TẠP CHÍ KHOA HỌC VÀ CÔNG NGHỆ ĐẠI HỌC DUY TÂN
DTU Journal of Science and Technology 04(65) (2024) 49-59
TRƯỜNG ĐẠI HỌC DUY TÂN
DUY TAN UNIVERSITY

Influence of some parameters in atmospheric plasma spray on particle kinetics

Ảnh hưởng của một số thông số trong phun plasma khí quyển đến động học hạt

Vu Duong[a,b*], Le Hong Ky[c]
Vũ Dương[a,b*], Lê Hồng Kỳ[c]

[a]School of Engineering Technology, Duy Tan University, Da Nang, 550000, Vietnam
[a]Trường Công nghệ, Trường Đại học Duy Tân, Đà Nẵng, Việt Nam
[b]Institute of Research and Development, Duy Tan University, Da Nang, 550000, Vietnam
[b]Viện Nghiên cứu và Phát triển Công nghệ Cao, Trường Đại học Duy Tân, Đà Nẵng, Việt Nam
[c]Vinh Long University of Technological Education, Vinh Long, 890000, Vietnam
[c]Đại học Sư phạm Kỹ thuật Vĩnh Long, Vĩnh Long, Việt Nam

(Date of receiving article: 20/01/2024, date of completion of review: 19/02/2024, date of acceptance for posting: 02/03/2024)

Abstract

The study focuses on analyzing the impact of various plasma spraying factors, including plasma current, plasma voltage, and air flow rate, on particle velocity, given their crucial role in determining coating effectiveness. Notably, this research innovatively incorporates ordinary air as the plasma-generating gas and introduces a mathematical model that explains the adjustment of particle velocity. A newly derived regression function aids in optimizing the procedure for maximizing particle velocity. A thorough investigation validates the parameters' effectiveness, showing strong agreement between the mathematical model and experimental results. The introduction elucidates the necessity of this study, while the methodology section details the equipment, analytical instruments, and chemical composition of the 85Ni15Al powder. The experimental phase outlines a series of experiments, employing a multi-criteria planning design to assess the significance of each parameter effectively.

Keywords: particle velocity; atmospheric plasma spray; ordinary air; plasma generation gas; mathematical model; regression equation.

Tóm tắt

Nghiên cứu tập trung vào phân tích tác động của các yếu tố phun plasma khác nhau, bao gồm dòng plasma, điện áp plasma và tốc độ dòng khí, đối với vận tốc hạt, do vai trò quan trọng của chúng trong việc xác định hiệu quả của lớp phủ. Đáng chú ý, nghiên cứu này kết hợp một cách sáng tạo không khí thông thường như khí tạo ra plasma và giới thiệu một mô hình toán học giải thích sự điều chỉnh vận tốc hạt. Một hàm hồi quy mới có nguồn gốc hỗ trợ tối ưu hóa quy trình tối đa hóa vận tốc hạt. Một cuộc điều tra kỹ lưỡng xác nhận hiệu quả của các tham số, cho thấy sự thống nhất mạnh mẽ giữa mô hình toán học và kết quả thực nghiệm. Phần giới thiệu làm sáng tỏ sự cần thiết của nghiên cứu này, trong khi phần phương pháp luận nêu chi tiết thiết bị, dụng cụ phân tích và thành phần hóa học của bột 85Ni15Al. Giai đoạn thử nghiệm phác thảo một loạt các thí nghiệm, sử dụng thiết kế lập kế hoạch đa tiêu chí để đánh giá tầm quan trọng của từng tham số một cách hiệu quả.

Từ khóa: vận tốc hạt; phun plasma khí quyển; không khí thông thường; khí tạo plasma; mô hình toán học; phương trình hồi quy.

---

[*] *Corresponding Author:* Vu Duong
Email: duongvuaustralia@gmail.com

1. Introduction

The efficiency and productivity of atmospheric plasma spray (APS) are highly dependent on the mean temperature and velocity of the powder particle prior to impact with the substrate. Because the condition of the in-flight particle is very important, B. Guduri et al. offered their inquiry in depth to set up a stable and adaptable instrument for obtaining a consistent value [1]. In the experiment, the authors employed argon and hydrogen in a mixture with flow rates of 30–60 standard liters per minute (slm) and 0–15 slm; current (300–600 A); voltage (30–70 V); and a plasma torch diameter of 8 mm. The powder for spraying had a particle size of 30–100 m, but no mechanical composition or size distribution was given, despite the fact that particle size is important in this complicated operation. ANOVA analysis revealed that the current and flow rate of argon had a significant influence on particle velocity. Although the response functions have been adequately implemented, more study is required to create a robust controller.

The velocity of the particle takes precedence over temperature in the cold spray procedure. However, the spray distance and powder feed rate have a significant impact on particle velocity [2]. The researchers identified the threshold velocity of the particle, beyond which it may bond to the substrate surface and form the coating [3]. In any case, they do not present a quantitative relationship between particle velocity and some key technical characteristics. Because the critical velocity of the particle in spraying is thought to be a crucial element in bonding, the researchers in [4] studied particle behavior in the kinetic spraying of AlSi feedstock using the method Kurochkin et al. [5] developed to identify the critical velocity approaching 400 m/s. It's worth noting that the particle with a maximum velocity greater than the crucial one will not be stuck to the substrate since the adhesion energy is less than the rebound energy. In [6], a large number of supersonic plasma sprayings of ceramic powder (YZS) over the nickel-based superalloy GH 3030 are performed. They obtained a collection of data that included current, voltage, argon, hydrogen, feedstock feeding rate, spray distance, and velocity, but not the assessment and analysis of the parameters due to a lack of a regression relationship between them. From this vantage point, the optimum range of spraying settings to achieve maximum particle velocity and temperature is insufficient to persuade. In [7], an attempt was made to derive a new mathematical model that included particle and gas velocity, particle mass, gas density, particle diameter, and drag coefficient. They compared the experimental measurement using a dual-slit velocimeter to the 2-D axi-symmetric calculation of the flow through the nozzle and the 1D isentropic gas-dynamic equations computed for the identical nozzle shape. The particle size distribution caused a difference in the theoretical computation of particle velocity. The major discovery in their investigation is that particles with velocities greater than the critical velocity deposit, but bigger particles with lower velocities do not. The primary disadvantage of [8] is that the model based on Newton's second law does not address the technological parameters in spraying deposition, such as stream power and gas flow rate, which are more useful in process design. The most favorable results were obtained in [9] when the authors used regression analysis (RA) and response surface methodology (RSM) to evaluate the significance of four parameters: the Ar and H2 flow rates; the current and powder feed rates in the atmospheric plasma spray process; but the power of the plasma stream also depends on the voltage, and ordinary air for plasma generation could have a different impact. Based on the foregoing reasoning, the goal of this work is to develop a mathematical model for the theoretical prediction of particle velocity in plasma spraying using ordinary air as the plasma-generating gas, including key factors such as current, plasma torch voltage, and air flow rate. In contrast to prior papers on the subject, the particle material used to deposit the anti-friction layer is Ni85Al15 powder. The ANOVA approach aids in determining the importance of each parameter in the regression equation. The proposed model of particle velocity prediction dealing with velocity optimization in future investigations demonstrated a disparity of less than 5%.

2. Methodology of investigation

Atmospheric plasma spraying was utilized in our experiment (SG-100 TAFA-Praxair, USA). Ordinary air serves as the main gas, while nitrogen serves as the carrier gas. In [10] they described the chemical composition and process of producing Ni85Al15 powders. The particle size of the powders is determined using the Cilas-1090 [11] instrument. Table 1 shows the fractional distribution of powders.

Table 1. The fraction distribution of particle Ni85Al15

Code	Mean diameter µm	Particle size fraction, %							
		0 -1	1-1.5	1.5-2.0	12-16	32-48	48 -64	64- 96	96 -128
Ni85Al 15	64	7.5	8.9	4.1	-	-	72	4.2	3.2

In this case, the powder Ni85AL15 is a good material recommendation for high-temperature coatings. This superalloy had a high oxidation resistance in the temperature range of up to 1250 °C in the atmosphere. Especially the γ Ni_3Al intermetallic phase has a melting point of about 1400 °C, thermal stability up to melting, and an increased yield point in the temperature range of 800-900°C. This material can be a good recommendation as a protection coating for components operating in heavy conditions, such as jet nozzles, afterburners, and jet blades in aerospace engineering [12]. The significant benefit of spraying protective coating on the aero-engine is available via a reduction in degradation of 25% and 50% compared to the uncoated version [13]. It is interesting to note the efficiency of atmospheric plasma spraying (APS) over chemical vapor deposition (CVD) in the repair of the MIG-29 fighter engine due to the simplicity of the equipment and the significant reduction in production cost [14]. Scanning electron microscopy combined with energy dispersive spectroscopy (SEM/EDS, SM-6510LV, Japan) was used to examine the surface morphology of the coatings and the topography of metallic particles. SEM investigation revealed that the feedstock particles had an uneven shape.

The Shimadzu HPV high-speed camera is used to monitor the velocity of spraying particles [15]. The camera can be used in combination with available image analysis software. Thus, high-speed images can be subjected to numerical analysis by saving the recorded images in a common format and then loading them into commercially available image processing software. The recorded images can be saved in some common formats, such as AVI, BMP, JPEG, and TIFF. The camera is working in two modes: half-pixel mode (HP) and full-pixel mode (FP). Figure 1 depicts the plasma spraying system. The plasma-generation gas is ordinary air. The carrier gas is also ordinary air. Ordinary air is a molecular gas that must be dissociated before it can be ionized. This means that ordinary air has greater enthalpy and thermal conductivity than argon plasma. Consequently, the molecular gases consume much higher input energy to become partially ionized. Because it is made up of excited ions and unbound electrons, plasma may carry electricity. In plasma spraying, the plasma-produced gases often include one or more of the following: argon, hydrogen, nitrogen, and helium. Argon is commonly utilized as the main plasma gas because it is the easiest to generate plasma and is less aggressive for electrodes and feedstock. Secondary gases include nitrogen, hydrogen, and helium. The noble gases are argon and helium. Despite its cost savings and advantages in some specialized applications of thermal spray coatings, there has been nothing published on the use of common air as a main plasma gas. Nonetheless, with torch construction innovation and suitable spraying settings, ordinary air may be suggested for the wear-resistant coating of ceramic materials, particularly Fe-based amorphous alloys [16, 17]. Argon plasma offers several advantages, but it has a lower thermal conductivity and enthalpy than binary gases. Because molecular gases must breakdown before ionization, the enthalpy and thermal conductivity of ordinary air plasma are significantly larger than those of argon plasma. As a result, they take significantly more energy to get partly ionized. As a result, the greater the energy input, the greater the enthalpy, and the greater the thermal conductivity. This reasoning reminded me of the substitution of inert and noble gases for plasma spraying with ordinary air.

The following is a brief summary of how the system works: G1 is the power

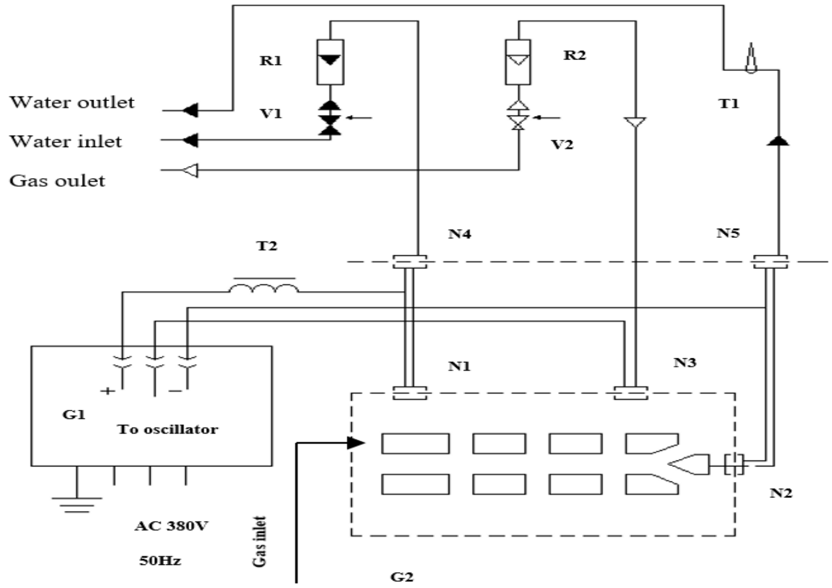

Figure 1. Plasma spraying system

G1 is the source; G2 is the plasma torch; R1 and R2 are rotameters; V1 and V2 are valves; N1, N2, N3, N4, and N5 are nipples; T1 is the thermometer; and T2 is the throttle. The power source is a direct current source with a steep volt-ampere slope, an idle voltage of 300 V, and a voltage adjustment range of 50–600 V. The plasma arc is created in a two-step process. Water is used as the coolant, with inlet and exit valves as well as the rotameter R1. The T1 thermometer is used to monitor temperature and give data for calculating plasma jet enthalpy. This rotameter has a precision of 2.5. The intake water flow pressure is 0.4–0.6 MPa. The primary and secondary gases are fed into the system via valve V2. The rotameter R2 determines the gas flow rate. T2 is used to smooth out the current pulsation.

3. Experiment & result

3.1. Regression equation and the analysis of the variation

Table 2 shows the results of a series of experiments with different input spraying settings and particle velocity measurements.

Table 2. Result of plasma spraying of the powder 85Ni15Al

No	Plasma current, I [A]	Potential, U [V]	Flow rate of air, G [g/s]	Particle velocity, V [m/s]
1	130	140	0.55	18
2	130	160	0.75	40
3	130	195	0.34	62
4	130	200	1.13	73
5	130	210	1.42	84
6	130	220	1.76	97
7	130	225	1.95	105
8	130	240	2.72	140
9	130	250	2.92	152
10	150	150	0.55	36
11	150	185	0.84	67
12	150	205	1.13	78
13	150	207	1.42	85
14	150	220	1.76	99
15	150	240	2.41	128
16	150	245	2.92	153
17	150	250	3.17	167
18	180	145	0.55	33
19	180	160	0.75	49
20	180	180	0.84	65
21	180	202	1.13	82
22	180	220	1.76	104
23	180	240	2.60	140
24	180	250	3.17	170
25	220	150	0.55	43
26	220	160	0.75	53
27	220	190	0.94	76
28	220	200	1.13	84
29	220	220	1.76	106
30	220	245	2.60	143
31	220	260	3.17	172

The experimental results have been processed (Table 3) using Minitab software and were preliminarily analyzed.

Table 3. First analysis of experimental results

Term	Coef	SE Coef	T-Value	P-Value
Constant	92.87	1.01	91.55	0.000
I	4.785	0.328	14.61	0.000
U	39.02	3.43	11.38	0.000
G	32.46	3.40	9.55	0.000
I^2	-1.547	0.383	-4.04	0.001
U^2	-30.33	4.19	-7.24	0.000
G^2	9.56	3.02	3.17	0.005
IU	-1.09	1.09	-1.00	0.329
IG	-0.75	1.12	-0.67	0.508
UG	27.81	7.81	3.56	0.002

It was discovered that several coefficients with p-values larger than the precision of a = 0.05, especially two-way interactions between I and U and I and G, were removed, and the experimental findings were reanalyzed (Table 4).

Table 4. Second analysis of experimental results

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	94.51	1.20	78.75	0.000	
I	4.856	0.317	15.31	0.000	1.27
U	35.01	4.32	8.10	0.000	144.33
G	36.59	4.27	8.57	0.000	168.78
I^2	-1.334	0.521	-2.56	0.017	1.10
U^2	-33.03	5.70	-5.79	0.000	73.59
G^2	10.65	4.15	2.57	0.017	40.48
UG	26.6	10.8	2.47	0.021	285.38

Analysis of the variance using the ANOVA method presented in Table 5. Subsequently, the regression equation in uncoded units is introduced in (1).

Table 5. Analysis of variance (ANOVA) from experiment

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	58310.8	8330.1	6000.79	0.000
Linear	3	55023.1	18341.0	13212.39	0.000
I	1	325.6	325.6	234.52	0.000
U	1	91.2	91.2	65.69	0.000
G	1	101.9	101.9	73.41	0.000
Square	3	394.0	131.3	94.61	0.000
I^2	1	9.1	9.1	6.57	0.017
U^2	1	46.6	46.6	33.58	0.000
G^2	1	9.1	9.1	6.59	0.017
2-Way Interaction	1	8.5	8.5	6.12	0.021
UG	1	8.5	8.5	6.12	0.021
Error	23	31.9	1.4		
Total	30	58342.8			

Regression Equation in Uncoded units:

$$V = -347.2 + 0.3385\,I + 3.703\,U - 55.5\,G - 0.000659\,I^2 - 0.00918\,U^2 + 5.32\,G^2 + 0.314\,UG \quad (1)$$

The analysis of the coefficients for the evaluation of the consistency of the regression equation (1) presented in Table 6:

Table 6. Analysis of the consistency

S	R^2	R^2 (adj)	R^2 (pred)
1.17821	99.95%	99.93%	99.82%

The suitability of the data was evaluated using a set of R^2, adjusted R^2, and predicted R^2 parameters. These values are all greater than 90%, indicating that the regression equation is perfectly compatible with the experimental data. The interaction plot (Figure.2) and Pareto chart (Figure. 3) reveal that the plasma current (I), plasma voltage (U), and air flow rate (G), including G^2 and U * G, are the factors that have the greatest influence on velocity (G). Other factors, such as I2 and U2, can be ignored.

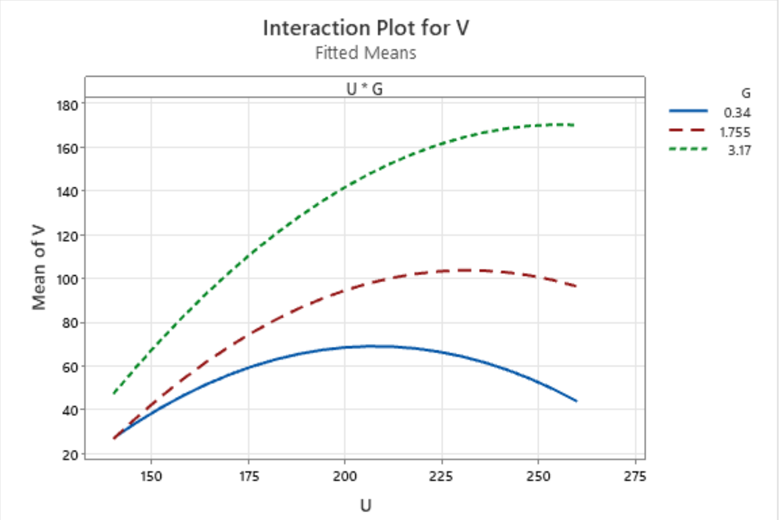

Figure 2. Interaction plot for particle velocity (V)

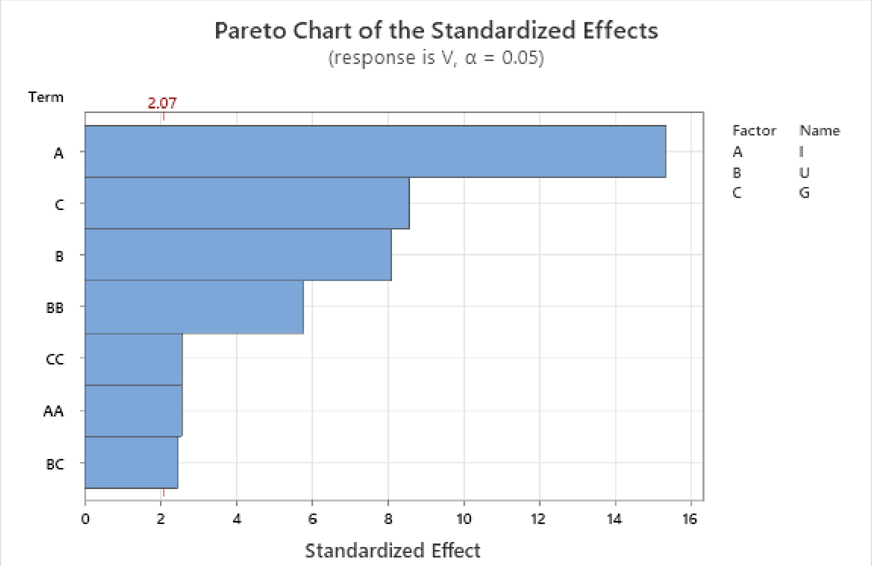

Figure 3. Pareto chart [18] for input parameters

This trend was also demonstrated by the normal plot (Figure. 4). As a result, the technical parameters I, U, and G are in the red. The large difference in the red line indicates that these factors have a considerable effect on the regression equation.

Figure 4. Standard distribution chart of the standardized effect parameters

3.2. *Preliminary optimization of the particle velocity*

It is useful to analyze the conditions for the localization of the optimum area for particle velocity because it provides good coating quality, such as density, adhesion, cohesion strength, and so on. Based on the experiment data, the following boundary conditions have been selected according to (2):

$$\begin{cases} 130 \le I \le 220 \\ 140 \le U \le 260 \quad (2) \\ 0.34 \le G \le 3.17 \end{cases}$$

The result of the preliminary optimization using the software Minitab, shown in Table 7

Table 7. Optimization solution

Solution	I	U	G	V Fit
1	220	256.364	3.17	174.014

In Figure. 5, it is expected that the current of plasma and the flow rate of the gas have a monotonous influence on the particle velocity, while the voltage of plasma specifies the extreme. It is useful to conduct a complete experiment in the future to make reliable findings dealing with this assumption.

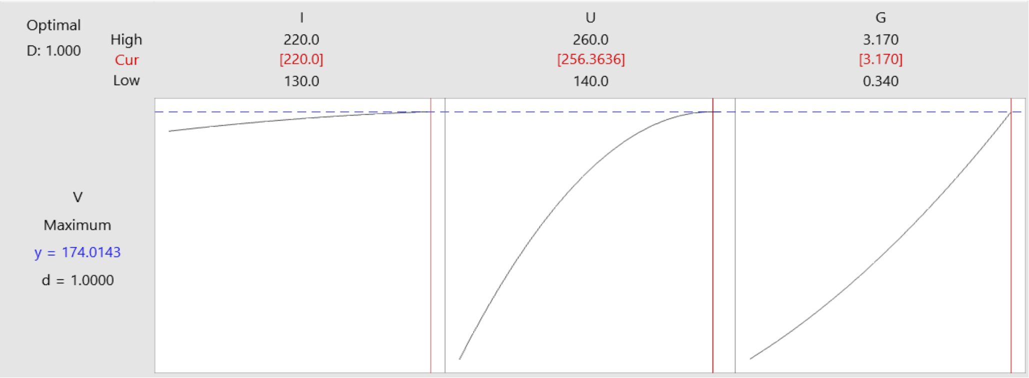

Figure 5. Result of preliminary optimization of velocity

The first preliminary localization of the optimum in the planning area: (see Figure .6)

$$I = 220$$
$$U = 256.36$$
$$G = 3.17$$

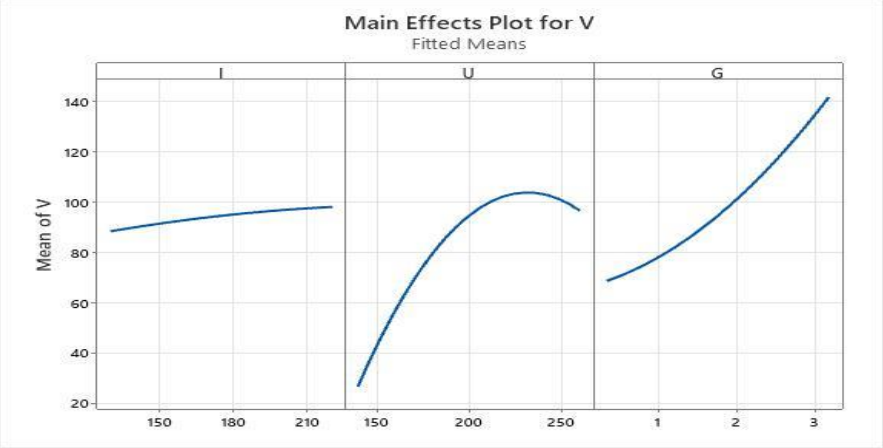

Figure 6. Main effects plot for V

4. Analysis & discussion

The voltage and current of plasma have different impacts on particle velocity, as shown by regression equation (1). The air flow rate also had a favorable impact on particle velocity. An increase in the electric current in plasma causes a rise in the number of electrons, which raises the amount of ionization and generates more heat. The expansion of gas is made easier, and the velocity of the plasma jet, which includes the particles, is supported by the greater temperature. The particle will experience significant drag forces due to the high plasma jet velocity, which will cause it to accelerate. However, it is important to keep in mind that the particle velocity is lower than the plasma jet velocity. For example, while plasma spraying alumina powder, the particle in-flight velocity rose by 70 m/s while the plasma jet velocity increased by 95 m/s [19]. The mechanical compression, energy density, and thermal conductivity of the plasma jet all increase as the gas flow rate rises, encouraging the plasma jet's velocity to accelerate more quickly. According to the dynamic phenomenon, an increase in gas flow rate contributes to a rise in the plasma stream's overall momentum, which raises particle velocity.

Since the mathematical model does not include a lot of variables, notably the size distribution [20], the issue of the size and density of the particle material as well as the fractional size distribution is still up for debate. However, in reality, no powder manufacturer offers a detailed specification on the size distribution. Size distribution and manufacturing costs are inextricably linked. In the future, it will be beneficial to conduct a number of experiments involving the plasma spraying of various powder materials to gather information on their mechanical and physical properties in order to enhance the approach for predicting the particle velocity in terms of optimization.

For the simplicity, all mathematical models assume that particles have a spherical shape. But in the production of the spraying particles, they can have different morphologies. This issue also contributes to some errors in the theoretical calculation of the velocity. To cover the gap between the theoretical prediction and the experiment, the empirical formula can be used as the predominant solution in the context.

5. Conclusion

The influence of some key parameters, such as plasma jet power, gas flow rate, and particle average size, on particle velocity is observed in atmospheric plasma spraying using ordinary air as the plasma generation gas. The increase in plasma power and the flow rate of gas elevates the in-flight velocity of the particles. The necessary condition for the deposition is the so-called critical velocity, and this value will determine the efficiency of the process. The increase in plasma power and the flow rate of gas elevates the in-flight velocity of the particles. The necessary condition for the deposition is the so-called critical velocity, and this value will determine the efficiency of the process. The presented mathematical model using the method of multi-criteria planning and design of experiments is well adapted to the experiment data and can be recommended to find the optimum particle velocity when some other related parameters will be involved, and a more complete planning experiment can be designed in a future study. In the future, it will be useful to make some corrections to the theoretical calculations of the particle velocity, taking into account the morphology of the particles and their size distribution.

Conflicts of interest

Authors identify and declare that they do not have any conflict of interest.

References

[1] B. Guduri., M. Cybulsky., G. R Pikrell. & R.C. Batra. (2021). "Adaptive process control for achieving consistent article's state in atmospheric plasma spray process" .*SN Applied Science, Springer Nature journal*, 3.294. https://10.1007/s42452-021-04296-y.

[2] Rong Gen Neo., Kaiqiang Wu., Sung Chyn Tan & Wei Zhou.(2022). "Effect of Spray Distance and Powder Feed Rate on Particle Velocity in Cold Spray Processes". *Metals* ,12, 75. https://doi.org/10.3390/met12010075.

[3] Francois Raletz., Michel Vardelle, & Guillaume Ezo'o.(2021). "Critical particle velocity under cold spray conditions" .*Surface & Coating Technology* , 201(5),1942-1947. Doi: 10.1016/j.surfcoat.2006.04.061.

[4] Jingwei Wu., Hongyuan Fang., Sanghoon Yoon., Changhee Lee, & HyungJun Kim.(2006). "Critical Velocities for High- Speed Particle Deposition in Kinetic Spraying". *Materials Transactions*, 47(7), 1723-1727. Doi: 10.2320/matertrans.47.1723.

[5] Y.V Kurochkin., Y.N Demin & S.I Soldatenknov. (2002). "Demonstration of the Method of Cold Gasdynamic Spraying of Coatings". *Chemical and Petroleum Engineering*, 38(3-4), 245- 248. https://link.springer.com/journal/10556/volumes-and-issues/38-3.

[6] Pei Wei., Zhengying Wei., Guanxi Zhao., Y Bai & Chao Tan.(2016). "Effect of Processing Parameters on Plasma Jet and In-Flight Particles Characters in Supersonic Plasma Spraying" .*High Temperature Materials and Processes* (SCIE/SSCI, IF =0.8), 35(8),775-786. Doi :10.1515/htmp-2015-0077. De Gruyter Publisher.

[7] Viktor K. Champagn., Dennis J.Helfritch., Syrya P.G. Dinavahi, & Phillip F. Leyman.(2010). "Theoretical and Experimental Particle Velocity in Cold Spray ". *Journal of Thermal Spray Technology*, 1059-9630/$1900 © ASM International. DOI:10.1007/s11666-010-9530-z.

[8] K.Bobzin., M.Oter., M.A. Knoch., I.Alkashli., U.Reisgen.,O.Mokrov,& O.Lysnyi.(2017). " Simulation of the Particle Melting Degree in Air Plasma Spraying " .*14th High-Tech Plasma Processes Conference, IOP Conf.Series: Journal of Physics: Conf Series* 825. 012002.

[9] R.C. Batra & Unchalisa Taetragool.(2020). "Numerical techniques to find optimal input parameters for achieving mean particles' temperature and axial velocity in atmospheric plasma spray process". *Scientific Reports,Nature Research*,10(1):21483. https://doi.org/10.1038/s41598-020-78424-w.

[10] D. Kotoban., S. Grigoriev. & I. Shishkovsky.(2014)." Study of 3D laser cladding for Ni85Al15 superalloy". *8th International Conference on Photonic Technologies LANE 2014, Physics Procedia* 56, 262-268. Doi:10.1016/j.phpro.2014.08.170.

[11] Duong Vu & Quy Le Thu.(2021). "The Correlation Between Main Parameters in the Air-Plasma Spraying of Fe-based Amorphous Coatings" .*The Proceedings of the International Conference on Advanced Mechanical Engineering, Automation and Sustainable Development* (AMAS 2021), November 04-07,2021, Ha Long city, Vietnam, Lecture Notes in Mechanical Engineering, Springer Publisher, 499-506. DOI: 10.1007/978-3-030-99666-6_72.

[12] Lezsek Ulanowicz., Andrzej Dudzinski., Pawel Szczepaniak. & Miroslaw Nowakowski.(2020)" .Applying Protective Coating on the Turbine Engine Turbine Blades by means of Plasma Spraying".

Journal of KONBiN,50(1), 193-213. DOI 10.2478/jok-2020-0012.

[13] Jasem Alqallaf & Joao A.Teixeira.(2022).” Quantifying the Economic Benefits of Using Erosion Protective Coatings in Low-Pressure Compressor (Aero-Engine): A Case Study Evaluation”. *Processes*, 10 (2),385. https://10.3390/pr10020385

[14] Andrzej Szczepankowski., Radoslaw Przysowa., Jerzy Perczynski. & Artur Kulaszka.(2022).” Health and Durability of Protective and Thermal Barrier Coatings Monitored in Service by Visual Inspection”. *Coatings,* 12,624. https://doi.org/10.3390/coatings12050624.

[15] N.A Buchman, C.Cierpka, C.J Kahler.(2014). “Ultra high speed 3D astigmatic particle tracking velocimetry: application to particle-laden supersonic impinging jets”. *Experiments in fluids,* 55:1842. Doi 10.1007/s00348-014-1842-1.

[16] Viktor Kuzmin, Igor Gulaev,Dmitriy Sergachev, Sergey Vashchenko, Anatoliy Lusakov & Boris Palagushkin.(2021).”Supersonic air-plasma spraying of carbide ceramic coatings”. *Materialstoday: Proceedings*,38(4),1974-1979. https://doi.org/10.1016/j.matpr.2020.09.150

[17] Viktor Kuzmin, Igor Gulyaev, Dmitriy Sergachev, Sergey Vaschenko, Elena Kornienko & Alexander Tokarev.(2017).” Equipment and technologies of air -plasma spraying of functional coatings”. *MATEC Web of conference*, 129, 01052. DOI: 10.1051/ matecconf/201712901052.

[18] Jiju Antony.(2014).” Design of Experiments for Engineers and Scientists”. *Second Edition, New York, Elsevier Publisher, MA* 02451, USA.

[19] Airingas Suopys.,Viktorija Grigaitiene., Liutauras Marcinauskas., Romualdas Kezelis., Rolandas Uscila & Mindaugas Aikas.(2022).” Influence of Plasma Torch Power on the Plasma Jet Properties and Microstructure of Alumina Coatings”. *Coatings*,12,934. https://doi.org/10.3390/coatings12070934.

[20] Yimin Deng., Raf Dewil ., Lise Appel., Huili Zhang., Shou Li, & Jan Baeyens.(2021).” The Need to Accurately Define and Measure the Properties of Particles”. *Standard*,1,19-38. https://doi.org/10.3390/standards1010004.