

OPTIMIZATION STUDY OF THE OPERATING CONDITIONS TO IMPROVE THE QUALITY OF SURFACES COATING OBTAINED BY PLASMA SPRAYING PROCESS

R. Djebali^{1,2,*}, A. Hleli³, A. Lamari¹, M.A. Abbassi¹ and B. Pateyron⁴

ABSTRACT

In the present paper we aim to present a numerical optimizing study on the operating conditions of an atmospheric plasma spraying process. The focus is mainly made on the powder injection parameters and the objective is to improve the quality of surface coatings.

First, a 'validation' test of the *Jets&Poudres* code is conducted based on various numerical and experimental former works. The results of the *Jets&Poudres* code seem to be a good compromise between the results of different numerical methods and the experimental measurements.

Second, a Taguchi experimental design is conducted to explore the influence parts for five operating parameters in the spraying process. This, results in a primary gas flow rate of 45 *SL/min*, a spray distance of 12 *cm*, a particle size around 55 μ m, a powder feed rate ranging close to 1 *l/min* and finally an electric power of about 25 *kW*.

Finally, a test case for a ternary gas mixture is conducted on 15000 particles using the *Jets&Poudres* code to assess the conclusions drawn in the studies using the experimental design. The results are confronted together and discussed.

Keywords: *Plasma Spraying, Thin Coatings, Deposit quality, Sommerfeld Number, Taguchi Experimental Design, Jets&Poudres Code.*

INTRODUCTION

The use of thin coatings in different areas (automotive, aerospace, aeronautics, medicine, etc ...) has an important challenge today. For surfaces engineering, various treatment methods exist such particularly plasma spraying. Corresponding coatings are generally used against frictional wear, erosion, abrasion, fatigue, etc. This technology allows spraying of any metal or ceramic on many substrate materials.

Today spraying process is part of the engineering of surfaces recognized techniques, it allows for thick coatings (few tens to a few hundreds of micrometers) of very different natures on diverse substrates while maintaining the desired performance. A coating carried out using plasma spraying is constituted by the multilayer stacking of melted particles at very high temperatures and high velocities on a previously prepared substrate. The quality of the deposit obtained depends on the thermal history of particles injected; particles impact parameters, substrate parameters, plasma jet flow characteristics and injection conditions. Great difficulties are encountered in the study of plasma-particles exchange due to the multitude of parameters and coupled multi-physics that exist from the injection of particles to the coating formation.

The objective this study is to conduct a numerical optimization study based experimental design toward the control of the operating conditions for the improvement of the quality of the deposits obtained. The monitoring parameter of this study is the K-Sommerfeld number that characterizes the impact behavior of the particle that is rebounding, coating or splashing, thus a single criteria response.

Besides, optimization studies in the fields of energy, renewable energies and materials attract today the attention of researchers and industrialists [1-6]. The Taguchi technique is one of the tools used for its reliability and power and flexibility [7, 8]. For these reasons, *Taguchi experimental design* method was chosen. It deals with both (not separately) the average value (desirable) of the selected criterion and its variability (to fight) without addressing the noise factors. The simulation code is '*Jets&Poudres*' [9].

This paper was recommended for publication in revised form by Regional Editor Mohamed Awad

¹UR-MEER, FS Gafsa, University of Gafsa, BP.19, Gafsa 2112, TUNISIA

²ISLAI – Béja, University of Jendouba, BP. 340, Béja 9000, TUNISIA

³LSAMA, FS Tunis, University of Tunis el Manar, TUNISIA

⁴CNRS – SPCTS/CEC 12, Rue Atlantis 87068, Limoges, FRANCE

*E-mail address: jbelii_r@hotmail.fr or ridha.djebali@ipein.mu.tn

Manuscript Received 28 October 2016, Accepted 2 March 2017

A 'validation' of the simulation code '*Jets&Poudres*' by reference to the numerical results of the Lattice Boltzmann method [10], the LAVA code [11] and experimental results of Smith [12] existing in the literature was done. A study of 16×5 trials of a fractional factorial design with five settings each of four levels was performed. Analysis of the effects on the measured values and the S/N ratio gives a mathematical model (combination of factors levels) which target value of 300 for the K- Sommerfeld number.

Confirmatory testing (validation) was then conducted and whose objective is to confirm that the retained combination of factors selected following the study by experimental design allows the expected profitability of the deposit.

PLASMA SPRAYING: A COMPLEX PROCESS

Complexities at various stages: The plasma spraying process (PSP) complexity has met with particular interest in former studies. Vardelle et al. (1993) [13] have in part conducted a work on spray parameters and particle behavior relationships during its sojourn in the hot plasma gas. The authors discussed the particle injection (injection momentum, powder injector tilting), the particle size and morphology, the spraying parameters and torch design.

The authors work addressed also a comparison of Ar-H₂ and Ar-He mixtures and explore the nozzle diameter surrounding atmosphere effects. The authors work emphasized through flux measurements the importance of the carrier gas flow rate that must be adjusted to the plasma jet momentum depending on some parameters such in particular gas nature. Which is in accordance with conclusions drawn by Djebali et al. (2013) [14] stating that the primary gas flow rate has the second key role in particle arrival state. In Figure 1, one can note the huge subsystems complexity of the process at different levels related mainly to the characteristics of the torch, the powder, the injector, the plasma jet and the substrate. Even further, a particle flying in the hot gas undergoes a very complicated momentum, heat and mass transfer phenomena occurring in its surrounding boundary layers.

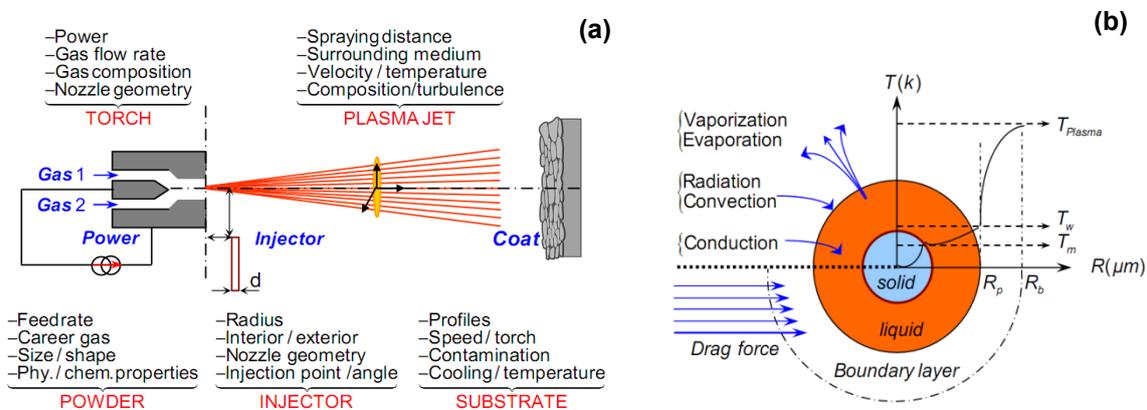


Figure 1. Sketch of the plasma spraying principle and complexities. (a): the d.c. plasma torch, the plasma jet, the powder injector, the substrate and the coat formation. (b): zoomed view of particle momentum, heat and mass transfer phenomena occurring in its surrounding boundary layers.

The dihydrogen (H₂) is not used as pure (for lack of mass), that is why Argon is generally added; and it is the same with Helium gas. For Nitrogen (N₂), it is typically used as pure and hydrogen or Helium are may be added. Then, optimal ternary mixtures currently appear to be of type Ar-He-H₂.

Additionally, dissociation and ionization temperatures play important rule in the choice of the plasma gas. In fact, the dissociation and ionization phenomena cause huge variations in thermal conductivity. Nitrogen and hydrogen are added to increase heat transfer in the vicinities of dissociation temperatures near 3500K for H₂ and 7500K for N₂. For H₂, with a lower dissociation temperature, it is the most widely used gas in a point of view of heat transfer. Helium gas has a much higher thermal conductivity; its ionization begins at 16000K. Helium gas improves the impact of the particles by increasing the viscosity of the gas mixture beyond 10000K and limiting the phenomena of turbulence in vicinities of the arc column.

When speaking about optimal plasma gas mixture, argon gas is the most used one in plasma gas mixture. It has better thermo-physical properties; it has the advantage of being inert, it has low ionization temperatures, low thermal conductivity and is heavy allowing a good particle transport in flight. Such thermo-physical characteristics distinguish Argon to be the primary gas in plasma spraying. More improvement of the Argon plasma may be accomplished by addition of Hydrogen and Helium gases. Former works state that ternary mixture Ar-H₂-He is considered as optimal mixture in plasma spraying; the percentages of the various components depend essentially on the intended application.

Motion and heat complex modeling: For the particles in-flight in plasma jet, two characteristics are studied: motion (trajectory, velocity, acceleration) and thermal evolution (temperature, physical state, heat flux).

A particle moving in a plasma jet is subjected to few forces: the drag force, the gravity force, the additive weight force, the force of thermophoresis, the history force of Basset. The most important force acting on the particle is the drift force that depends on the morphology of the particle and the Reynolds number and accounts for strongly varying plasma properties and Knudsen non-continuum effects in the boundary layers where the temperature of the hot gas flowing over a particle/droplet drops drastically (Figure. 1- b). However, the thermal treatment of particles during its sojourn in the plasma jet follows four sequences: solid particle heating, melting at constant temperature, liquid particle heating and vaporization at constant temperature.

The semi-empirical Ranz-Marshall-type correlation with corrections is always used to estimate the convective heat transfer between the droplet and the surrounding hot gas.

$$Nu_p = 2.0 + 0.6Re_p^{1/3}Pr^{1/2} \tag{1}$$

RESULTS AND DISCUSSION

To demonstrate the validity of the plasma-particle interaction model, the our results are compared to those of previous numerical findings and measurements [9,11,12]. The particle velocity and temperature obtained by the present model (Figure 2) for an Ar-H₂ plasma jet show satisfactory agreement with reference results for both thin and thick models, which let us to rely on the credibility of the *Jets&Poudres* model.

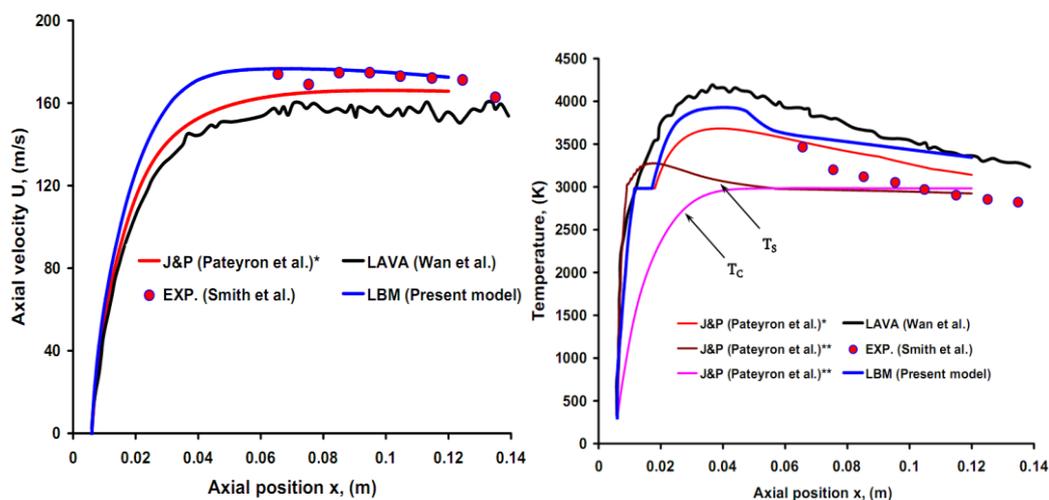


Figure 2. Axial velocity and temperature of sprayed ZrO₂ particles vs the axial distance. *Jets&Poudres* [9] and LAVA [11] softwares predictions and experimental data of Smith et al. [12] are plotted as references. (*) thin model is used and (**) for thick model.

Table 1. Controlled factors, their symbols and levels.

Factors / Levels	Sym.	L1	L2	L3	L4
Primary gas flow rate (NL/min)	A	25	35	45	55
Spraying distance (cm)	B	9	10	11	12
Powder size (µm)	C	25	45	65	85
Powder feed rate (NL/min)	D	0.8	1.0	1.2	1.4
Power (kW) (η=0.57)	E	15	20	25	30

In the following we'll investigate the influence of processing factors on droplet impact properties. The spraying conditions used in this study are: the primary gas is the ternary mixture He-Ar-H₂-65-30-05 % vol., the sprayed powder material is the dense Zirconia (ZrO₂), the nozzle diameter is 8 mm, the injector position is (5mm, -7mm), the nozzle exit temperature is 12000 K, the environment atmosphere is the air and the particle size distribution is Gaussian.

Note that in a former work [14] we have conducted a study using five factors of two levels (1: min and 2: max) and thus a linear effects of factors are considered. However, a discrepancy was remarked by comparison to experimental conclusions. In the present study we choose the factors with four levels, namely the primary gas flow rate (A) ranging from 25 to 55 SL/min, the spray distance (B) from 9 to 12 cm, the particle size (C) ranging from 25 to 85µm, the powder feed rate (injection velocity) (D) ranging from 0.8 to 1.4 l/min and finally the electric power (E) ranging from 15 to 30 kW and interactions are assumed to be negligible (see Table 1). We assume that each factor level has a Gaussian-like dispersion at each level.

For each particle treated separately, we calculated the Sommerfeld number (Eq. 2) which is usually used to characterize the droplets impact behaviors (K<3: rebound, 3<K<57.7: deposition and K>57.7: deposition with splashing).

$$K = We^{0.5} Re_p^{0.25} \tag{2}$$

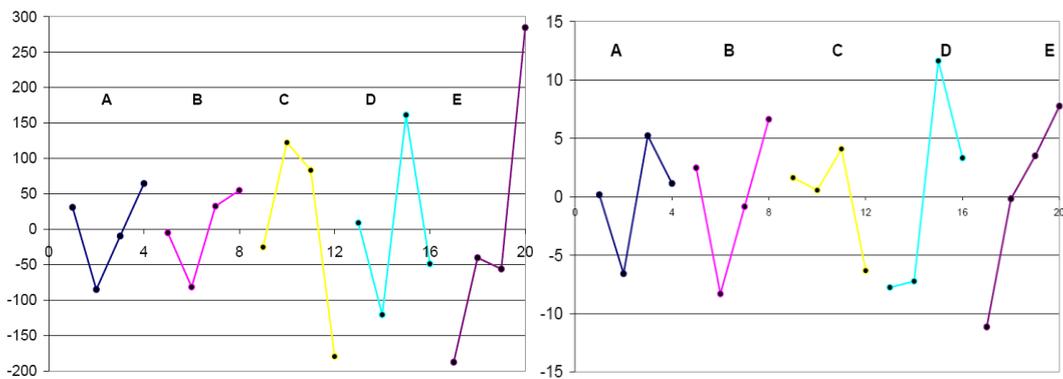


Figure 3. Effects of factors levels on the measured (average) values (left) and the S/N ratio (right) of the Sommerfeld number.

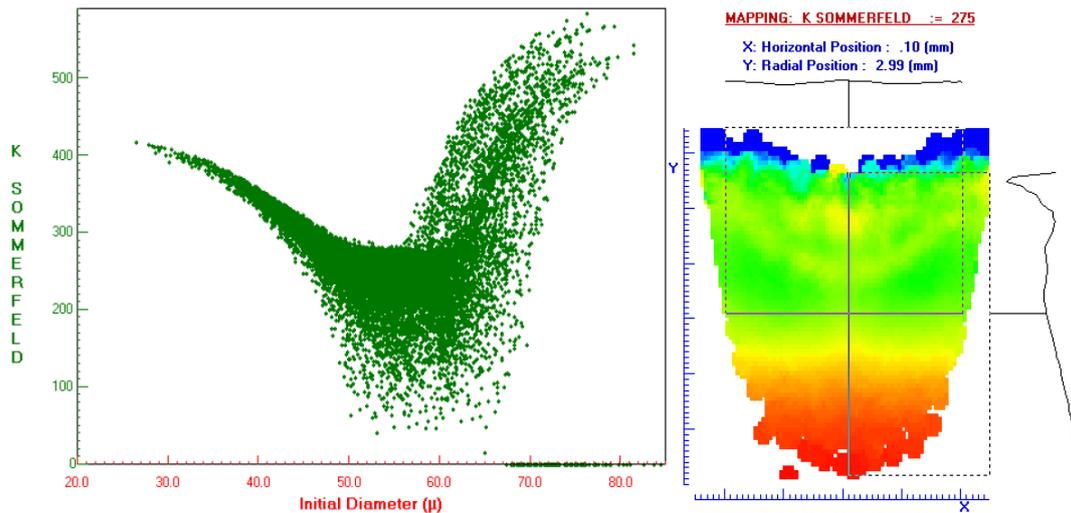


Figure 4. Cloud points of K number depending on the initial diameter (left) and its distribution for the coat obtained on the substrate (right).

Where We is the Weber number and Re_p is the Reynolds number based on the particle diameter. Means

that for low impact-velocity or if impact-temperature is very lower compared to the melting point, particles will rebound; and contrarily, we'll have the splashing phenomenon which alters the coating efficiency.

A study of 16×5 trials of a fractional factorial design is performed. The results of the factors levels effects on the measured (average) values (left) and the S/N ratio (right) are given in Figure (3).

Remarks: First, it should be noted here that the average K values (measured value) are of the order 300 so we are contented in this study to target this value for two reasons: (a) I'll seek to stay slightly above the value $K = 3$, below which we surely have droplet rebound. (b) It has been observed by Escure et al. [15] that for injected alumina Al_2O_3 particles in a d.c. plasma, the Sommerfeld number is found between 50 and 1800, this shows that the splashing phenomenon is a rule not exception. Second, the value $K = 57.7$ is characteristic of water and ethanol impacting on a smooth substrate. Means that the transition from 'deposited state' to splashing phenomenon occurs for $K = 57.7$. Third, Escure et al. [15] showed that in the case of alumina plasma spraying, there is ejection of material as soon as the Sommerfeld K criterion is greater than 30 for particles of diameter 30 microns whose velocities vary from 50 to 270 m/s. Forth, According to first remark, we calculate the Signal to noise S/N ratio for a target criterion in Figure 3 (right)..

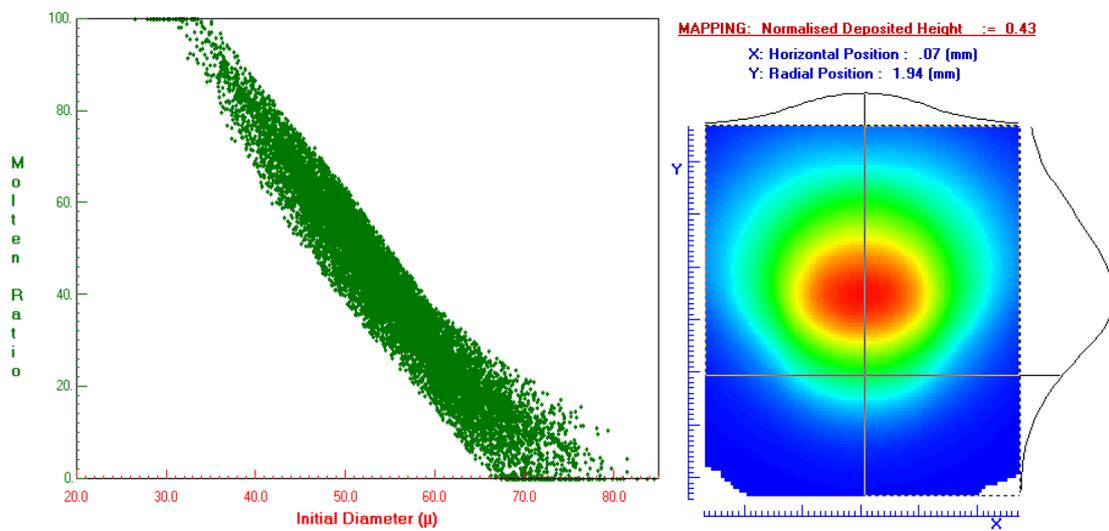


Figure 5. Melting percentage of a sample of 15000 particles of size Gaussian distribution $N(55\mu\text{m}, 8\mu\text{m})$ as function of the initial diameter (left) and the illustration of the normalized height of the obtained ZrO_2 coat.

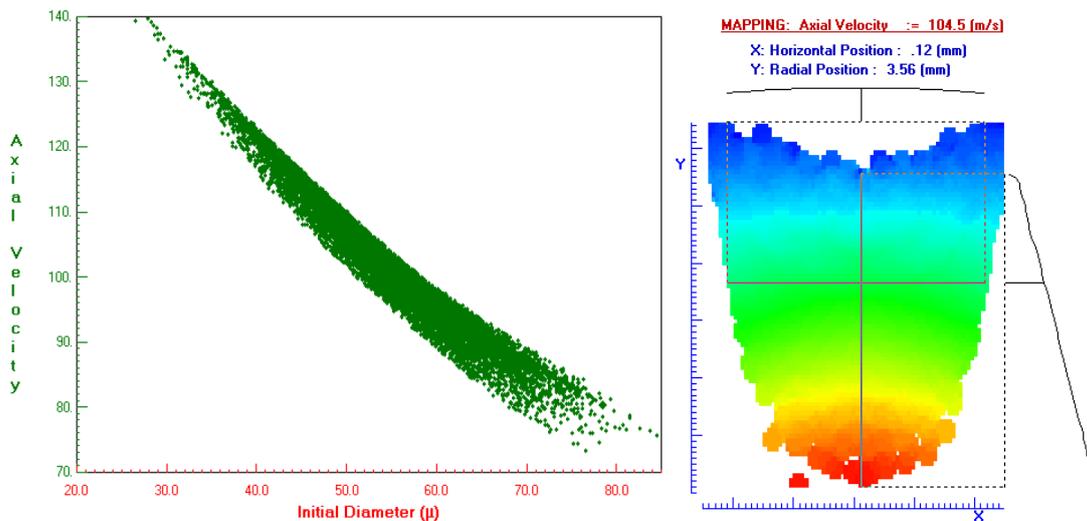


Figure 6. Cloud points of the particle axial velocity as function of initial diameter (left) and its distribution for coat obtained on the substrate (right).

Our purpose is to determine the combination of factors levels that target value 300 of K Sommerfeld number while ensuring good certainty to finally have a maximum particles spreading of projected ZrO_2 onto the substrate. This returns to compensate the effects of parameters on the averaged value and maximize the ratio S/N (dB) to minimize noise effects.

The analysis of the process factors effects leads to the combination of levels: $A_3B_4.C_{(2+3)/2}D_2E_3$ which results in a primary gas flow rate (A) of 45 SL/min, the spray distance (B) of 12 cm, the particle size (C) around $55\mu m$, the powder feed rate (injection velocity) (D) ranging close to 1 l/min and finally an electric power (E) of about 25 kW.

The resulting effect on the K-Sommerfeld measured value or the signal to noise ratio S/N is calculated by adding the effects of parameters (taken in levels of retained combination) to the overall average of all tests. This leads to $\bar{K} \approx 279$ and $\overline{S/N} \approx 25.2$ dB. The estimation of the standard deviation on the K-number gives $s \approx 15$. Here, if we consider that the cloud points of the Sommerfeld number follows the normal law, and then we can say that 99.75% of the population is found between [225,315].

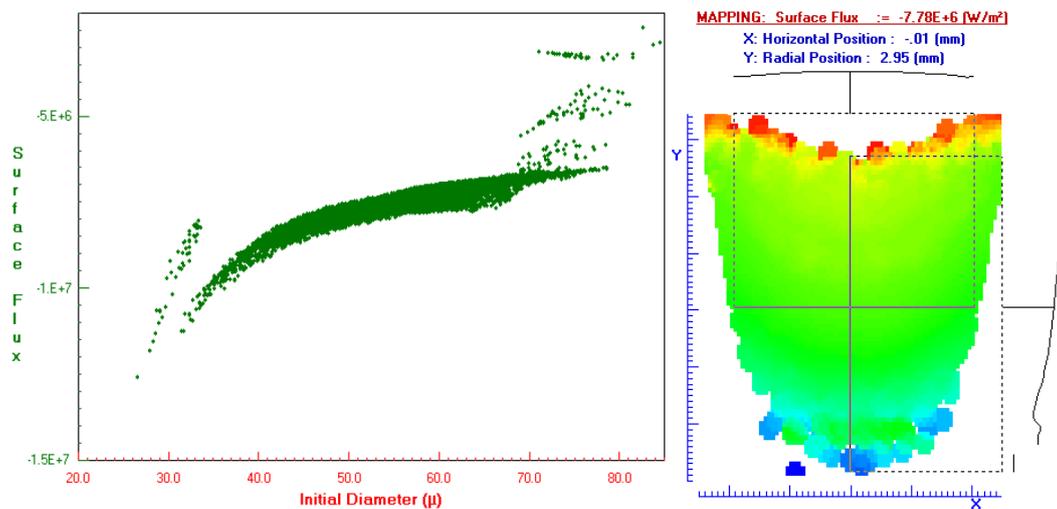


Figure 7. Cloud points of the coat surface flux depending on the initial diameter (left) and its distribution for the coat obtained on the substrate (right).

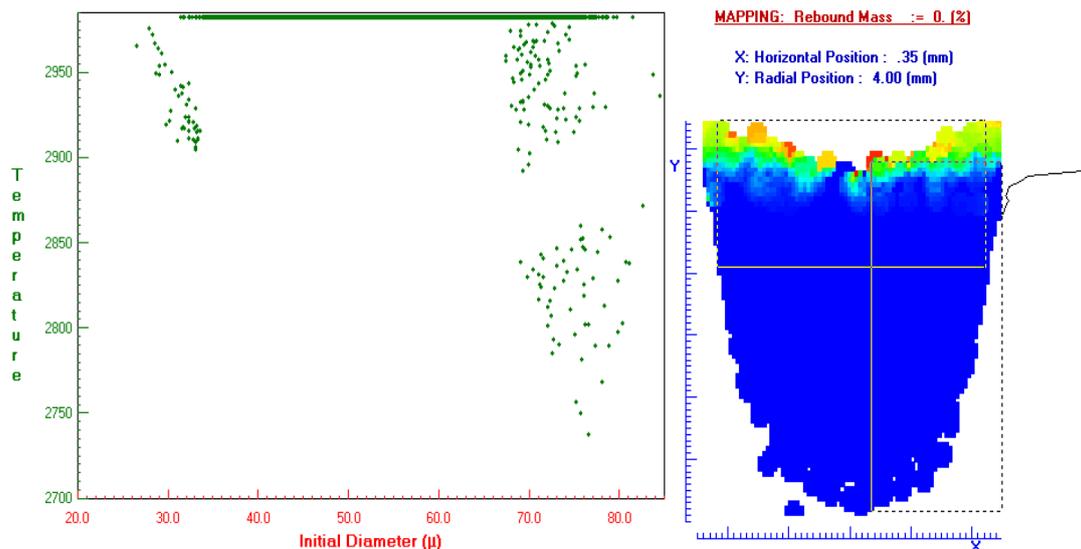


Figure 8. Cloud points of the particle surface temperature depending on the initial diameter (left) and the distribution of the percentage of rebound mass from substrate (right).

The confirmatory test aims to ensure the achievement of the desired result, which is to numerically verify the assumption of additivity effects of all factors. We choose a Gaussian distribution of particles around the average diameter of the injected particles ($\mu = 55\mu\text{m}$, $\sigma = 8\mu\text{m}$). It is estimated in our study, that the sieving revealed to us a population of dimensions to 99.75% ranging between $\mu - 3\sigma$ and $\mu + 3\sigma$ thus in $[26.6\ \mu\text{m}, 84.5\ \mu\text{m}]$. A simulation according to the condition of combination of the equation was performed on 15000 particles.

Figure 4 (left) shows the scatter plot of the K number as a function of the initial diameter. The average value is 250.6 with a standard deviation 64.5. The average value of this validation test is close to the value determined by the design of experiments. This validates our experimental design study. Figure 4 (right) gives the K- number distribution on the substrate. The highest values are localized from center to substrate down. The extrema (min and max) of the K- number are justified by the fact that particles arriving at the bottom acquire large heating and acceleration due to the driving around the jet axis where high acceleration and high temperatures.

Figure 5 (left) shows the droplets melting ratio. Average value is close to 45%, lower and higher values correspond to higher and lower initial particle size respectively. The normalized deposited height has a Gaussian profile under horizontal and vertical sections.

Figures 6 (left and right) show the cloud points of the axial velocity depending on the diameter of the particle and its distribution at the impact on the substrate. The average velocity is close to $102 \pm 5\ \text{m / s}$. This value is very interesting from the experimental study of literature; it allows good adhesion and particles spreading. The velocity distribution shows that it increases as linearly way from top to bottom of the substrate to have a maximum value of $140\ \text{m / s}$. This is due to the fact that the particles arriving at the bottom of the substrate acquire significant acceleration after training near the jet axis where high velocities.

Figures 7 (left and right) show the point cloud surface heat flux transferred by the deposit to the substrate according to the initial diameter of the particle and its distribution on the substrate screen. We remark that large particles yield a smaller surface flows (in absolute value) to the substrate. The larger particles are colder at their centers and because they hit the top of the substrate they give it less heat flux. The average flow is assigned in the order of $-7.4\ \text{MW / m}^2$

The 'Cloud' points of impact particles temperature as function of initial diameters is shown in Figure (8). We note here that nearly all particles (15000) impact the substrate with a temperature equal to the melting temperature $T_m = 2983\text{K}$, this great result is from the power Taguchi experimental designs that allow the expected result with very reliable confidence. This result allows the temperature to not have too much heating ($T \gg T_m$) which can cause evaporation, vaporization or splashing at impact and on the other hand not to have the particle bouncing the case of lack of heating ($T < T_m$).

CONCLUDING REMARKS

The present work aims to conduct a numerical investigation on the operating conditions to improve the quality of surface coating obtained by plasma spraying process. Taguchi experimental design method was chosen for the reason that it deals with both average value (desirable) of the selected criterion and its variability without addressing the noise factors. We may draw conclusions as:

First, a 'validation' of the simulation code '*Jets&Poudres*' by reference to numerical and experimental results show excellent agreements.

Second, Taguchi experimental design was done for five factors of four levels. The effects of setting levels are analyzed and a levels combination was retained.

Finally, a confirmatory testing (validation) was conducted under the retained factors level combination and whose objective is to confirm that the retained combination selected following the study by experimental design allows the expected profitability of the deposit.

It was noticed following the analysis 15000 particles of Gaussian dimension centered at $55\mu\text{m}$ that the surface temperature is absolutely equal to the melting temperature of $2983\ \text{K}$, the axial average velocity of impact is of the order of $102\ \text{m / s}$, the melting rate of about 45% and the Sommerfeld number is close to 251. Such values are of great industrial interest. It should be however very interesting to confirm these results experimentally.

NOMENCLATURE

Nu_p Particle Nusselt number

Pr_p	Prandtl number
Re_p	Particle Reynolds number
We	Weber number
T	Temperature (K)
T_m	Material melting point (K)
K, \bar{K}	Sommerfeld number and its average value
μ	Average value of a statistical distribution
σ	Standard deviation of a statistical distribution
s	Estimation value of standard deviation σ
d.c.	Direct Current
PSP	Plasma Spraying Process
SL	Standard liter
S/N	Signal-to-noise ratio (dB)

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