design of plasma torch.

In order to see the evolution of the velocity and temperature when the flowrate changes, different measures are carried out for a given arc current of 400 A. The effect of Ar flowrate with and without H_2 on particle properties is shown in Figure 5 (without H_2) and Figure 6 (with H_2). As observed previously a steady rise in both particle velocity and temperature is observed for the two set of operating parameters. However, in contrast to what could be expected, the highest values are obtained with the 9 stacks cascaded torch and a plasma without H_2. Results show the highest velocity and temperature of nearly 500 m/s and 2900 °C. Independently to the presence of H_2 forming gas, the obtained temperature exceeds the melting temperature of the material for all experiments. However, as the velocity exhibits a clearly increase with Ar flowrate, the evolution of the temperature is less dependent on this parameter with a decreasing trend. Comparing these values with the HVOF process, we may point out that the measured velocity is the lower range of the particle velocity obtained with the HVOF process (500 – 700 m/s) but with a much higher particle temperature. This may induce to explore new potential coating properties (change in coating internal stresses and microstructure) obtained with a low cost more environmentally friendly thermal spray process in comparison with the HVOF process.

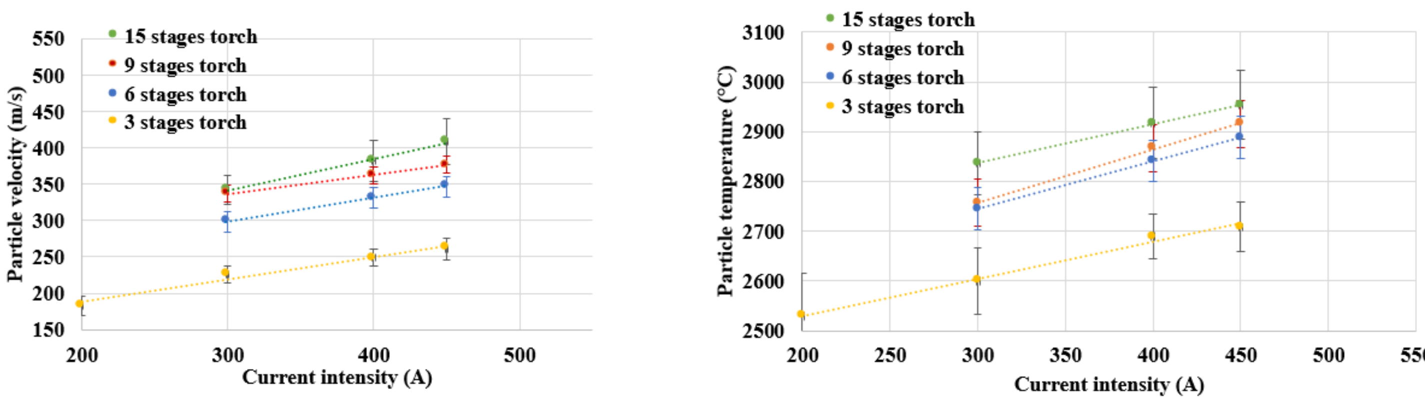

Figure 4: Influence of arc current intensity on velocity and temperature of alumina particles for an Ar/H_2 (50/2) plasma with different cascaded torch configurations.

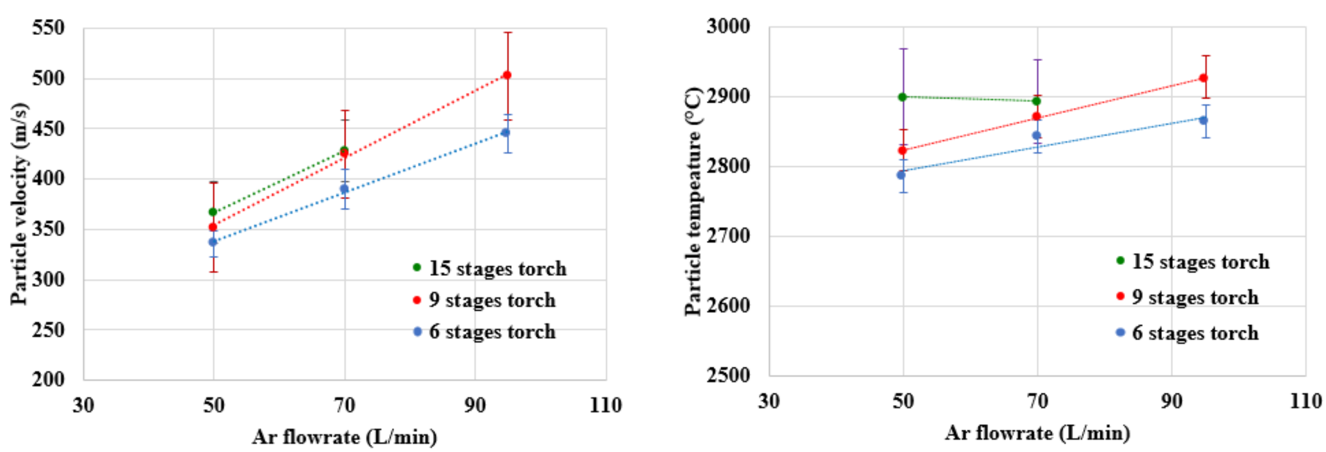

Figure 5: Influence of argon flowrate on velocity and temperature of alumina particles for 400 A current intensity without hydrogen with different cascaded torch configurations.

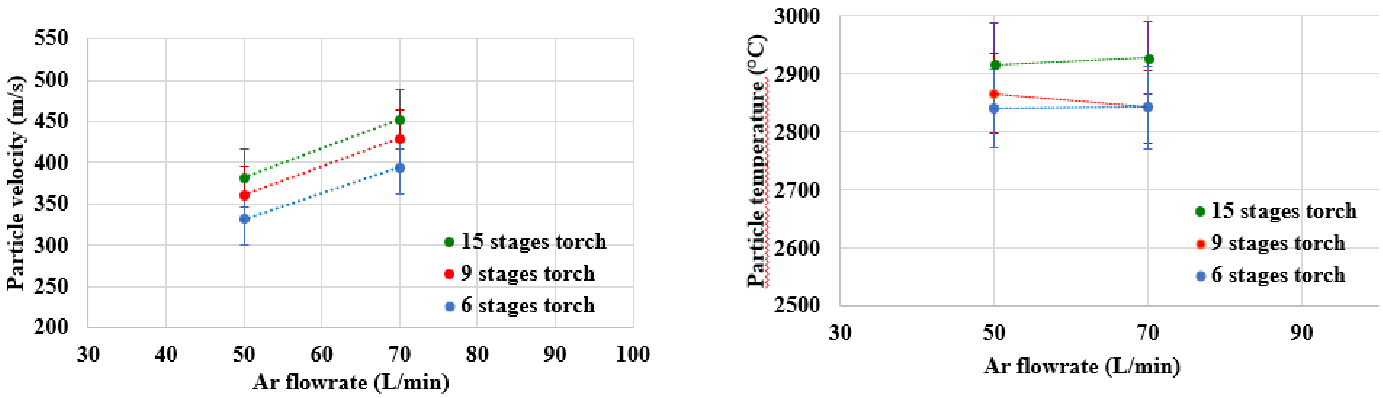

Figure 6: Influence of Ar flowrate on velocity and temperature of alumina particles for 2 L/min H_2 and 400 A plasma with different cascaded torch configurations.

Coating Microstructures

Different coatings are realized with the cascade configurations 3, 9 and 15 stacks. The spraying parameters used and the coatings presented have for the moment no correlation with the in-flight particle diagnosis performed. The primary objective is to work with low energy parameters, the use of a low quantity of hydrogen and a torch power between 30 and 40 kW (compared to 47 kW for the F4MB one). Work is in progress to correlate the temperature and velocity characteristics of the particles obtained with an F4MB torch with reference parameters, to transpose them to a cascade torch for different configurations. Different operating parameters such as the number of cascades, the composition of the plasma gas with or without hydrogen, and the current intensity will then be selected with identical particle characteristics. The microstructures and properties of the deposits will be compared.

Figures 7 and 8 present the microstructure of a reference alumina coating obtained with the F4MB torch as well as the microstructures of different coatings obtained with the cascade configurations. As a reminder, the spraying parameters are presented in Table 2 and Table 3. The reference alumina coating is characterized by a porosity of 2.8 % and a microhardness of 1053 ± 62 HV. These first tests show that for a 3-stacks configuration, coatings C1 to C5, the argon flow rate should not be too high to obtain a good performance coating. At 60 L/min, the higher speed of the particles must be compensated by a higher hydrogen flow rate in order to increase the energy of the plasma (C1 and C3). For a same 500 A arc current intensity and a hydrogen flow rate of 3 L/min, the decrease of the argon flow rate from 60 to 35 L/min results in a better deposition efficiency, an increase of the microhardness and a decrease of the porosity (C3 to C5). Particle residence time is increased which improves the number of molten particles. The microhardness and porosity obtained are similar to the reference coating with the F4MB torch, i.e. 1036 ± 126 HV and 3.3 % porosity (see Table 5).

With the 9-stacks configuration, an argon flow rate of 40 L/min is chosen due to the previous results with the 3-stacks torch. Comparing the C6 and C7 coatings, the increase in hydrogen flow rate results in an increase in microhardness (1072 ± 171 HV) and a decrease in porosity to 6.1 %.

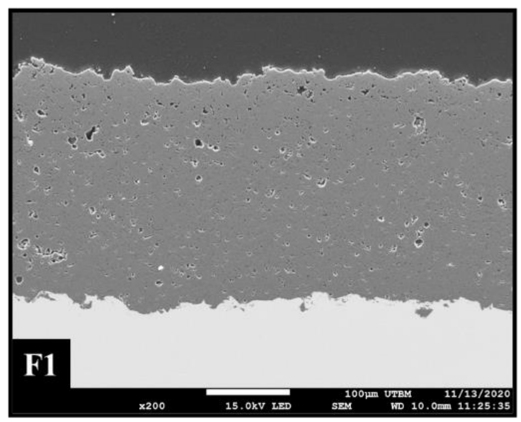

Figure 7: Alumina coating microstructure obtained with F4MB plasma torch.

Table 5: Hardness and porosities of alumina coatings

Reference	Hardness (HV0.3)	Porosity (%)
F1	1053 ± 62	2.8 ± 0.6
C1		
C2	903 ± 224	8.7 ± 2.2
C3	861 ± 123	7.0 ± 1.8
C4	1020 ± 106	5.5 ± 1.0
C5	1036 ± 126	3.3 ± 0.8
C6	1019 ± 166	8.5 ±2.0
C7	1072 ± 171	6.1 ±2.3
C8	1075 ± 125	4.6 ±0.7

Switching to a 15-stacks torch configuration with an argon flow rate of 40 L/min but reducing the current intensity to 350 A and without using hydrogen, allows to obtain a higher microhardness at 1075 ± 125 HV for a porosity of 4.6%. Using a cascade plasma torch, it is possible to obtain alumina coatings comparable to those made with the F4MB torch but with the advantage in the case of the last C8 coating to use only argon and a low amperage. The use of a higher voltage allows to reduce the parameters critical to the electrode life (high amperage, hydrogen) thus increasing the longevity of the parts.

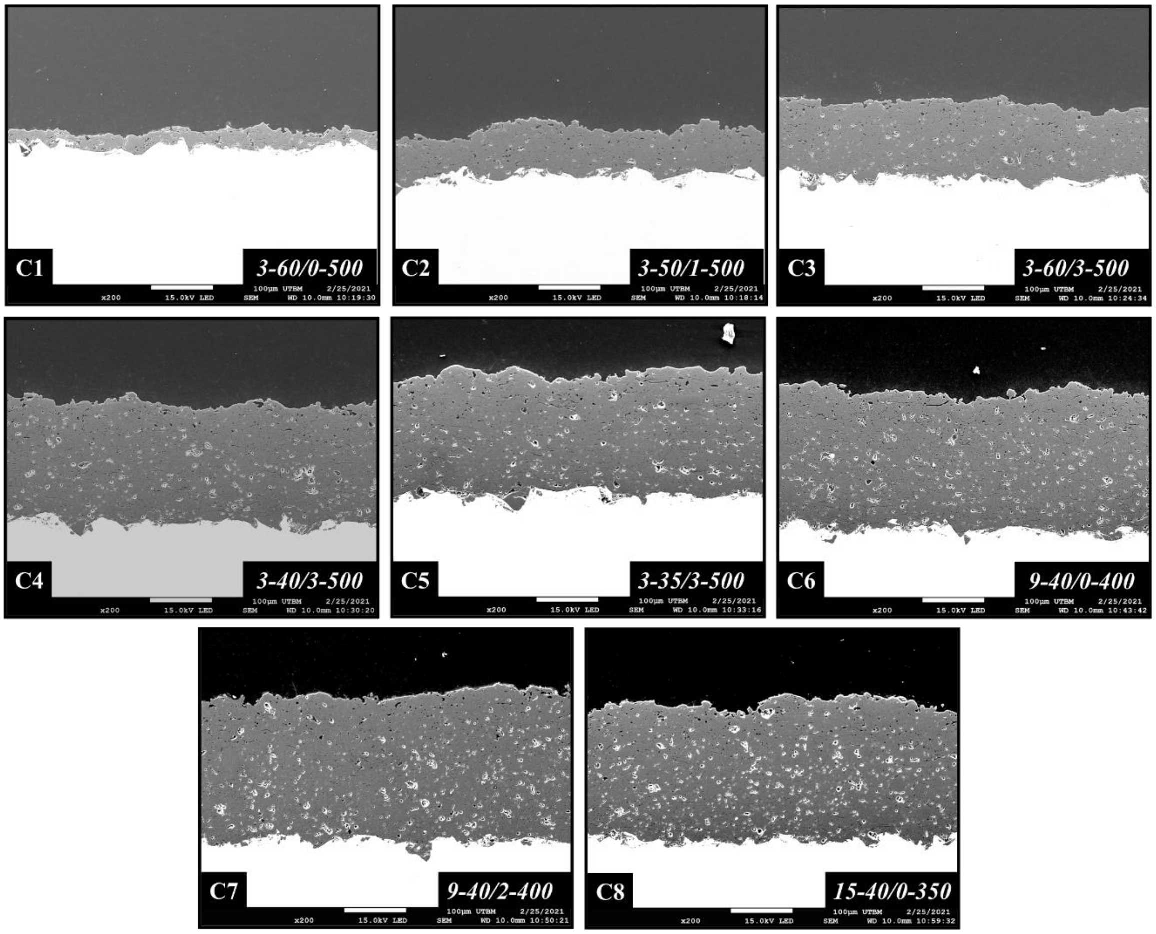

Figure 8: Alumina coating microstructures obtained with cascaded plasma torches (stacks-Ar/H_2-arc current).

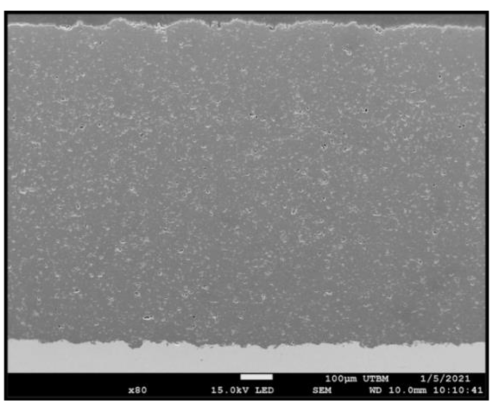

Figure 9: Thick alumina coating microstructure obtained with 9-stacks cascaded plasma torches.

For an industrial company, this translates into a reduction in production costs by reducing the frequency of electrode replacement and reducing energy consumption. Another parameter being studied will be the powder mass flow rate that can be achieved with these cascade torch configurations in order to save production time. Figure 9 shows a 1mm thick coating of alumina obtained with the plasma torch in a 9-stacks configuration. It is relatively dense and has no apparent cracking. The increase in thickness of the alumina coating also seems possible

Conclusions

Diagnostic systems have been setup to monitor online the plasma spray process with various cascaded torch. The results have been compared to those obtained with a conventional F4MB plasma torch. The shape of the time resolved signals and the respective Fast Fourier Transforms of such signals provided a convenient way to demonstrate the increased stability of the arc issued from the cascaded torch. It is confirmed that the voltage fluctuation level is strongly reduced in comparison to the standard single anode/cathode configuration.

Depending on the length of the cascade the voltage fluctuation level may vary. The results show that with a cascade length of 39.1 mm the voltage fluctuation is minimized. For higher cascade length an additional low frequency fluctuation is appearing in the fluctuation spectra. The root of this this additional fluctuation is not explained.
The study of the alumina particle velocity/temperature in the plasma jet shows that particle velocity up to 495 m/s and a temperature up to 2900 °C may be achieved. The combination of high particle velocity and high melting temperature may result in new coating design and properties.

Alumina coatings have been manufactured with different torch configurations and operating parameters. The properties obtained are comparable or even superior to those of the reference alumina coating. Microhardness higher than 1070 HV and porosity lower than 5% have been obtained. The most interesting lesson is that these coatings have been obtained without or with a very low quantity of hydrogen (< 3 L/min) and arc current intensities lower than 400 A. The industrial interest is therefore demonstrated with the reduction of critical parameters for the electrode life and the reduction of the energy cost of the process.

Acknowledgments

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