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Optimization of Process Parameters for Electrostatic Rotary Bell Spraying Based on Response Surface Methodology

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Abstract

The electrostatic rotary bell (ESRB) sprayer is widely used in the coating industry due to its ability to achieve uniform film thickness and reasonable paint transfer efficiency. However the efficiency of paint transfer and spraying coverage in ESRB systems remain highly sensitive to process parameters. Therefore, optimizing these parameters is essential to reducing paint consumption, energy use, and environmental impact. In this study, a simulation model of the ESRB spraying process was established using ANSYS/Fluent. The spraying flow field, paint deposition profile, and film thickness distribution were validated through the experiment. Based on a single-factor test and the Box–Behnken response surface method, a multi-parameter optimization framework was designed to investigate the effects of six spraying process parameters, including inner and outer shaping air flow rate, bell rotational speed, applied voltage, target distance, and paint flow rate, on coating pattern width and paint transfer efficiency. Based on the Z-score standardization, a mathematical model of the comprehensive score with six factors was established to evaluate spraying efficiency and paint transfer efficiency and predict optimal spraying process parameters. The results indicate that voltage and spray distance are significant factors affecting the comprehensive score, with the order of influence being voltage > spray distance. The optimal parameters were as follows: bell rotational speed X1, 40 kr/min; inner shaping air flow rate X2, 196 sl/min; outer shaping air flow rate X3, 298 sl/min; paint flow rate X4, 249 cc/min; applied voltage X5, 52 kV; and target distance X6, 154 mm. Validation tests showed deviation between the predicted comprehensive score and the actual value from simulation and experiment were 2.03% and 1.36%, respectively. These results demonstrate that the proposed optimization model has high reliability and can be used to optimize spraying process parameters.

Keywords: electrostatic rotary bell spraying; response surface methodology; process parameters; coating spray width; paint transfer efficiency; Z-score standardization



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1. Introduction

The coating process accounts for 30%–50% of the total production costs in automotive manufacturing, primarily due to expenses associated with facilities and materials, such as painting and drying systems and heating, ventilation, and air conditioning (HVAC) operations, as well as volatile organic compound (VOC) removal systems [1]. Hence, finding ways to reduce these costs has been a long-standing focus of both the automotive industry and researchers. Paint transfer efficiency (TE) is defined as the ratio of the mass of paint deposited on the workpiece surface to the total mass of paint supplied to the atomizer. In general, low TE is an economic burden, an environmental concern, and a health concern

for workers. Although TE of electrostatic rotary bell (ESRB) spraying can reach up to 80%, a portion of the paint is still lost to the atmosphere as overspray [2]. This overspray contains hazardous substances such as VOCs, which not only pose serious risks to the occupational health of operators but also contribute significantly to atmospheric pollution [3]. Spraying coverage efficiency (SCE) refers to the area effectively covered by the paint per unit time, usually expressed by the width of the coating pattern (coatings pattern width, CPW). A larger coating pattern width indicates a broader effective coverage area per single spraying pass. Common automotive paint sprayers include conventional air, airless, high-volume low-pressure (HVLP), air-assisted airless, and high-speed rotary atomizers, all of which can potentially be coupled with electrostatic capacity. Among these, ESRB is the predominant industrial spraying technology, owing to its superior atomization quality and operational efficiency [4].

During past decades, some numerical and experimental work has been conducted on the spray painting process in ESRB sprayers, but this has primarily focused on the electrical charge process, droplet size, droplet disintegration, transport, or mapping procedure [5,6]. Ye et al. [7] carried out numerical simulations of the spraying process using an ESRB sprayer with internal charging, focusing on the effects of droplet charge on coating deposition. Their study found that the droplet size-to-charge ratio plays an important role in spraying performance. Chen et al. [8] investigated the near-nozzle atomization characteristics in air-assisted spraying using a novel three-dimensional transient model that couples the volume of fluid (VOF) and discrete phase model (DPM) methods. The numerical results were experimentally validated through droplet distribution measurements (using a Malvern analyzer) and coating thickness profiles. The study revealed that surface tension plays a dual role by inhibiting droplet atomization while simultaneously extending the ligament breakup length.

Poozesh [9] summarized current issues in automotive painting and the influential parameters for spraying applicators, and discussed several problems associated with evaluating and improving paint transfer efficiency. Zhang et al. [10] investigated the paint film thickness distribution characteristics on curved surfaces to elucidate the relationship among target surface curvature, electrostatic field, and flow field distribution. The spray coating process on conical surfaces with varying curvatures was simulated using ANSYS/Fluent. The results demonstrated that as the curvature increases, the airflow velocity rises, leading to greater spreading of the spray flow field, which results in reduced paint film thickness and decreased transfer efficiency. Pendar and Pascoa [11] investigated the fundamental flow behavior around the ESRB sprayers, with particular emphasis on the role of the applied electric field. Their findings demonstrate that paint transfer efficiency is positively impacted by applied voltage. However, the effects of other critical process parameters, such as target distance, bell rotational speed, fluid flow rate, and shaping air velocity, on transfer efficiency remain unquantified and have not been systematically studied.

Guettler et al. [12] proposed a framework that integrates experimental input data, an injection model, and a metamodel-based optimization to specify the initial conditions of the discrete phase. These conditions critically influence both the resulting paint deposition thickness distribution and the total amount of paint transferred to the workpiece. Their study further revealed that optimizing injection model parameters, such as the initial axial velocity and the Rayleigh limit coefficient, can improve the simulated coating transfer efficiency. Toljic et al. [13] compared different charge to mass ratio values for various droplet sizes and examined their influence on the particle movement trajectory and distribution. Their results showed that these factors had a remarkable impact on the paint film thickness. They concluded that increasing the droplet surface charge value by up to 1 mC/kg produced a significant improvement in paint transfer efficiency. Amine Benmoussa et al. [14] used

OpenFOAM to simulate electrostatic spraying using a rotary bell sprayer equipped with a high-voltage control ring conductor. Their study concluded that applying pulsed voltage to the sprayer's body cup at varying frequencies reshapes the spray plume, narrows droplet size distribution, and improves uniformity, enhancing transfer efficiency. Nevertheless, the sprayer with a high-voltage control ring remains at the laboratory research stage and has not yet been implemented in industrial production.

In summary, several studies have been conducted to examine how ESRB spray process parameters influence the flow field, electric field, and droplet size distribution during electrostatic rotary bell spraying, as well as their effects on coating deposition patterns and paint transfer efficiency. However, most of these studies have focused on the effects of individual process parameters on the spraying process, coating distribution, and paint transfer efficiency. In practice, the ESRB spraying process involves strong coupling between flow field and electrostatic field, wherein coating deposition is governed by the interactions of multiple spray parameters. This study develops a multi-parameter optimization framework for ESRB spraying to improve paint transfer efficiency and spraying coverage efficiency. The framework integrates six key spraying process parameters, including inner and outer shaping air flow rates, paint flow rate, target distance, bell rotational speed, and applied voltage, and quantifies their coupled effects on coating pattern width and transfer efficiency.

The optimal combination of multi spraying parameters constitutes a typical multi-factor, multi-level factorial study. Orthogonal experimental design (OED), central composite design (CCD), and Box–Behnken design (BBD) are three commonly used factorial experimental design methods [15]. These methods establish a model relating input variables to response variables, enabling not only the evaluation of interactions among parameters but also the continuous analysis across experimental levels during the optimization of experimental conditions. Compared to CCD with the same number of factors, BBD generally requires fewer design points and thus incurs lower operating costs [16]. Therefore, this study adopts the BBD response surface method for multi-parameter collaborative optimization.

2. Numerical Methods for the Electrostatic Rotary Bell Spraying Process

2.1. Electrostatic Rotary Bell Spray Model and Boundary Condition

In the electrostatic rotary bell spraying process, paint droplets are generated by centrifugal force atomization. These droplets are then charged to the same potential polarity as the spray gun, via either induction or corona charging methods, and are propelled toward the grounded target surface under the combined influence of electrostatic forces and shaping air drag. To investigate the effects of various spray process parameters on spraying coverage efficiency and paint transfer efficiency, an electrostatic rotary bell spraying process model needed to be constructed.

An ERBS with a 64 mm bell cup and a direct charging mechanism was selected, as shown in Figure 1a. The shaping air ring consists of 37 outer and 37 inner shaping air nozzles, hereinafter referred to as SAout and SAin, respectively. The outer and inner shaping air nozzles feature different axial angles, enabling the painting of complex target [17]. The computational domain, as shown in Figure 1b, is a cylinder with a diameter of 600 mm and a height of 300 mm, which fully encloses the spray gun and the target. The distance between the spray gun and the target is set according to different spraying conditions.

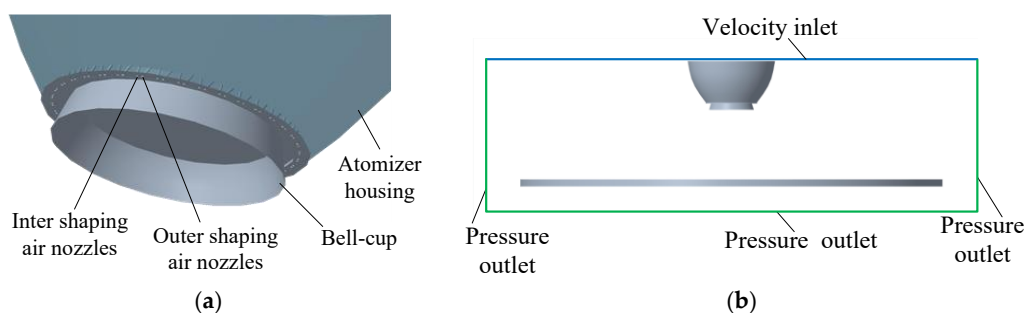


Figure 1. Electrostatic sprayer: (a) geometric model of the ESRB; (b) sketch of the fluid domain including ESRB and target (Adapted from Ref. [12]).

The top boundary is specified as a velocity inlet with a downward airflow velocity of 0.3 m/s, which is representative of a typical booth airflow, while the sides and bottom of the domain are set as pressure outlets. The volumetric flow rates of the inner and outer shaping air are specified as velocity inlets at the top surfaces of the corresponding shaping air nozzles. For the electric potential field, a fixed potential is applied at the bell cup and the gun collar, whereas the target plate is grounded (0 V). All other solid surfaces, such as the spray gun body, are treated as insulated boundaries, where a zero normal gradient of the electric potential is imposed.

The flow field and electrostatic field are solved using the finite volume method implemented in ANSYS/Fluent 19.0. A hybrid unstructured mesh containing approximately 1,340,000 cells is applied to the computational domain, with a high-density mesh distributed near the cup edge and all shaping air nozzles regions where high flow gradients and high droplet concentrations are resolved properly. The computational domain and shaping air nozzles mesh distribution are shown in Figure 2.

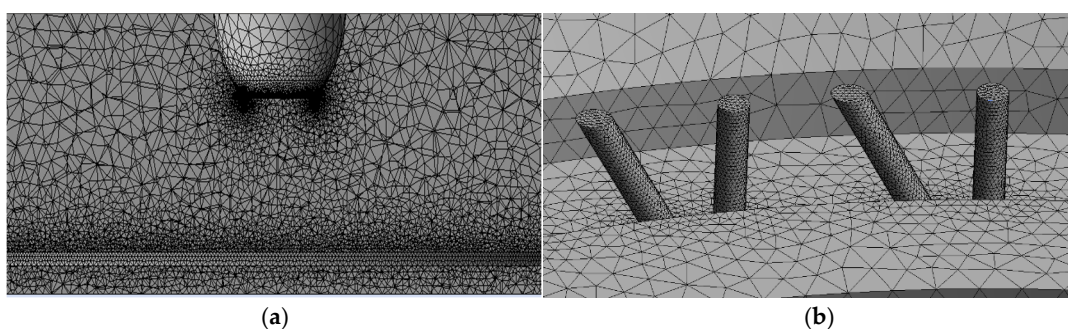


Figure 2. Mesh generation: (a) computational domain mesh; (b) shaping air inlet mesh refinement.

2.2. Turbulence Model and Solver Settings

In the direct charging mechanism, the paint flows over the edge of the rotating cup, which is maintained at a negative high voltage, thereby negatively charging the droplets. Under the combined effects of electrostatic force, gravity, and air drag, the charged droplets are efficiently transported toward the target surface. The flow field and electrostatic field are computed using the Eulerian approach, while the motion of droplets is modeled using the Lagrangian approach, which tracks the trajectory of each droplet and captures the evolution of its physical properties throughout the process [18,19]. The air is treated as a continuous phase and is governed by the Eulerian conservation equations for mass and momentum. Turbulence effects are incorporated using the realizable $k-\epsilon$ model, which imposes specific constraints on the Reynolds stresses, thereby ensuring greater consistency with the physics of turbulent flow [20].

2.3. Initial Conditions of the Droplet

The initial conditions of the discrete phase include the initial position, velocity, particle size, and charge of the droplet. As shown in Equations (1)–(5). In order to simulate the initial movement of the atomized droplets at the edge of the rotating cup under the action of centrifugal force, the injection model is applied in the study. In this case, 180 injection points are uniformly distributed around the bell cup [12]. The entire particle size distribution is injected from each point per DPM iteration.

A dynamic user-defined function (UDF) is developed to define the initial position and initial velocity of the droplets. The droplet size distribution is assumed to follow a logarithmic distribution, and the breakup model uses the KHRT model, which considers the interaction between aerodynamic breakup and instability caused by droplet acceleration, making it suitable for fluids with high Weber number.

The droplet size:

$$D_{32} = 5.75 \cdot n^{-0.79} \cdot Q^{0.32} \cdot r_{bell}^{-0.69} \cdot \rho^{0.29} \cdot \sigma^{0.26} \cdot (1 + 0.23\eta_s^{0.65}) \quad (1)$$

The charge on the droplet:

$$q = Coeffray 8\pi \sqrt{\varepsilon_0 \gamma r_{bell}^3} \quad (2)$$

Coeffray is the Rayleigh limit coefficient.

Particle injection is applied circumferentially along the bell cup rim at a radial distance equal to the cup radius, with the initial velocity specified via a user-defined function (UDF).

The radial velocity:

$$v_{rad} = \left(\frac{9\rho\omega^2 \sin\beta Q^2}{32\pi^2\eta_s r_{bell}} \right)^{\frac{1}{3}} \quad (3)$$

The tangential velocity:

$$v_{tan} = \tan\alpha \cdot v_{rad} \quad (4)$$

The axial velocity:

$$v_{axi} = \sin\beta \cdot v_{rad} \quad (5)$$

where ρ denotes paint density, ε_0 denotes the vacuum permittivity, ω represents the angular velocity of the rotary bell cup, β is the cone angle at the cup rim, Q stands for the paint flow rate, r_{bell} denotes the radius of the rotary bell cup, γ represents surface tension, η_s represents paint viscosity, and α indicates the offset angle of the injection point.

2.4. Spraying Process Parameters

The material used in this experiment was water-based paint, with a density of 980 kg/m³, a viscosity of 0.185 Pa·s, and a surface tension of 0.04 N/m. The spraying experiments were conducted in a spray booth. The ambient temperature was maintained at 20–25 °C, the relative humidity was controlled at 60%–70%, and the airflow velocity was typically maintained at 0.3–0.5 m/s. The experimental equipment employed was a third-generation VersaBell manufactured by FANUC Corporation.

In this study, inner and outer shaping air flow rates (Sin, Sout), cup rotational speed (n), applied voltage (U), target distance (H), and paint flow rate (Q) were used as input variables, while the coating film profile width on the sprayed surface and the amount of paint deposited served as response variables. The aim was to investigate the interactive effects of spray painting parameters on painting coverage efficiency and transfer efficiency, aiming to improve spraying efficiency and reduce paint waste. The relevant data are shown in Table 1.

Table 1. Spraying process parameter range.

Spraying Parameter	Range
Bell rotational speed/ n	20~50 kr/min
Applied voltage/ U	−30~−70 kV
Target distance/ H	50~250 mm
Paint flow rate/ Q	200~300 mL/min
Inner shaping air flow rate/ S_{in}	100~250 sl/min
Outer shaping air flow rate/ S_{out}	200~350 sl/min

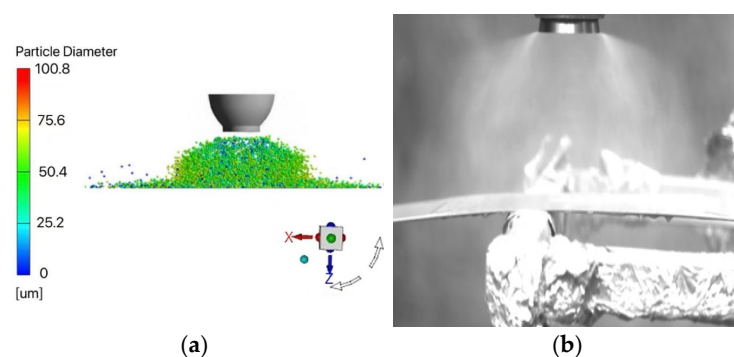
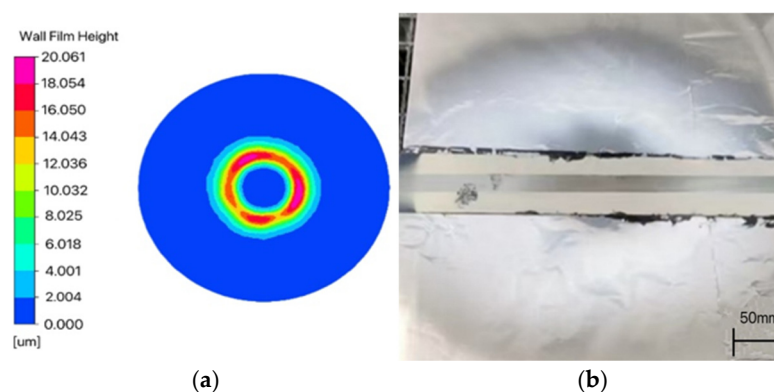
3. Simulation Results

Numerical simulations of the spraying process were performed under initial spraying process parameter conditions, listed in Table 2, followed by experimental validation using identical parameter settings.

Table 2. Initial spray painting process parameters.

n	S_{in}	S_{out}	U	Q	H
40 kr/min	200 sl/min	300 sl/min	50 kV	250 cc/min	150 mm

The spraying process in the experiment was recorded using a high-speed camera, as shown in Figure 3b. The simulated spraying process is illustrated in Figure 3a. The simulation results of the coating thickness distribution and the experimental paint film deposition profile are presented in Figure 4. The cross-sectional distribution plot of coating deposition is shown in Figure 5.

**Figure 3.** Spraying process: (a) simulation; (b) experiment.**Figure 4.** The results of paint film deposition profile: (a) simulation; (b) experiment.

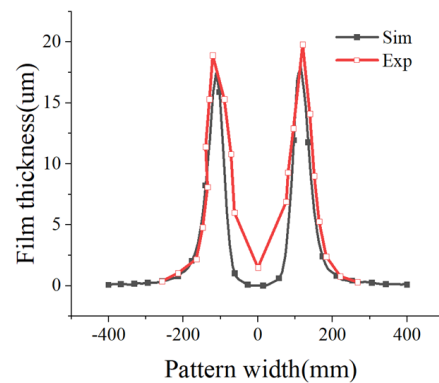


Figure 5. Cross-sectional distribution plot of coating deposition.

As shown in Figure 3, the paint mist contour captured by the high-speed camera is in good agreement with the simulated trajectories of the paint droplets. Figure 4 further reveals good agreement between the simulation and experimental results, as both produce a hollow toroidal film profile. Figure 5 also shows good agreement between the simulated and measured coating thickness distributions along the central cross section, with only relatively minor deviation at the center. These results collectively confirm that the present numerical model accurately captures the key aerodynamic and deposition dynamics of the electrostatic rotary bell spraying process. Consequently, to improve experimental efficiency by reducing reliance on physical spraying robots and instrumentation, minimizing paint waste, and mitigating volatile organic compound emissions, subsequent parametric sensitivity analyses (single-factor tests) and response surface method optimizations will be performed using Ansys/Fluent to simulate the ESRB spraying process.

4. Design and Analysis of the Response Surface Method

4.1. Single-Factor Test Analysis

To obtain an initial understanding of the relationships between the factors and the responses and to define feasible ranges of spraying process parameters, single-factor tests were first conducted with the parameters listed in Table 2 held constant. The individual effects of six key process parameters, namely, inner and outer shaping air flow, applied voltage, target distance, cup rotational speed, and paint flow rate, on the coating pattern width and paint transfer efficiency were systematically investigated, with all other parameters held constant. Single-factor test results are presented in Figure 6.

It can be seen from Figure 6 that different spraying process parameters significantly influence CPW and TE.

As the inner shaping air flow rate S_{in} increases, shown as Figure 6a, the CPW first increases and then decreases, while the TE exhibits an opposite trend: it initially decreases and then increases. When $150 \leq S_{in} \leq 200$ sl/min, the width decreases slowly, whereas TE increases significantly. For $S_{in} > 200$ sl/min, the width decreases markedly, and TE continues to rise. Based on these observations, S_{in} is set to 200 sl/min.

As the outer shaping air flow rate S_{out} increases, as shown as Figure 6b, the coating pattern width decreases, while TE increases. When $250 \leq S_{out} \leq 300$ sl/min, the width increases noticeably and TE decreases slowly. For $S_{out} > 300$ sl/min, the width increases slowly, but TE drops significantly. Consequently, S_{out} is set to 300 sl/min.

As the applied voltage increases, as shown as Figure 6c, the CPW first increases and then decreases, reaching a maximum at $U = 50$ kV. Meanwhile, TE increases monotonically. Considering the trade-off, the voltage is set to 50 kV.

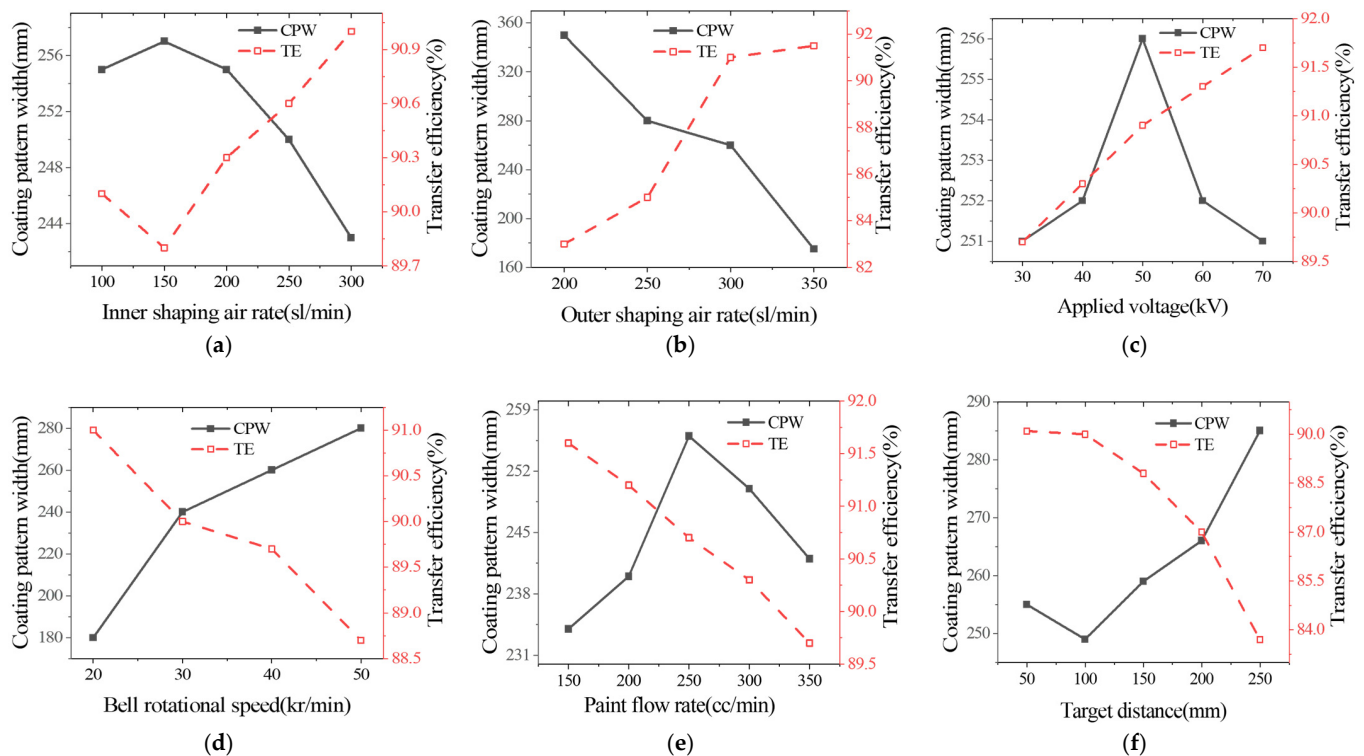


Figure 6. Effects of various factors on CPW and TE: (a) inner shaping air flow rates; (b) outer shaping air flow rates; (c) applied voltage; (d) bell rotational speed; (e) paint flow rate; (f) target distance.

As the cup rotational speed N increases, as shown as Figure 6d, the CPW increases, whereas TE decreases. When $30 \leq n \leq 40$ kr/min, both the increase in width and the decrease in TE are gradual. For $n > 40$ kr/min, the width continues to increase slowly, but TE declines more rapidly. Therefore, n is set to 40 kr/min.

As the paint flow rate Q increases, as shown as Figure 6e, the CPW first decreases and then increases, reaching a maximum at 250 cc/min, while TE decreases continuously. In light of these results, the paint flow rate Q is set to 250 cc/min.

As the target distance H increases, as shown as Figure 6f, the CPW first decreases and then increases, reaching a minimum at $H = 100$ mm, while TE consistently declines. For $100 \leq H \leq 150$ mm, the width increases significantly, but TE remains nearly constant. For $H > 150$ mm, the width continues to increase, yet TE drops substantially. Based on this analysis, the target distance H is set to 150 mm.

4.2. Response Surface Model Establishment and Variance Analysis

4.2.1. Response Surface Model Establishment

Based on the results of single-factor tests, a Box–Behnken design was employed to optimize the spraying process parameters. Bell rotational speed (X_1), inner shaping air flow rate (X_2), outer shaping air flow rate (X_3), paint flow rate (X_4), applied voltage (X_5), and target distance (X_6) were set as the control variables for the response surface model. A three-level factorial design was employed for each factor, with each factor set at three levels: low (−1), center (0), and high (+1). Response surface regression models were developed with coating pattern width (Y_1 /mm) and TE (Y_2 /%) as the response variables. The corresponding coded levels for all factors are summarized in Table 3.

Table 3. Factors and levels of the BBD.

Factor	Levels		
	−1	0	1
X ₁ : Bell rotational speed(kr/min) n	30	40	50
X ₂ : Inner shaping air flow rate (sl/min) Sin	150	200	250
X ₃ : Outer shaping air rate(sl/min) Sout	250	300	350
X ₄ : Paint flow rate (cc/min) Q	200	250	300
X ₅ : Applied voltage (kV) U	40	50	60
X ₆ : Target distance (mm) H	100	150	200

The 51 sets of simulation results were analyzed using Design-Expert 13.0. Table 4 lists the Box–Behnken design along corresponding response values. The response data were subjected to multiple regression analysis to obtain the following regression equations for CPW (Y_1) and TE (Y_2).

$$Y_1 = 267 + 4.50X_1 + 0.1667X_2 - 0.45X_3 - 0.25X_4 - 1.00X_5 + 5.04X_6 - 1.12X_1X_2 + 0.05X_1X_3 - 0.875X_1X_4 + 0.125X_1X_5 + 1.00X_1X_6 + 5.00X_2X_3 - 3.12X_2X_4 - 0.9375X_2X_5 - 5.63X_2X_6 - 1.75X_3X_4 + 3.50X_3X_5 - 0.50X_3X_6 + 0.125X_4X_5 + 1.25X_4X_6 + 0.125X_5X_6 - 0.4306X_1^2 - 12.51X_2^2 - 8.47X_3^2 - 8.93X_4^2 - 5.51X_5^2 - 6.60X_6^2 \quad (6)$$

$$R^2 = 0.9814$$

$$Y_2 = 88.89 - 0.670X_1 - 0.020X_2 - 0.659X_3 - 0.082X_4 + 0.605X_5 - 0.552X_6 + 0.023X_1X_2 - 0.136X_1X_3 + 0.095X_1X_4 - 0.050X_1X_5 - 0.015X_1X_6 - 0.048X_2X_3 - 0.023X_2X_4 - 0.294X_2X_5 - 0.186X_2X_6 - 0.049X_3X_4 - 0.098X_3X_5 - 0.003X_3X_6 - 0.085X_4X_5 + 0.029X_4X_6 - 0.201X_5X_6 + 0.434X_1^2 - 0.826X_2^2 - 1.420X_3^2 - 1.140X_4^2 - 1.680X_5^2 - 1.550X_6^2 \quad (7)$$

$$R^2 = 0.9933$$

Both correlation coefficients of Y_1 and Y_2 are greater than 0.9, indicating that the quadratic polynomials in Equations (6) and (7) accurately capture the effects of spraying process parameters variations on coating pattern width and TE. Based on the coefficients of the linear terms in Equation (6), the degree of influence on coating pattern width is as follows: target distance > outer shaping air flow rate > bell rotational speed > applied voltage > paint flow rate > inner shaping air flow rate. For TE, the order of influence is: bell rotational speed > outer shaping air flow rate > applied voltage > target distance > paint flow rate > inner shaping air flow rate. The CPW and TE values were converted into standard Z-scores, and a regression equation of comprehensive score (CS) of the true values of X_1 , X_2 , X_3 , X_4 , X_5 , and X_6 is as follows:

$$CS = -93.506 - 0.121X_1 + 0.107X_2 + 0.102X_3 + 0.354X_4 + 0.454X_5 + 0.227X_6 - 1.030 \times 10^{-4}X_1X_2 - 3.900 \times 10^{-5}X_1X_3 - 5.700 \times 10^{-5}X_1X_4 - 9.900 \times 10^{-5}X_1X_5 + 1.890 \times 10^{-4}X_1X_6 + 4.900 \times 10^{-5}X_2X_3 - 6.200 \times 10^{-5}X_2X_4 - 1.470 \times 10^{-4}X_2X_5 - 1.430 \times 10^{-4}X_2X_6 - 3.000 \times 10^{-5}X_3X_4 + 1.51 \times 10^{-4}X_3X_5 - 1.000 \times 10^{-5}X_3X_6 - 4.300 \times 10^{-5}X_4X_5 + 6.000 \times 10^{-5}X_4X_6 - 1.210 \times 10^{-4}X_5X_6 + 2.434 \times 10^{-3}X_1^2 - 1.860 \times 10^{-4}X_2^2 - 1.830 \times 10^{-4}X_3^2 - 6.770 \times 10^{-4}X_4^2 - 4.232 \times 10^{-3}X_5^2 - 6.900 \times 10^{-4}X_6^2 \quad (8)$$

Table 4. Box–Behnken design (BBD) and simulation results.

Simulation Order	X ₁	X ₂	X ₃	X ₄	X ₅	X ₆	Y ₁ (Z-Score Normalization)	Y ₂ (Z-Score Normalization)	Com. Score
1	0	−1	1	0	−1	0	224 (−2.411)	84.92 (−0.707)	−3.118
2	0	−1	−1	0	−1	0	255 (0.836)	83.16 (−1.878)	−1.042
3	1	0	1	0	0	−1	247 (−0.002)	86.20 (0.298)	0.296
4	0	−1	−1	0	1	0	248 (0.103)	85.04 (−0.627)	−0.524
5	−1	0	−1	0	0	−1	246 (−0.107)	86.68 (0.465)	0.358
6	1	0	0	1	1	0	255 (0.836)	85.29 (0.332)	1.168
7	1	0	1	0	0	1	259 (1.255)	84.83 (−0.081)	1.174
8	−1	0	0	−1	−1	0	248 (0.103)	86.48 (0.332)	0.435
9	0	0	−1	−1	0	−1	240 (−0.735)	84.93 (−0.700)	−1.435
10	1	1	0	1	0	0	244 (−0.316)	85.77 (0.531)	0.215
11	0	0	1	−1	0	−1	237 (−1.049)	86.09 (0.072)	−0.977
12	0	−1	0	0	1	−1	231 (−1.678)	86.26 (0.185)	−1.493
13	−1	−1	0	1	0	0	244 (−0.316)	87.89 (1.270)	0.954
14	−1	0	0	−1	1	0	245 (−0.212)	88.06 (1.383)	1.171
15	0	1	0	0	1	−1	244 (−0.316)	86.10 (0.079)	−0.237
16	0	0	1	1	0	1	244 (−0.316)	84.65 (−0.886)	−1.202
17	0	1	1	0	−1	0	239 (−0.840)	85.47 (−0.341)	−1.181
18	−1	0	0	1	1	0	248 (0.103)	87.79 (1.203)	1.306
19	−1	0	1	0	0	−1	238 (−0.945)	88.25 (1.509)	0.564
20	0	−1	1	0	1	0	235 (−1.259)	86.41 (0.285)	−0.974
21	−1	0	−1	0	0	1	256 (0.941)	85.88 (−0.068)	0.873
22	0	−1	0	0	1	1	250 (0.312)	85.15 (−0.553)	−0.241
23	0	0	−1	−1	0	1	250 (0.312)	83.77 (−1.472)	−1.160
24	0	1	0	0	−1	−1	247 (−0.002)	85.19 (−0.527)	−0.529
25	1	−1	0	1	0	0	254 (0.731)	85.46 (0.391)	1.122
26	−1	1	0	−1	0	0	243 (−0.421)	88.23 (1.496)	1.075
27	1	1	0	−1	0	0	252 (0.522)	86.18 (0.451)	0.973
28	0	1	1	0	1	0	240 (−0.735)	86.01 (0.019)	−0.716
29	1	0	0	1	−1	0	257 (1.045)	85.24 (−0.360)	0.685
30	0	−1	0	0	−1	−1	233 (−1.468)	84.40 (−1.053)	−2.521
31	1	−1	0	−1	0	0	249 (0.207)	85.74 (0.518)	0.725
32	−1	1	0	1	0	0	239 (−0.840)	87.79 (1.203)	0.363
33	0	0	1	1	0	−1	231 (−1.678)	85.96 (−0.014)	−1.692
34	0	0	0	0	−1	1	243 (−0.421)	84.14 (−1.226)	−1.647
35	0	−1	0	0	−1	1	251 (0.417)	83.64 (−1.558)	−1.141
36	1	0	−1	0	0	1	267 (2.093)	83.46 (−0.953)	1.140
37	1	0	0	−1	1	0	255 (0.836)	85.52 (0.405)	1.241
38	0	0	0	0	0	0	267 (2.093)	88.94 (1.982)	4.075
39	0	0	1	−1	0	1	245 (−0.212)	84.86 (−0.746)	−0.958
40	0	0	0	0	0	0	266 (1.988)	88.87 (1.922)	3.910
41	1	0	0	−1	−1	0	258 (1.150)	84.51 (−0.687)	0.463
42	−1	0	1	0	0	1	247 (−0.002)	87.38 (0.930)	0.928
43	0	0	−1	1	0	1	256 (0.941)	83.56 (−1.611)	−0.670
44	−1	0	0	1	−1	0	251 (0.417)	86.29 (0.205)	0.622
45	0	1	−1	0	1	0	237 (−1.049)	84.83 (−0.766)	−1.815
46	0	0	0	0	0	0	268 (2.197)	88.82 (1.902)	4.099
47	0	1	−1	0	−1	0	246 (−0.107)	83.90 (1.385)	−1.492
48	0	1	1	0	1	1	240 (−0.735)	83.79 (−1.458)	−2.193
49	0	0	−1	1	0	−1	241 (−0.630)	84.41 (−1.046)	−1.676
50	1	0	−1	0	0	−1	252 (0.522)	84.75 (−0.141)	0.381
51	−1	−1	0	−1	0	0	236 (−1.154)	88.20 (1.476)	0.322

The results of ANOVA for quadratic regression equations of response surface are listed in Table 5. The results show that: (a) The integrated regression model is correct as the model has a significant p -value. (b) X_5 and X_6 reach significance level. (c) Based on the F -values, the magnitude of the effect of the significant factors can be inferred: $X_5 > X_6$. (d) The interactions effect of X_2X_3 , X_2X_4 , X_2X_5 , X_2X_6 , and X_3X_5 are significant. Their interaction effects on the comprehensive score are shown in Figure 7.

Table 5. ANOVA for quadratic regression equations of response surface.

Variance Source	Sum of Squares	DOF	Mean Square	F-Value	p -Value	Significance
Model	114.82	27	4.250	76.190	<0.0001	**
X_1	0.016	1	0.016	0.279	0.6020	
X_2	0.023	1	0.023	0.417	0.5250	
X_3	0.026	1	0.026	0.47	0.4995	
X_4	0.019	1	0.019	0.345	0.5626	
X_5	2.140	1	2.140	38.260	<0.0001	**
X_6	0.622	1	0.622	11.150	0.0029	**
X_1X_2	0.084	1	0.084	1.510	0.2316	
X_1X_3	0.012	1	0.012	0.218	0.6449	
X_1X_4	0.013	1	0.013	0.231	0.6355	
X_1X_5	0.003	1	0.003	0.057	0.8140	
X_1X_6	0.072	1	0.072	1.290	0.2683	
X_2X_3	1.940	1	1.940	34.700	<0.0001	**
X_2X_4	0.781	1	0.781	13.990	0.0011	**
X_2X_5	1.380	1	1.380	24.760	<0.0001	**
X_2X_6	4.070	1	4.070	72.920	<0.0001	**
X_3X_4	0.182	1	0.182	3.270	0.0837	
X_3X_5	0.728	1	0.728	13.050	0.0015	**
X_3X_6	0.040	1	0.040	0.724	0.4036	
X_4X_5	0.015	1	0.015	0.269	0.6085	
X_4X_6	0.181	1	0.181	3.240	0.0852	
X_5X_6	0.117	1	0.117	2.090	0.1618	
X_1^2	0.512	1	0.512	9.170	0.0060	**
X_2^2	29.910	1	29.910	535.910	<0.0001	**
X_3^2	29.010	1	29.010	519.740	<0.0001	**
X_4^2	24.740	1	24.740	443.260	<0.0001	**
X_5^2	24.760	1	24.760	443.630	<0.0001	**
X_6^2	25.700	1	25.700	460.540	<0.0001	**
Residual	1.280	23	0.056			
Lack of Fit	1.260	21	0.060	5.680	0.1602	not significant
Pure Error	0.021	2	0.011			
Cor Total	116.100	50				

Note: * indicated that $0.01 < p < 0.05$, ** indicated that $p < 0.01$.

As shown in Figure 7a, the comprehensive score first increases and then decreases with increasing S_{in} and S_{out} . Similarly, the score exhibits the same trend with increasing paint flow rate, as shown in Figure 7b; applied voltage, as shown in Figure 7c; and target distance, as shown in Figure 7d. In Figure 7e, the comprehensive score also initially increases and subsequently decreases with increasing outer shaping air rate and paint flow rate, indicating that the interactions between X_2 and X_3 , X_2 and X_4 , X_2 and X_5 , X_2 and X_6 , and X_3 and X_5 have a significant influence on the model.

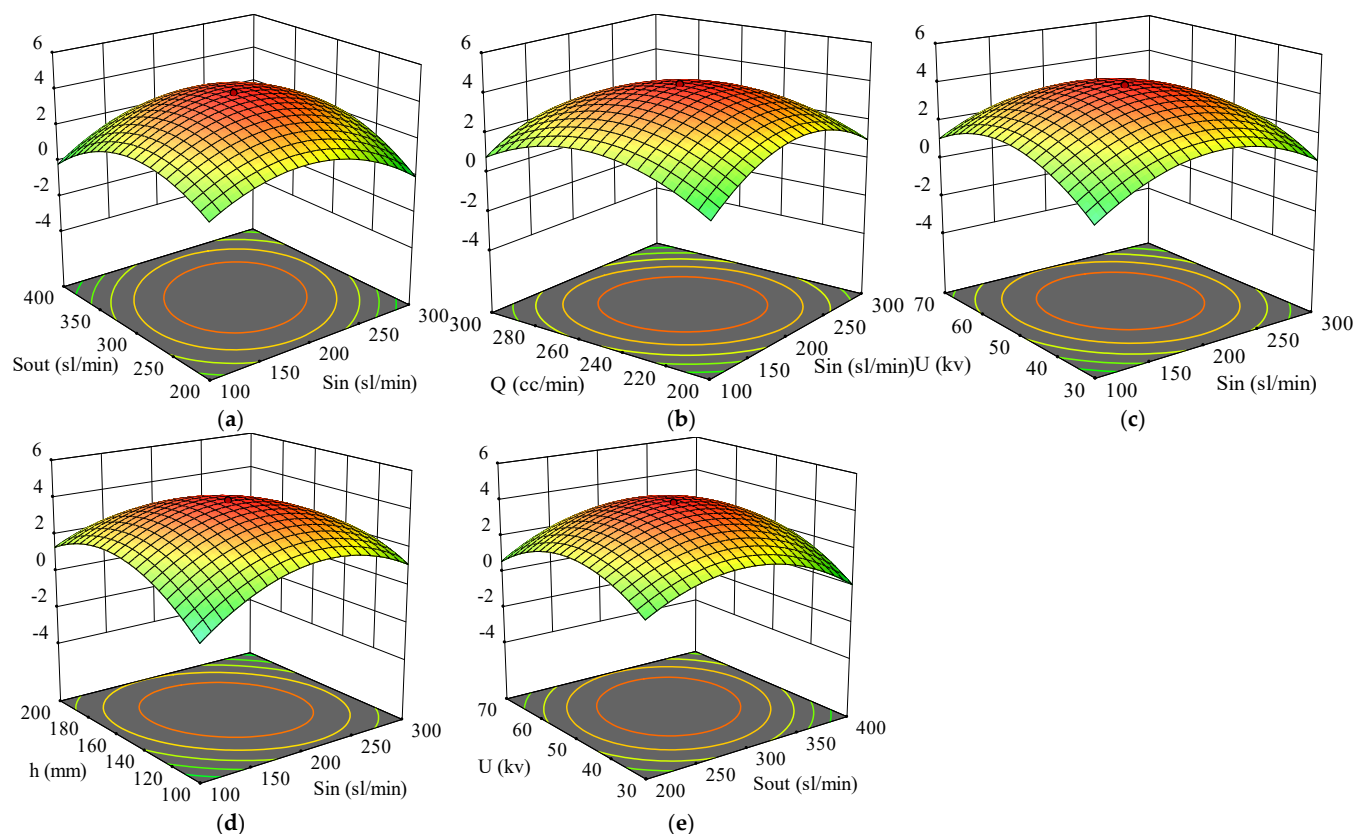


Figure 7. Response surface plots of interaction of different factors: (a) Sin and Sout; (b) Sin and Q; (c) Sin and U; (d) Sin and H; (e) Sout and U.

4.2.2. Spraying Process Parameter Optimization

Based on the established quadratic regression model, the numerical optimization module in Design-Expert 13.0 software was used to predict the spraying process parameters that maximize the comprehensive score of ESRB by determining the extreme value of the regression model. The optimal parameters are as follows: bell rotational speed X_1 , 40 kr/min; inner shaping air flow rate X_2 , 196 sl/min; outer shaping air flow rate X_3 , 298 sl/min; paint flow rate X_4 , 249 cc/min; applied voltage X_5 , 52 kV; and target distance X_6 , 154 mm. The predictive value of the comprehensive score is 4.343.

4.2.3. Experimental Validation Results

To verify the reliability of the optimized parameters, both the simulation and the experiment were conducted using the optimal values under identical constraint conditions. The test results are presented in Table 6.

Table 6. Results of verification tests.

$(X_1, X_2, X_3,$ $X_4, X_5, X_6)$		Response Value		Test Com. Score	Predicted Com. Score	Relative Error (%)
		CPW (mm)	TE (%)			
(39.98, 195.59,	Simulation	271 (2.493)	88.64 (1.762)	4.255	4.343	2.03
298.04, 249.49,	Experiment	269 (2.302)	88.96 (1.982)	4.284	4.343	1.36
51.65, 153.99)						

After Z-score standardization, the simulation and experimental comprehensive average scores were 4.255 and 4.284, respectively. Compared with the predicted value of the

model, the relative errors were 2.03% and 1.36%, respectively, indicating that the regression equation model is both reliable and predictable.

5. Conclusions

This work mainly studies the effect of ESRB spraying process parameters on coating pattern width and paint transfer efficiency and proposes a spraying process parameter optimization method. Bell rotational speed, inner and outer shaping air flow rate, paint flow rate, target distance, and applied voltage are the six investigating factors. The influence of these factors on the spraying coverage efficiency and paint transfer efficiency were studied by combining the single-factor test and Box–Behnken response surface method. Test data were standardized by Z-score, and a comprehensive score was used to evaluate the spraying performance. Variance analysis and multiple quadratic regression fitting were performed on the test data by using Design-Expert 13.0 software. The mathematical model of the comprehensive score with six factors was established to predict the optimal process parameters; the main conclusions are as follows:

- (1) In the single factor experiments, the factors significantly affecting spray width were rotary bell speed X_1 , external shaping air flow rate X_3 , and spray distance X_6 , with the order of influence strength being $X_6 > X_3 > X_1$. The factors significantly affecting paint transfer efficiency were rotary bell speed X_1 , external shaping air flow rate X_3 , voltage X_5 , and spray distance X_6 , with the order of influence strength ranked as $X_1 > X_3 > X_5 > X_6$.
- (2) Voltage X_5 and spray distance X_6 significantly influenced the comprehensive score of spray width and paint transfer efficiency, with the magnitude of effect following the order $X_5 > X_6$. The interaction terms that exerted a significant effect on the comprehensive score were X_2X_3 , X_2X_4 , X_2X_5 , X_2X_6 , and X_3X_5 . Furthermore, the quadratic terms of all factors exhibited a significant influence on the response.
- (3) The optimal combination of process parameters was determined using the regression equation. Validation tests indicated that the deviation between the predicted comprehensive score and both the simulation and experimental results was less than 2.1%, demonstrating that the response surface methodology employed to optimize the ESRB spraying process parameters was both valid and feasible.

Overall the work will contribute to the design and optimization of spraying process parameters combinations for ESRB. Future work will investigate the coating uniformity on complex workpieces, the deposition behavior of multiple spray layers, and the coupling effects of multiple parameters on the coating deposition mechanism, with the aim of establishing a more comprehensive spraying process optimization model.

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