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Taguching the Atmospheric Plasma Spraying Process: Influence of Processing Factors on Droplet Impact Properties Obtained on Dense ZrO_2 and $H_2Ar75\%$ Plasma Gas

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Abstract: In this paper a study of the atmospheric plasma spraying process was conducted. The *Jets&Poudres* code was used to solve the partial differential equations for the conservation of mass, momentum and energy involved in the problem together with the K-ε turbulent model. The Taguchi technique was used to study the influence of processing factors on droplet impact properties obtained on dense zirconia (ZrO_2) under $H_2Ar75\%$ plasma gas that allow optimal functioning condition. The test of the operating parameters for the studied ranges showed that the "thermal power" factor plays a key role on the state of sprayed powder. It was found also that the carrier gas flow rate and the powder size do not influence the dispersion of the impact behavior of droplets/particles. The validation of the chosen levels combination was conducted on the *Jets&Poudres* code and showed good agreement with the results predicted by the Taguchi technique.

Keywords: Plasma spraying process, dispersion in processing parameters, Taguchi method, experiment design, droplet impact properties.

1 Introduction

The coating treatment of surfaces by plasma spraying is an important manufacturing process which was and remains extensively used in industrial applications to enhance the performance of engineering components such as coating of pistons, piston rings and shafts, and improving resistance to thermal degradation, corrosion and wear. The process is also source of experimental and numerical works to achieve high performance and to reduce experimental efforts. Moreover, the arc plasma spraying processes are of great complexity due to the various parameters involved

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in three levels [Djebali, Pateyron and El Ganaoui (2011) and (2013); Arcondéguy, Gasgnier, Montavon, Pateyron, Denoirjean, Grimaud and Huguet (2008); Chen, Heberlein, Pfender, Pateyron, Delluc, Elchinger and Fauchais (1995); BenEttouil, Pateyron, Ageorges, El Ganaoui, Fauchais and Mazhorova (2007)]. First, the generation of the plasma arc into the torch (nozzle diameter, current I, voltage U). Second, the plasma jet flow in interaction with the powder jet, where the plasma jet parameters (composition, enthalpy, temperature, velocity, viscosity and thermal conductivity are highly variable, the jet length, the air engulfment in the jet enhancing turbulence, etc.), others parameters are related to the powder-injector (internal diameter, position, inclination angle, carrier gas: composition and flow rate, etc.), adding the parameters related to the powder itself (material, morphology, shape, size, residence time in the jet, etc.). In a third level, one cites the parameters related to the coat formation (materials properties, substrate preparation, spraying distance, relative movement torch/target, incidence tilt, substrate cooling, residual stresses, etc.) and eventually the variability of the above-mentioned parameters (dispersion).

To these complexities are added difficulties of higher order in modeling by conventional approaches (numerical simulations and modeling) based on Euler and Lagrange formalisms of phenomena governing the plasma - powder transport mechanisms and transfer interaction during the flight time in the hot gas. Therefore, it is more convenient to consider and to rely on techniques of lower costs. This study deals with the analysis of plasma spraying by the *Taguchi method*. This technique, which is required in the industrial practice of experiments design, has met with growing interest in engineering process. The key idea of this technique is that it treats jointly the parameters *average* that govern the system (product or process) and the *dispersion* (noise) of these parameters.

Arcondéguy, Gasgnier, Montavon, Pateyron, Denoirjean, Grimaud and Huguet (2008) have performed an experimental study based on experimental design to investigate the effects of operating parameters on coatings structure, mainly on the coating thickness and the coating porosity level in glaze coating flame spraying case. The study allowed highlighting the effects of some major operating parameters on coatings morphologies. It was shown that the spray distance and the scanning step (per pass) are the most influent factors on coating thickness and pore level. Hadiwidodo and Bin-Mohd (2010) have applied the Taguchi experiments design in Self Compacting Concrete (SCC) freshened properties studies. It was concluded through the obtained results that the Taguchi technique is a promising approach for optimizing mix proportions of SCC to meet several freshened concrete properties. It can distinctly simplify the test procedure required to optimize mix proportion of SCC by reducing the number of trial batches. Mohamad Nor, Muhamad, Ibrahim, Ruzi, Ahmad and Jamaludin (2011) used the Taguchi method in a L^{27} (3^{13}) orthogonal array to optimize the metal injection molding parameters of Ti-6Al-4V powder mixed palm stearin and polyethylene for the highest green strength. The authors concluded that the most influential factors are the mold temperature (with a contribution of 27.59%), followed by the powder loading (15.44% of contribution) and the injection pressure with 12.30%. A confirming experiment has been performed to verify the obtained optimum parameter and has shown that the Signal/Noise ratio obtained is within the confident interval.

Jagannatha, Hiremath and Sadashivappa (2012) have employed a modified Taguchi robust design analysis to determine optimal combination of process parameters for abrasive hot air jet machining for glass. Authors have observed a good agreement between the predicted values of Taguchi analysis model and measurements. It has been concluded also that the air temperature is the most significant factor on material removal rate (MRR) and roughness of machined surface (R_a) and that -from the experimental results- the air temperature has the greatest impact on MRR and R_a of grooved surface. Babu, Kumar, Prabhakar and Shankar (1996) (with recent revisions in Lintona, Jiangb, Gatti and Embrechts (2013)) have conducted an experimental study using ASTM specimens to produce coatings which have high cohesive strengths. The Taguchi technique was used to optimize the spraying process parameters in order to produce high quality coatings. Micro-structural studies are conducted on the sprayed coatings and the changes in the microstructure with different spraying conditions are correlated with the strength variations of the coating. The authors have found that Taguchi techniques were very useful in obtaining the best setting of each of the process parameters with reduced experimental efforts.

In this work, we'll attempt to use the Taguchi methodology to study the effects of the most influential parameters on the state and behavior (solid, liquid or plastic and rebound, deposit or splash) of molten particles at its impact on the substrate, measured using the Sommerfeld number K which should typically be less than 57.6 in [Cedelle, Vardelle, Pateyron and Fauchais (2005)]. Thereby,

- Is it possible to avoid, even for a certain limit, the rebound and splashing phenomena?
- Can we target a Sommerfeld K value less than 57.6 ? assuming that the splashing phenomenon occurs for $K > 58$ as commonly known for liquid drops of water or ethanol [Escure, Vardelle and Fauchais (2003)].
- Can we optimize the spraying process by choosing the 'right' parameter levels, and thus reduce the number of inputs (energy, etc.) and improve the efficiency of outputs (cost, quality of the coat, etc.)?

These are challenging problems facing designers, which we illustrate in example for some operating conditions in thermal spraying.

2 Taguchi method vs. classic experiment design tool

In a context of improving production processes and product quality, new concepts and approaches emerge. This is particularly the tools of experimental design whose main objective is the search for parameters that characterize a product and the control parameters values of the production characteristics' means to obtain the desired performance [Alexis (1995)].

2.1 Classic method of experiments plans

Developed in the early twentieth century by Ronald Fisher and Jacques Hadamard, the experimental designs are used to pass from experimentation to quality assurance, and cost results. An experimental plan is a set of tests organized in advance to determine the least number of tests and the effects of control parameters of a system designed to optimize (maximize or minimize) a parameter output (product, productivity, product quality, etc.), by statistical analysis. Each factor (parameter) is represented by various levels in the matrix of experiences. An experiment with a full factorial design studies all possible combinations of factor levels tested. However, in an experiment using fractional factorial design we account only for the tests that provide the most effective information.

2.2 Taguchi experiment design

The Taguchi methodology intended to simplify the experimental formalities, in order to highlight the effects of factors on the response, and also enriches the methods of experiment designs providing a significant improvement by a structure of a test plan that studies separately the effect of essential variables (that have the preponderant effects on the response) and the effect of external variables (noise within Taguchi meaning).

The Taguchi method is characterized by a significant reduction in the number of tests while maintaining good accuracy. The technique places the model as a key element of the experimental design strategy. The experimenter chooses freely the factors and interactions to study, depending on the model he proposes, closely aligned with his objectives. The factor rank in Taguchi designing is important; it is chosen according to the difficulty of achieving factor in the experiment [Sabre (2007)].

The standard experimental designs seek to eliminate *noise factors*. The approach adopted by the idea of G. Taguchi is to seek a combination of factor levels that minimize or eliminate the *effects* of noise factors. In a context of quality improvement, there are three categories of quality characteristics, so that the Taguchi quality-loss-functions can be given as follows:

- Smaller-is-the-better: $L(y) = K\,y^2$
- Nominal-is-the-better: $L(y) = K\,(y - \bar{y})^2$
- Larger-is-the-better: $L(y) = K/\,y^2$

The superiority of the Taguchi concept is the introduction of the quality-loss function transformed afterward into utility function called Signal-to-Noise (S/N) ratio (called also 'figure of merit') that calculate the deviation between the experimental value and the desired value. The noise factors are causes of variability in performance and products fail by a deviation from target value (of a measurable product or process characteristic). Signal-to-Noise (S/N) ratio combines jointly:

- The desired value (the average $\bar{y}$), and
- The variability (dispersion) of this value, which is to combat (standard deviation, $s = \sigma_{n-1}$).

The desired measurable value may be:
Smaller-the-better: chosen in case of a criterion to minimize, the S/N ratio is written as:

$$\text{S/N}(dB) = -10\,\text{Log}_{10}(s^2 + \bar{y}^2)$$

Nominal-the-better: chosen when the goal is to target the response, the S/N ratio is written as:

- $\text{S/N}(dB) = 10\,\text{Log}_{10}\left[(\bar{y}/s)^2 - 1/n\right]$, for positive y values.
- $\text{S/N}(dB) = -10\,\text{Log}_{10}(s^2)$, for negative and positive y values.

Larger-the-better: chosen when the objective is to maximize the response, the S/N ratio is written as:

$$\text{S/N}(dB) = -10\,\text{Log}_{10}\left[(1/\bar{y}^2)(1 + 3\,s^2/\bar{y}^2)\right]$$

Where $s^2 = \sigma_{n-1}^2 = \sum (y_i - \bar{y})^2/(n-1)$ and $\bar{y} = \sum y_i/n$.
The performance is all the more-better when the algebraic value of the S/N(dB) ratio is the larger.

Besides, it was noted in [Fauchais (2004)] that in the case of d.c. arc plasma spraying, K values are generally between 80 and 2000; and that with alumina particles d.c. plasma sprayed, the calculated values of the number K vary between 50 and 1800 [Fridman and Cho (2007)]. It was found, also, in [Djebali, Pateyron and El Ganaoui (2013)] that based on the Sommerfeld number, the splashing phenomenon is found to be predominant, which is consistent with former experimental and numerical observations, which concluded that in plasma spraying process, the impact splashing behaviour is more the rule than the exception. Accordingly, and thought the Taguchi's classification, the present study comes under the category of being a "smaller-the better type problem" as much as possible.

3 Results and discussion

3.1 Analysis of the results using Taguchi experimental design

The primary gas used in this study is the $H_2Ar75\%$ vol, the sprayed powder material is the dense zirconia (ZrO_2). One chooses to test five factors of two levels (1: min and 2: max), namely the primary gas flow rate (A) ranging from 25 to 45 SL/min, the electric power (B) ranging from 15 to 25 kW, the spray distance (C) from 8 to 11 cm, the particle size (D) ranging from 35 to 75μm and finally the powder injection velocity (E) ranging from 0.765 to 1.53 *l*/min. The minimum temperature at the torch exit is 12000K and the injection point is chosen to be (5mm, -6mm). The plasma jet discharges in ambient air. Two interactions AB and AC are also considered and others interactions are assumed to be negligible. We assume that each factor level has a Gaussian-like dispersion.

Table 1: Parameters and their levels.

Controlled parameters	level 1	level 2	N°
Carrier gas flow rate (NL/min)	25	45	A
Electric Power (kW) (η=0.52)	15	25	B
Spraying distance (cm)	8	11	C
Powder size (μm)	35	75	D
Powder feed rate (NL/min)	0.765	1.53	E

For each particle treated separately, we calculated the Sommerfeld number K which characterizes the impact state of the particle/droplet on the substrate; and therefore, its contribution to coat formation. During the calculation step, each particle that will not contribute to the coat formation: being evaporated (EV) or does not penetrate into the plasma jet (deflection), crosses the jet, or it reaches the substrate in a solid state (SL), is supposed to bounce back; and therefore is assigned a default value of the Sommerfeld number $K<3$. The definition of factors and their levels are summarized in Table 1. Taguchi table adopted in this study is presented in Appendix A. The results of experiments carried out on the *Jets&Poudres* code [Pateyron, website] are presented in Table 2 and the computed effects of the factors levels on measured value $\bar{K}$ and the S/N (dB) ratio are presented in Table 3. Results of the main effects plots are presented in Figs. 3 and 4.

Table 2: Results of experiments: mean and Signal/Noise (dB) ratio.

Tests	Experiments					Avg.	S/N(dB)
n°	n°1	n°2	n°3	n°4	n°5		
1	370	376	375	435	399	391	-51.9
2	461	469	468	467	466	466	-53.4
3	525	503	352	523	544	489	-53.9
4	413	258	321	302	344	328	-50.4
5	449	450	460	444	418	444	-53.0
6	621	620	684	602	665	638	-56.1
7	209	366	241	260	267	269	-48.8
8	543	571	560	570	527	554	-54.9
9	519	490	451	552	484	499	-54.0
10	1	670	1	2	709	277	-53.4
11	420	446	424	443	427	432	-52.7
12	453	1	2	1	2	92	-46.9
13	762	640	765	806	746	744	-57.5
14	548	542	697	461	763	602	-55.8
15	697	723	700	752	695	713	-57.1
16	658	695	836	720	725	727	-57.3
Reponses averages						479	-54.0

According to Figures 1 and 2, one can state that the factor B (electric power) is very influential to combat dispersion when taken in level 1. The choice of level 1 of the factor B appears also to go in the right way of minimizing the measured value of the Sommerfeld number K. The same effect is also remarked for the factor A (primary gas flow rate), but with less contribution. Therefore, we select the factor level A_1. However, we note that there is a strong interaction between factors A and B (both for the measured value and the ratio S/N (dB)), and if one chooses level 1 for the two factors, interaction A_1B_1 could increase the measured value $\bar{K}$ and reduce the ratio S/N (dB). It would be better, therefore, to choose the combination A_2B_1. But, such a combination goes against experimental findings, indicating that the particles should impact the substrate in melt state (increase thermal power) and at moderate velocity. We finally recommend the combination A_1B_1.

We also note that the interaction A_1C_2 implies a favorable interaction to reduce (slightly) the dispersion effect by summing the effects of C_2 and interaction I_{A1C2} and, in addition, reduces the measured value $\bar{K}$which enhances the droplets deposition (coat formation). Factor D does not contribute significantly to the measured value $\bar{K}$; however, in its level D_2, it reduces slightly the dispersion characterized by the ratio S/N(dB). The same analysis given for the level D_2 plays for the level E_1 of the factor E (powder flow rate).

Table 3: Effects of process parameters and interactions.

Effect on measured value				Fac. n°	Effect on S/N(dB) ratio			
Level 1		Level 2			Level 1		Level 2	
-31.64		31.64		A	0.77		-0.77	
-107.36		107.36		B	1.48		-1.48	
28.61		-28.61		C	-0.81		0.81	
18.61		-18.61		D	-0.04		0.04	
-3.49		3.49		E	0.05		-0.05	
Interactions					Interactions			
I_{A1B1}	78.46	I_{A1C1}	8.89		I_{A1B1}	-1.09	I_{A1C1}	0.02
I_{A1B2}	-78.46	I_{A1C2}	-8.89		I_{A1B2}	1.09	I_{A1C2}	-0.02
I_{A2B1}	-78.46	I_{A2C1}	-8.89		I_{A2B1}	1.09	I_{A2C1}	-0.02
I_{A2B2}	78.46	I_{A2C2}	8.89		I_{A2B2}	-1.09	I_{A2C2}	0.02

3.2 Optimal parameter combination of Multi-Response

Finally, we assume that the combination retained is expressed as follows:

$$K=A_1.B_1.C_2.D_2.E_1.I_{A1B1}.I_{A1C2} \quad (1)$$

Such a combination gives a Sommerfeld value K= 470 + (-31.64) + (-107.36) +(-28.61) + (-18.61) + (-3.49) + (78.46) + (-8.89) = 358.95, this value may foster splashing phenomenon, considering as lower limit values K=57.6. It is worth to mention that in the case retained combination as $A_1.B_1.C_2.D_1.E_1.I_{A1B1}.I_{A1C2}$, the ratio S/N (dB) value is estimated to $\hat{\mu}$= -54+(0.77)+(1.48) +(0.81) +(0.04)+(0.05)+(-1.09)+(-0.02)= -51.52 dB. The Sommerfeld number value K can be obtained, therefore, within an estimated dispersion: $s = (10^{-\hat{\mu}/10} - \bar{y}^2)^{1/2} \approx 114$!

Such a dispersion value is surely unacceptable. However, we note that we just increase the estimated value $\hat{\mu}$ of the S/N(dB) ratio by just 0.4168 so that the dispersion be of the order of s=3.5. In this case, the sprayed powder arrives in state characterized by a number of estimated Sommerfeld value of 358.95 $\pm$ 3.5.

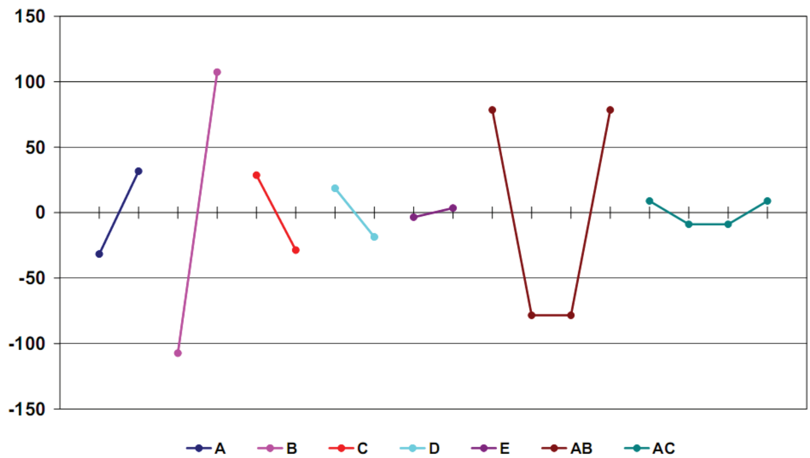

Figure 1: Plots of main effects on the average value of the Sommerfeld number $\bar{K}$.

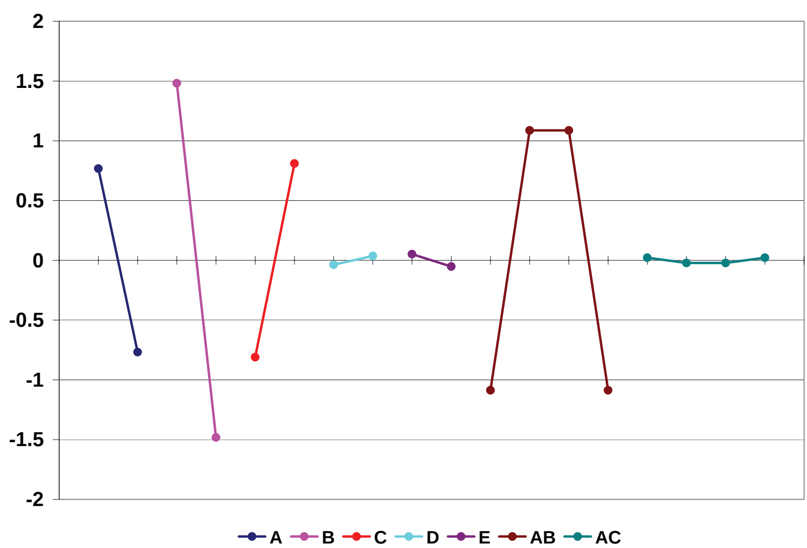

Figure 2: Plots of main effects on the Signal/Noise S/N (dB).

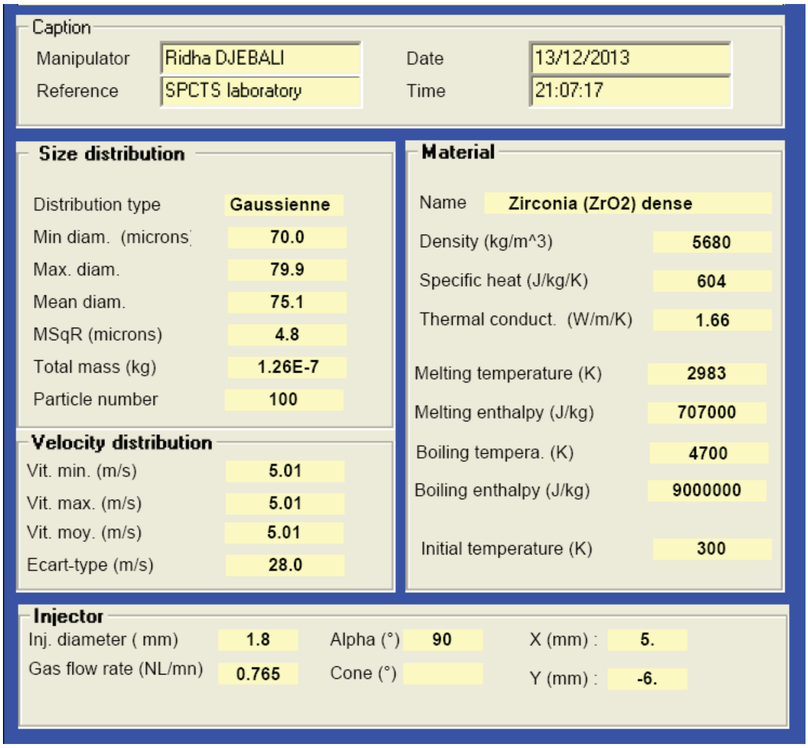

Figure 3: Parameters settings of confirmation test.

3.3 Confirmation test

The final step in the Taguchi technique, after identifying the most influential parameters, consists of conducting confirmation tests with optimum parameters settings of the retained combination, and then compares the S/N ratio at optimum conditions with the predicted range of S/N ratio values. A validation test of the combination K = $A_1.B_1.C_2.D_2.E_1.I_{A1B1}.I_{A1C2}$ retained in this study was, therefore, performed by the help of the code *Jets&Poudres* on a sample of 100 particles of size between 70 and 80 microns according to a Gaussian-like distribution (mean=75μm, σ=4μm), primary gas flow rate of 25 NL/min, electric power of 15 kW, a spraying distance of 11 cm, a torch exit temperature close to 12000K and the injection point is chosen to be (5mm, -6mm), as summarized in Figure 3. The results of the confirmation test are given in Figure 4. It is found that the predominant behavior is the splashing. However, the average value of Sommerfeld number K is 353 and the standard deviation is close to 3.46. This value of the Sommerfeld number is in very good agreement with the value predicted by Taguchi technique and scatterplot does not present large variability.

We note, also, that the combination $K = A_2.B_1.C_2.D_2.E_1.I_{A2B1}.I_{A2C2}$leads to a Sommerfeld number close to 283.08. However the estimated dispersion s is close to 203 which is not acceptable. A simulation corresponding to this combination using the code *Jets&Poudres* leads to the same conclusion. Indeed, among 100 tested particles, 27 have a Sommerfeld number around 420 and 73 have a Sommerfeld number of 0 (prior way to rebound), then an average of 114.37 and a standard deviation of 188.06. Therefore, increasing the primary gas flow rate implies that the particles arrive in solid state and can not take the heat required to melt. So, this combination should be rejected.

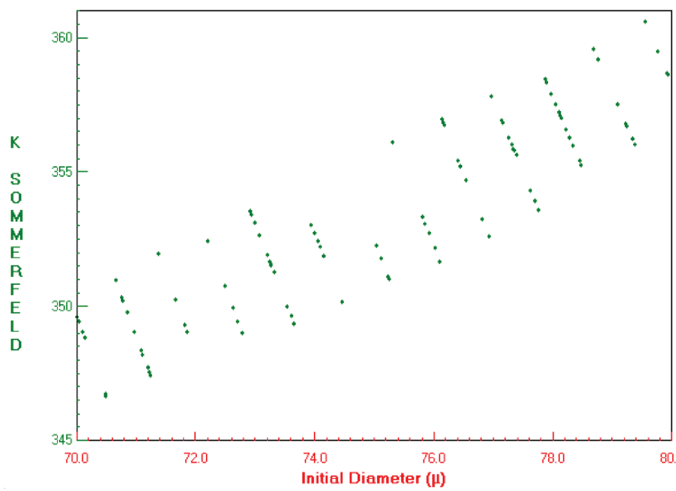

Figure 4: Scatterplot of the Sommerfeld number vs. initial particle diameter. Simulation made on the code *Jets&Poudres*.

4 Conclusions

In this paper, a study of the thermal spray process was conducted using the Taguchi method. We found that for the ranges of the parameters studied, the "thermal power" plays a key role on the state's projected powder and there is a strong interaction between the thermal power and the primary gas flow rate in determining the sprayed particles impact state. The dispersion of the studied parameters can influence the robustness of the desired result. The validation of the chosen levels combination using the code *Jets&Poudres* shows a satisfactory agreement in general point-of-view of molten particles behavior and variability of impact state measured using the Sommerfeld number K. We conclude through this study that the Taguchi experiment design method is a powerful tool for in obtaining the best setting of the process parameters with reduced experimental efforts.

Acknowledgement: The 'Fonds de dotation PERENNE' – Limoges, is thankfully acknowledged by first author for financial support.

Appendix A

Fractional matrix experiment according to Taguchi's L_{16} orthogonal array to test particle/droplet impact state.

Exp. n°:	Controlled factors					interactions	
	A	B	C	D	E	AB	AC
1	1	1	1	1	1	1	1
2	1	1	1	2	2	1	1
3	1	1	2	1	2	1	2
4	1	1	2	2	1	1	2
5	1	2	1	1	2	2	1
6	1	2	1	2	1	2	1
7	1	2	2	1	1	2	2
8	1	2	2	2	2	2	2
9	2	1	1	1	2	3	3
10	2	1	1	2	1	3	3
11	2	1	2	1	1	3	4
12	2	1	2	2	2	3	4
13	2	2	1	1	1	4	3
14	2	2	1	2	2	4	3
15	2	2	2	1	2	4	4
16	2	2	2	2	1	4	4

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