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MULTI-PARAMETER COUPLED OPTIMIZATION OF AL6061 COATING POROSITY BASED ON THE RESPONSE SURFACE METHOD

*The **objective of this study** is to study the multi-particle deposition process of cold spray through numerical simulation methods and to use multi-factor coupling to optimize the porosity of Al6061 coating to more accurately characterize the real cold spray deposition process. **This study aimed** to predict and optimize the porosity of Al6061 coatings using numerical simulation methods. The **tasks** to be solved are: to nest the multi-particle model established by the Python script in the CEL deposition model to simulate the cold spray deposition process. A multi-parameter function with particle temperature, substrate temperature, and particle velocity as independent variables and Al6061 coating porosity as dependent variables was established. The response surface analysis method was used to predict the optimal spraying parameters and coating porosity of Al6061 coating. The **methods** used are as follows: optimize the porosity of the coating through multi-factor coupling through response surface analysis; use a multi-particle model established through a Python script to be nested in the CEL deposition model to simulate the deposition process of cold-sprayed Al6061 multi-particles. To characterize the coating porosity more accurately, the average value of multiple groups of samples was taken as the final coating porosity value. **Conclusions.** the porosity value of Al6061 coating obtained by the prediction model is 1.969%; Under the influence of multi-factor coupling, particle velocity has the greatest impact on the porosity of the Al6061 coating, and substrate temperature has the least impact. Optimum spraying parameters: particle temperature 649.692K, substrate temperature 536.437K, and particle velocity 672.385m/s. Under the optimal spraying parameters, the porosity value of the Al6061 coating is 1.91875%; The error between the predicted value and the actual value obtained by numerical simulation is only 2.55%.*

Keywords: *Cold spraying; CEL; Multi-factor; Multi-particle; RSM; Porosity.*

1. Introduction

Cold spraying is a solid-state deposition technology, that is widely used in the field of additive manufacturing [1]. The pressurized gas in the nozzle accelerates the particles (1-50 um) to high speed (300-1200 m/s) [2]. The particles deposit on the substrate at high speed and deform to form a dense and high-quality coating [3, 4]. Adiabatic shear instability and local plastic flow are considered to be the main mechanisms of particle/substrate, particle/particle bonding [5, 6]. The formation of the coating can be seen as an iterative process, with repeated impact-deformation-adhesion between particles. In the cold spraying process, porosity is an important indicator. Porosity that is not easily controlled will cause the structure to be brittle, thus affecting the mechanical properties of the coating [7].

In cold spraying, particle/substrate, particle/particle contact occurs within tens of nanoseconds and follows highly transient nonlinear and dynamic rules [8]. Interactions during deposition are difficult to analysis experimentally, so numerical simulations are useful in helping to understand particle/substrate and particle/particle bonding mechanisms [9]. The CEL method simulates the process of multi-particle formation of coatings. The multi-particle deposition model is between the microscopic method of single particle simulation and the macroscopic method of homogeneous material deposition [10, 11]. The CEL method is proven to be more suitable for analysis large deformation problems that occur during cold spraying [8]. The method has higher accuracy and robustness than other finite element techniques in the range of large deformation, large displacement and large strain. Its advantage is that particles are wrapped in Eulerian domain, which avoids the need for remeshing and highly distorted elements; The CEL method tracks the material as it flows through the grid by calculating the Euler volume fraction in each cell. If the material completely fills the cell, its volume fraction is 1. If the material is not present in the element, its volume fraction is 0, the sum of the volume fractions of all materials in the unit is less than 1, then the rest of the unit will automatically be filled with void materials, which have no mass and strength [8]. There are two ways to check the porosity of

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the coating, one is obtained through experiments [12]. The other is obtained through numerical simulation [13]. The numerical simulation method is a reliable method for predicting coating porosity [14]; In order to get closer to the real cold spray process, multiple spray parameters are introduced to affect the porosity of the coating, and the coating under multi-factor coupling is obtained [15]. The method closest to the real coating porosity obtained through numerical simulation calculation.

At present, there are few results using numerical simulation methods to study coating porosity, especially the CEL method to simulate multi-particle deposition and optimize coating porosity through multi-parameters coupling. MacDonald [16] used the CEL method to study the thermal softening effect of single particle temperature. As the particle temperature increases, the particle flattening rate increases. The thickness of the coating is estimated by the flattening rate after particle deposit, which makes the prediction results very rough. Zahiri [17] used the CEL method to study the deposit of single Cu particles on the Al substrate. Increasing the particle temperature and speed can increase the density of the sprayed sample. This is only limited to studying the impact of a single factor of technical parameters on the porosity of the coating. It is inaccurate to use the CEL method to simulate single particle deposition with substrate to study coating porosity. Single particle deposition model cannot represent the interaction between coating accumulation, particle size, velocity and temperature [18, 19]. Therefore, simulating the multi-particle deposition process is more representative. The multi-particle deposition model is between the microscopic method of single particle simulation and the macroscopic method of homogeneous material deposition [17]. Multi-particle deposition models can be used to simulate complex interactions between multiple particles, which are beyond the reach of single-particle deposition model. Matteo [20] used the CEL method to simulate the spraying of multi-particle Ti-Al and Ti-Cu particles. By calculating the weight of the particles and the mass of the raw material particles, the corresponding volume percentage is calculated to predict the porosity of the coating. This is not a direct study of the porosity of the coating after deposition. Weiller [15] used the CEL method to simulate the deposition of multi-particle Al/Al2017. Studying the formation mechanism of porosity, it was concluded that interface porosity and stacking porosity have a great influence on the porosity of the coating. Interfacial porosity is caused by the arrangement between particles, and stacking porosity is caused by changes in particle density in gas flow; Randomly generated particles will lead to irrational distribution of particles in the Euler domain, thus affecting the final numerical result of porosity. Song [14] used the CEL method to simulate the deposition of multi-particle Ti6Al4V particles on the Ti6Al4V substrate to study the influence of a single factor on the porosity of the coating; The deposition process of cold spray is jointly affected by the coupling of multiple factors. Therefore, it is impossible to characterize the deposition process of cold spray particles by studying the coating porosity affected by a single factor. Therefore, a model of multi-factor coupling affecting coating porosity is established, which can more accurately characterize coating porosity; Finally, the coating porosity is optimized through a multi-parameter model; This makes the settlement results closer to the actual particle deposition process of cold spraying.

This article uses particle temperature, substrate temperature and particle velocity as independent variables, and the three variables interact with each other in pairs. Establish a linear regression equation model about the porosity of Al6061 coating through Design-Expert. The response surface analysis method was used to predict the optimal spraying parameters and coating porosity of Al6061 coating. Al6061 coating obtained through optimal spraying parameters predicted by numerical simulation. In order to obtain a more accurate coating porosity, multiple groups of sampling methods are used at the same height of the coating, and the average porosity of multiple groups of samples is calculated as the final result of the coating.

2. Experimental/Theoretical Details

The cold spray process is an extremely complex process, which includes the acceleration part of the particles by the cold spray device and the deposition part of the particles. The porosity of metal coatings has always been an important parameter to characterize the performance of the coating, and the pursuit of low porosity has always been the goal of scholars. There are often various factors that affect coating porosity; therefore, a method through numerical simulation is introduced to predict coating porosity; then the coating porosity is optimized through multi-factor coupling; finally, coating prediction for cold spraying is achieved is of great significance to optimization. In the multi-parameter optimization process, the RSM method has better accuracy than BP+GA optimization; this article uses the RSM optimization method. There are often various factors that affect coating porosity; therefore, it is very meaningful to introduce a method through numerical simulation to predict and optimize coating porosity. Tan [8] proposed that Al6061 particles form a coating during the deposition process. The temperature and velocity of Al6061 particles and the temperature of the substrate are important parameters that affect the porosity of the coating. Multi-factor coupling prediction and optimization of Al6061 coating porosity can better characterize real particles deposition process.

2.1. Experiment design

The three-factor and three-level BBD experimental design method was adopted, and the particle temperature, substrate temperature and particle velocity were selected as key test factors. The porosity of the Al6061 coating was used as the target, and -1, 0, and +1 respectively represented the numerical simulation factor levels. as shown in Table 1 for the design parameters.

Design-Expert DX10 data analysis software is used to process and analysis the numerical simulation results. The experimental arrangement and results are shown in Table 2.

2.2. Establishment of linear regression equation for porosity of Al6061 coating

The porosity regression equation of Al6061 coating is:

$$Y = 63.43 - 0.0104X_1 + 0.0227X_2 - 0.1757X_3 - \\ - 6.999X_1X_2 + 3.4X_1X_3 - 4X_2X_3 - 8.5X_1^2 - \\ - 1.45X_2^2 + 1.605X_3^2.$$

Table 3 shows the variance analysis of the porosity of Al6061 coating. It can be seen from Table 3 that the model $P < 0.0001$, and the model regression equation is significant. The correlation between the three factors and the experimental indicators is significant, the fitting degree is very good, and the error is small, indicating that the model is suitable for predicting the porosity of Al6061 coating.

2.3. The degree of influence of each test factor on the test indicators

The contribution rate of experimental factors to experimental indicators is shown in Table 4. According to the F Value, the contribution rate of the three influencing factors of particle temperature, substrate temperature and particle velocity to the porosity of the Al6061 coating can be judged. It shows that the particle speed has the greatest impact, followed by particle temperature, and the substrate temperature has the least impact.

Table 1

Design parameters

Level	Factors		
	T_p / K	T_s / K	V_p / m/s
	Particle temperature	Substrate temperature	Particle velocity
-1	600	500	585
0	650	550	635
1	700	600	685

Table 2

Simulation arrangement and results

Run	High and low level code			Actual value			Porosity %
	Particle temperature	Substrate temperature	Particle velocity	Particle temperature (K)	Substrate temperature (K)	Particle velocity (m/s)	
1	0	0	0	650	550	635	2.65
2	+1	-1	0	700	500	635	2.49
3	0	-1	-1	650	500	585	3.91
4	0	-1	+1	650	500	685	1.89
5	0	0	0	650	550	635	2.65
6	+1	0	+1	700	550	685	1.71
7	0	0	0	650	550	635	2.65
8	-1	-1	0	600	500	635	2.73
9	0	+1	-1	650	600	585	3.89
10	-1	0	+1	600	550	685	2.01
11	-1	0	-1	600	550	585	4.25
12	0	0	0	650	550	635	2.65
13	0	+1	+1	650	600	685	1.83
14	+1	+1	0	700	600	635	2.42
15	+1	0	-1	700	550	585	3.61
16	-1	+1	0	600	600	635	2.73
17	0	0	0	650	550	635	2.65

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Table 3

Variance analysis of the porosity of Al6061 coating

Source	Sum of Squares	df	Mean Square	F Value	P-Value, Prob>F
model	9.06	9	1.01	361.74	<0.0001
X_1	0.27	1	0.27	98.82	<0.0001
X_2	2.842e-3	1	2.842e-3	1.02	0.3458
X_3	8.35	1	8.35	3002.81	<0.0001
X_1X_2	1.225e-3	1	1.225e-3	0.44	0.5282
X_1X_3	0.029	1	0.029	10.39	0.0146
X_2X_3	4e-4	1	4e-4	0.14	0.7158
X_1^2	1.901e-3	1	1.901e-3	0.68	0.4357
X_2^2	5.533e-3	1	5.533e-3	1.99	0.2013
X_3^2	0.3	1	0.3	107.28	<0.0001
Residual	0.019	7	2.782e-3		
Lack of Fit	0.019	3	6.492e-3	2.37	
Pure Error	0	4	0		

3. Results and Discussion

Figure 1 show the interaction of three factors on the porosity of Al6061 coating. From Figure 1 and combined with the analysis of the contribution rate of experimental factors to experimental indicators in Table 4, it can be seen that the contribution rate of particle speed is more significant. Taking the Al6061 coating porosity as the target, the optimal Al6061 coating porosity is predicted to be 1.969%, as shown in Figure 2.

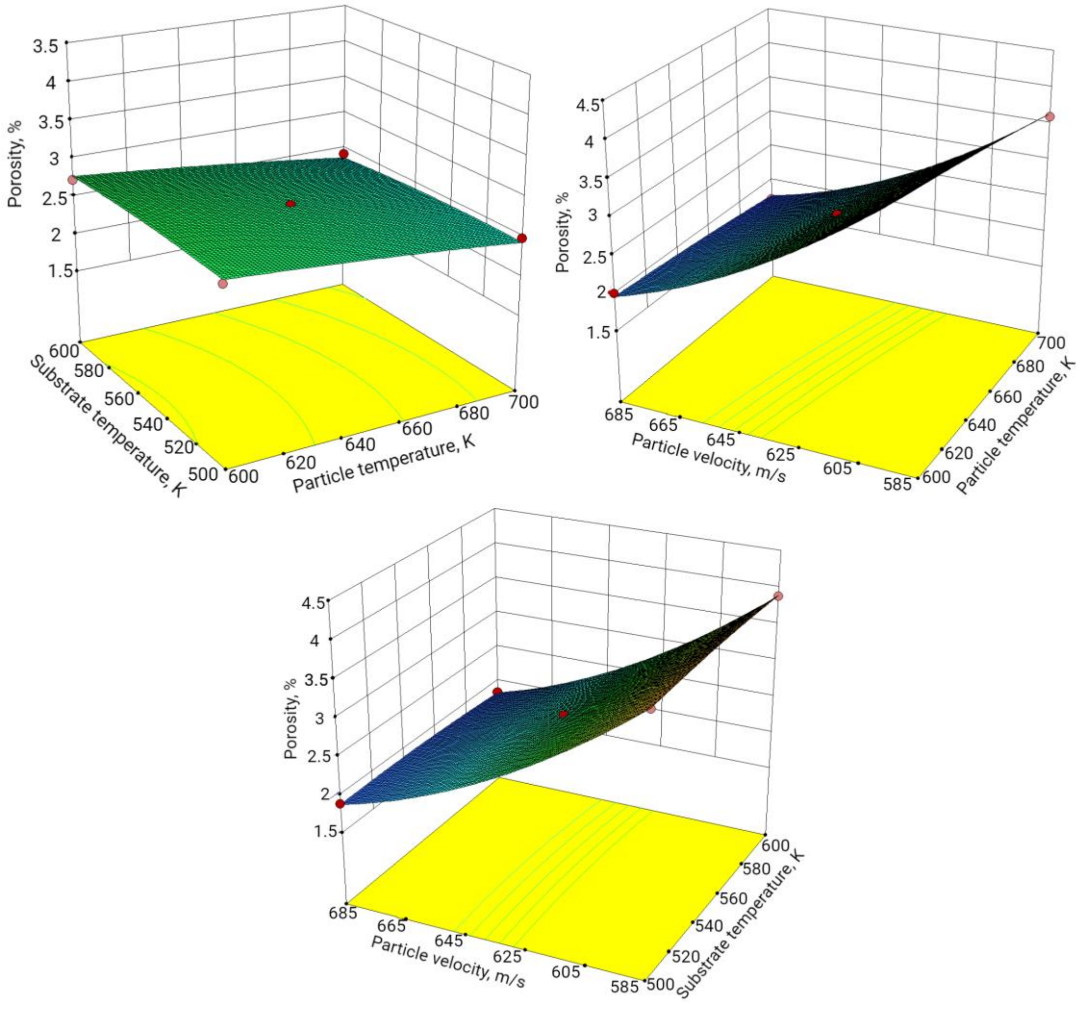

Fig. 1. The interaction of three factors on the porosity of Al6061 coating

Table 4

Contribution rate of experimental factors to experimental indicators

Test index	Contribution rate of experimental factors			Contribution ranking
	X_1	X_2	X_3	
Y	98.82	1.02	3002.81	$X_3>X_1>X_2$

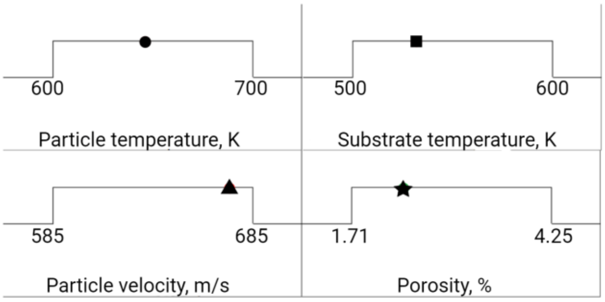

Fig. 2. Numerical simulation Al6061 coating porosity under optimal parameter conditions

Figure 3 show cross-sectional view of the Euler volume fraction voids of the Al6061 coating obtained with optimal spraying parameters. And select the samples at the same height in the middle area of the layer. Take the samples in the central area of the coating, and finally calculate the average value of the samples as the porosity of the final coating, which makes the result error smaller and more representative. As shown in Figure 4, there are 1-4 sets of porosity sampling cuboid sliced from the middle area of the coating; The size of each group of sampling cuboids: 20*20*10um. In order to characterize the porosity level more accurately, The sampling were used to calculate the average value of samples as the coating porosity. Figure 5 shows cross-sectional view of the Euler volume fraction voids after slicing each layer of the 1-4 groups of sampling cuboids. Through calculation, The porosity value of each layer in the samples 1-4 are shown in Figure 6, the average porosity of the 1-4 groups of sampling cuboids is 1.91875%.

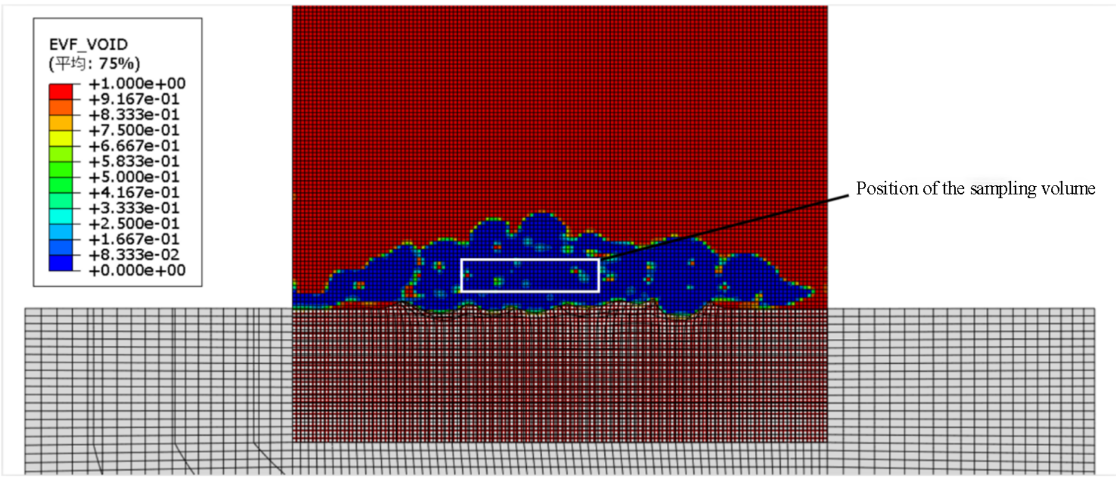

Fig. 3. Cross-sectional view of the Euler volume fraction voids of the Al6061 coating obtained with optimal spraying parameters

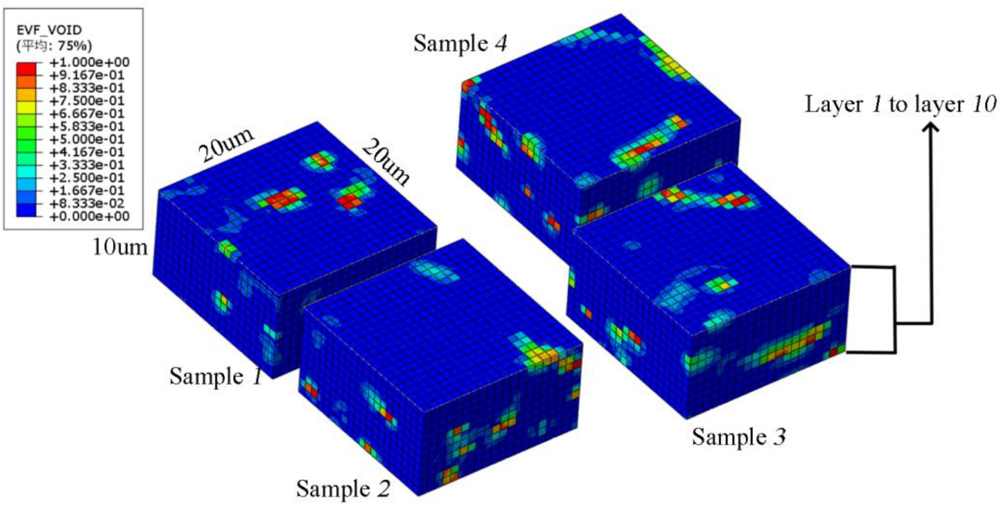

Fig. 4. The porosity value of each layer in the samples 1-4

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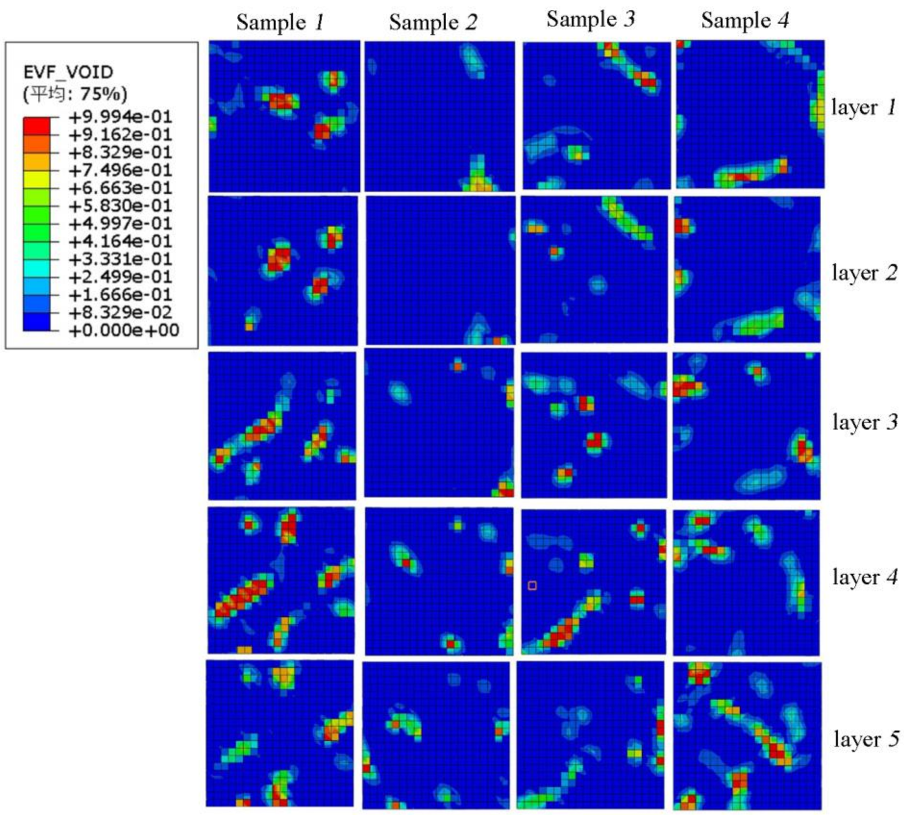
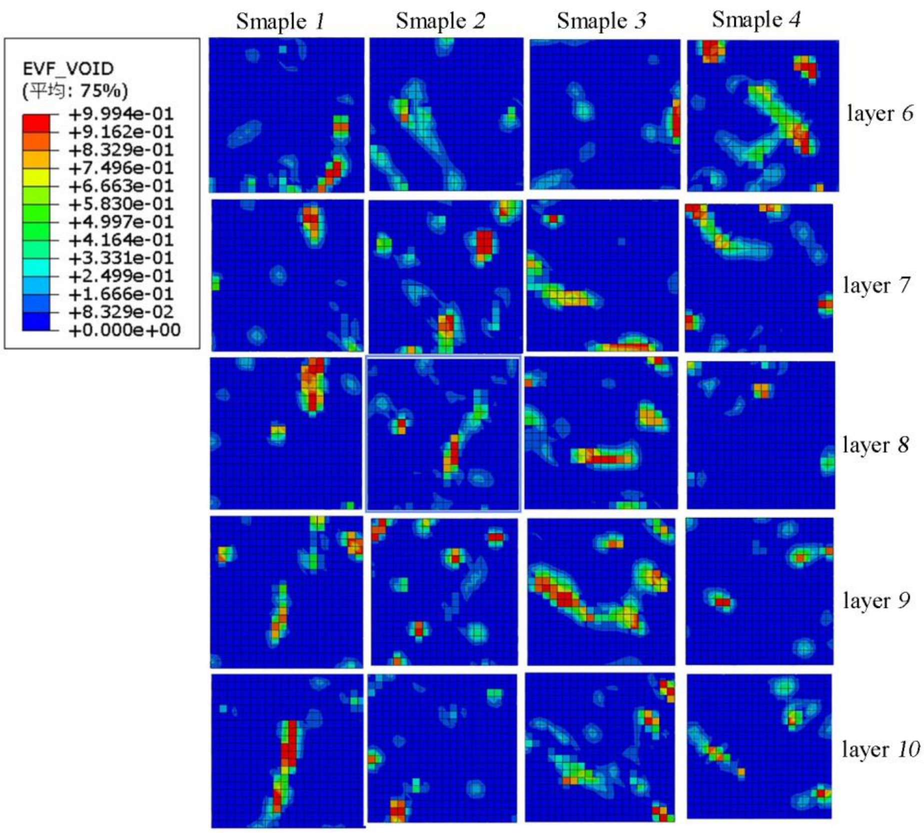


(a)



(b)

Fig. 5. Cross-sectional view of the Euler volume fraction voids after slicing each layer of the 1-4 groups of sampling cuboids; (a) layer 1-5; (b) layer 6-10

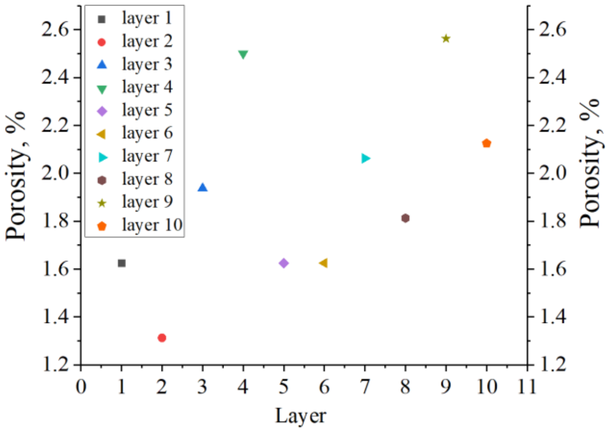


Fig. 6. The porosity value of each layer.

The optimal Al6061 coating porosity was obtained through response surface analysis method. Compare the predicted value with the actual simulated value. Table 5 shows the optimized parameter Al6061 coating porosity predicted value and actual value and error. It can be seen from the results that the error between the predicted value and the actual value of Al6061 coating porosity is only 2.55%; It shows that the regression equation about the porosity of Al6061 coating established through the response surface analysis method is reliable, and the simulation results can be effectively predicted through the regression equation.

4. Conclusions

This paper uses the CEL method to establish a multi-particle Al6061 deposition model, and studies the particle temperature, substrate temperature and particle velocity through response surface analysis method; The regression equation for the porosity of the Al6061 coating was established by pairwise interaction between the three variables, and the predicted value for the porosity of the Al6061 coating was 1.969%. From the multi-factor coupling image, it can be seen that the particle velocity has the greatest influence on the porosity of the Al6061 coating, followed by the particle temperature, and the smallest influence is the substrate temperature. Optimum spraying parameters: particle temperature 649.692K, substrate temperature 536.437K, particle velocity 672.385m/s. In the calculation process of the porosity of the Al6061 coating, multiple groups of samples were used to take the average, and the porosity value of the Al6061 coating under the optimal spraying parameters was obtained as 1.91875%; The error between the predicted value and the actual value obtained through numerical simulation is only 2.55%.

It is recommended that in future numerical simulation works, shot peening technology be introduced to improve the porosity of the coating; multi-particle models of two spray materials are established through Python scripts and embedded into the CEL deposition model.

Contribution of authors: conceptualization – **Kun Tan, Wenjie Hu; Oleksandr Shorinov; Yurong Wang;** Material parameter model – **Yurong Wang;** Multi-particle model – **Oleksandr Shorinov;** Multi-particle deposition model – **Kun Tan, Wenjie Hu;** Numerical simulation work – **Kun Tan;** analysis of results – **Kun Tan.**

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, author ship or otherwise, that could affect the research and its results presented in this paper.

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Data Availability

The work has associated data in the data repository.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

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All the authors have read and agreed to the published version of this manuscript.

Table 5

Optimized parameter Al6061 coating porosity predicted value and actual value and error

Parameters	Factor			Predicted value	Actual value	Error
	Particle temperature, K	Substrate temperature, K	Particle velocity, m/s	P_e , %	P_s , %	δ , %
Value	649.692	536.437	672.385	1.969	1.91875	2.55

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References

1. Vaz, R. F., Garfias, A., Albaladejo, V., Sanchez, J., & Cano, I. G. A Review of Advances in Cold Spray Additive Manufacturing. *Coatings*, 2023, vol. 13, no. 2. article no. 267. DOI: 10.3390/coatings13020267.

2. Zhang, Z., Li, W., Yang, J., & Huang, C. Prediction of deformation characteristics and critical velocities during cold-spray: A new 3D model. *Surface and Coatings Technology*, 2024, vol. 478, article no. 130492. DOI: 10.1016/j.surfcoat.2024.130492.

3. Sample, C. M., Spangenberger, A. G., Champagne, V. K., & Lados, D. A. Mechanical properties and growth mechanisms of long and small fatigue cracks in as-deposited bulk cold spray Al-6061. *International Journal of Fatigue*, 2024, vol. 181, article no. 108152. DOI: 10.1016/j.ijfatigue.2024.108152.

4. Shorinov, O., Dolmatov, A., & Polyvian, S. The effect of process temperature and powder composition on microstructure and mechanical characteristics of low-pressure cold spraying aluminum-based coatings. *Materials Research Express*, 2023, vol. 10, no. 2, article no. 026401. DOI: 10.1088/2053-1591/acb6f0.

5. Adaan-Nyiak, M. A., & Tiamiyu, A. A. Recent advances on bonding mechanism in cold spray process: A review of single-particle impact methods. *Journal of Materials Research*, 2023, vol. 38, no. 1, pp. 69-95. DOI: 10.1557/s43578-022-00764-2.

6. Yang, X., Meng, T., Su, Y., Chai, X., Guo, Z., Yin, S., Ma, T., & Li, W. Evolution of microstructure and mechanical properties of cold spray additive manufactured aluminum deposit on copper substrate. *Materials Science and Engineering: A*, 2024, vol. 891, article no. 146024. DOI: 10.1016/j.msea.2023.146024.

7. Nault, I. M., Ellingsen, M., & Nardi, A. Prediction of Geometry-Induced Porosity in Cold Spray Additive Manufacturing of Leading Edges. *Journal of Thermal Spray Technology*, 2024, vol. 33, pp. 839-857. DOI: 10.1007/s11666-024-01730-6.

8. Tan, K., Hu, W., Shorinov, O., & Wang, Y. Simulating multi-particle deposition based on CEL method: studing the effects of particle and substrate temperature on deposition. *Aerospace Technic and Technology*, 2024, vol. 1, no. 193. pp.64-75. DOI: 10.32620/aktt.2024.1.06.

9. Vinay, G., Halder, S., Kant, R., & Singh, H. Examining the contribution of tamping effect on inter-splat bonding during cold spray. *Materials Science and Engineering: A*, 2024, vol. 893, article no. 146112. DOI: 10.1016/j.msea.2024.146112.

10. Weiller, S., & Delloro, F. A numerical study of pore formation mechanisms in aluminium cold spray coatings. *Additive Manufacturing*, 2022, vol. 60, iss. Part A, article no. 103193. DOI: 10.1016/j.addma.2022.103193.

11. Han, X., Li, C., Li, S., & Chen, X. Correlation study of random deposition for WC–12Co multiparticles on the TC18 substrates. *International Journal of Applied Ceramic Technology*, 2024, vol. 21, iss. 3, pp. 1700-1721. DOI: 10.1111/ijac.14695.

12. Unnikrishnakurup, S., Zhang, Z., Seng, D. H. L., Zhang, Z. Q., Pan, J., Kumar, V., & Ngo, A. Exploring thermal dynamics and porosity of cold-sprayed Ti-6Al-4V coatings on Al6061-T6 substrates: A pulsed thermography and numerical modeling approach. *International Journal of Thermal Sciences*, 2024, vol. 196, article no. 108732. DOI: 10.1016/j.ijthermalsci.2023.108732.

13. Ashokkumar, M., Thirumalaikumarasamy, D., Sonar, T., Vignesh, P., & Deepak, S. Optimization of cold spray coating parameters using RSM for reducing the porosity level of AA2024/Al2O3 coating on AZ31B magnesium alloy. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 2023, pp. 1-15. DOI: 10.1007/s12008-023-01597-x.

14. Song, X., Ng, K. L., Chea, J. M. K., Sun, W., Tan, A. W. Y., Zhai, W., & Liu, E. Coupled Eulerian-Lagrangian (CEL) simulation of multiple particle impact during Metal Cold Spray process for coating porosity prediction. *Surface and Coatings Technology*, 2020, vol. 385, article no. 125433. DOI: 10.1016/j.surfcoat.2020.125433.

15. Weiller, S., Delloro, F., Lomonaco, P., Jeandin, M., & Garion, C. A finite elements study on porosity creation mechanisms in cold sprayed coatings. *Key Engineering Materials*, 2019, vol. 813, pp. 358-363. DOI: 10.4028/www.scientific.net/KEM.813.358.

16. MacDonald, D., Fernández, R., Delloro, F., & Jodoin, B. Cold spraying of armstrong process titanium powder for additive manufacturing. *Journal of thermal spray technology*, 2017, vol. 26, pp. 598-609. DOI: 10.1007/s11666-016-0489-2.

17. Zahiri, S. H., Fraser, D., Gulizia, S., & Jahedi, M. Effect of processing conditions on porosity formation in cold gas dynamic spraying of copper. *Journal of thermal spray technology*, 2006, vol. 15, pp. 422-430. DOI: 10.1361/105996306X124437.

18. Farid, M. H., McDonald A., & Hogan, J. D. Impact Deposition Behavior of Al/B4C Cold-Sprayed Composite Coatings: Understanding the Role of Porosity on Particle Retention. *Materials*, 2023, vol. 16, no. 6. article no. 2525. DOI: 10.3390/ma16062525.

19. Indu Kumar, K. K., Patel, M. B., Boese, S., Gouldstone, A., Champagne Jr, V. K., & Özdemir, O. Ç. Quantitative Nondestructive Evaluation of Cold Spray Manufactured Aluminum Alloy 6061 and Copper Samples. *Journal of Thermal Spray Technology*, 2023, vol. 33, pp. 688-704. DOI: 10.1007/s11666-024-01738-y.

20. Terrone, M., Lordejani, A. A., Kondas, J., & Bagherifard, S. A numerical Approach to design and develop freestanding porous structures through cold spray multi-material deposition. *Surface and Coatings Technology*, 2021, vol. 421, article no. 127423. DOI: 10.1016/j.surfcoat.2021.127423.

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БАГАТОПАРАМЕТРИЧНА ЗВ'ЯЗАНА ОПТИМІЗАЦІЯ ПОРИСТОСТІ ПОКРИТТЯ AL6061 НА ОСНОВІ МЕТОДУ ПОВЕРХНІ ВІДГУКУ

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Предметом статті є вивчення процесу осадження багатьох частинок холодним розпиленням за допомогою методів чисельного моделювання та використання багатофакторного зв'язку для оптимізації пористості покриття Al6061, щоб більш точно охарактеризувати реальний процес осадження холодним розпиленням. **Метою** є прогнозування та оптимізація пористості покриттів Al6061 за допомогою методів чисельного моделювання. **Завдання**, які необхідно вирішити: вкласти багаточастинкову модель, створену скриптом Python, у модель осадження CEL для імітації процесу осадження холодним розпиленням. Було встановлено багатопараметричну функцію з температурою частинок, температурою підкладки та швидкістю частинок як незалежними змінними та пористістю покриття Al6061 як залежними змінними. Метод аналізу поверхні відгуку використовувався для прогнозування оптимальних параметрів напилення та пористості покриття Al6061. Використовувані **методи**: оптимізація пористості покриття за допомогою багатофакторного зв'язку через аналіз поверхні відгуку; використовуйте багаточастинкову модель, створену за допомогою сценарію Python, яка буде вкладена в модель осадження CEL, щоб імітувати процес осадження холодним напиленням багатьох частинок Al6061. Щоб більш точно охарактеризувати пористість покриття, за остаточне значення пористості покриття було прийнято середнє значення кількох груп зразків. **Висновки**. значення пористості покриття Al6061, отримане за моделлю прогнозування, становить 1,969%; Під впливом багатофакторного зв'язку найбільший вплив на пористість покриття Al6061 має швидкість частинок, а найменший – температура підкладки. Оптимальні параметри розпилення: температура частинок 649,692 К, температура основи 536,437 К, швидкість частинок 672,385 м/с. При оптимальних параметрах напилення значення пористості покриття Al6061 становить 1,91875%; Похибка між прогнозованим значенням і фактичним значенням, отриманим чисельним моделюванням, становить лише 2,55%.

Ключові слова: Холодне напилення; CEL; багатофакторне; багаточастинкове; RSM; пористість.

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