

Article

Thickness Profile Modeling and Uniformity Control for Internal Diameter Atmospheric Plasma Spraying on Internal Cylindrical Surfaces

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Abstract

Internal diameter atmospheric plasma spraying (ID-APS) commonly employs an inherently inclined nozzle configuration to overcome geometric interference in confined cylindrical components. This non-orthogonal deposition condition breaks the symmetry of the plasma jet and produces asymmetric thickness distributions, making uniform coating formation difficult to control using conventional models developed for planar or external spraying. In this study, a kinematic-based mathematical model was developed from experimentally measured single-path deposition data obtained under representative internal spraying conditions. A skew-normal formulation was introduced to describe the asymmetric cross-sectional profile, and a superposition framework was established to relate kinematics and geometric constraints to coating quality metrics, including mean thickness, profile uniformity, flatness, and lateral distance. The effects of kinematic parameters and work-piece geometric characteristics were systematically analyzed, and the resulting model was implemented on an internal cylindrical surface to predict spatial thickness evolution. Experimental validation was conducted at both macroscopic and microscopic scales through surface reconstruction and cross-sectional microscopy, confirming that the proposed approach can capture the main features of coating buildup and provide reliable estimates of thickness uniformity. The developed framework offers a practical tool for process design and quality control in ID-APS, reducing dependence on empirical parameter tuning and enabling more consistent thickness control on internal surfaces.

Keywords: ID-APS; kinematic-based modeling; thickness prediction; coating uniformity



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1. Introduction

Thickness uniformity is a critical quality attribute of thermally sprayed coatings because it directly affects coating integrity, residual stress distribution, dimensional accuracy, and service performance under wear, corrosion, and thermal loading conditions [1,2]. Thermal spray technologies therefore play a pivotal role in modern surface engineering by providing wear resistance, corrosion protection, and thermal insulation for high-performance industrial components [3,4]. With the increasing complexity of engineering components, the deposition of functional coatings within restricted internal geometries has become an

important industrial requirement. ID-APS is essential for enhancing the durability of critical components such as turbine shafts and cylinder liners. To operate within such confined geometries, internal diameter plasma torches are engineered with compact architectures and inclined nozzle exits to overcome spatial interference [5]. Although high-velocity oxygen fuel (HVOF) spraying is typically preferred for bond coat deposition [6,7], the large size of HVOF torches often limits their application in narrow bores, making ID-APS a practical solution because of its geometric accessibility [8]. However, the inclined spray orientation breaks the symmetry of the plasma jet, resulting in complex and non-uniform coating profiles that conventional thickness prediction models developed for planar or external spraying typically fail to characterize accurately [9–11]. Consequently, establishing a robust thickness prediction model and an optimized scanning strategy is imperative for precise control of deposition thickness and coating quality in confined environments.

To accurately characterize the asymmetric single-path coating thickness profile arising from the inherent inclination of the internal diameter plasma spray nozzle in ID-APS, the selection of an appropriate mathematical distribution is critical. Traditional symmetric models, such as Gaussian and Cauchy distributions [12,13], fail to capture the directional tail elongation caused by non-orthogonal particle impingement. While various asymmetric probability density functions exist, most exhibit inherent limitations for engineering trajectory modeling. For instance, the log-normal distribution is strictly defined on a positive domain, necessitating artificial coordinate offsetting that complicates 3D spatial transformations, and its mathematical parameters lack an intuitive mapping to actual engineering characteristics [14]. Similarly, the Beta distribution is bounded by finite intervals, imposing a rigid cutoff that contradicts the continuous geometric extension of actual coating profiles at the boundary regions [15]. Furthermore, although the Pearson Type IV distribution offers high flexibility for asymmetric fitting, its parameters exhibit strong correlation, frequently leading to poor numerical stability and non-convergence during non-linear curve fitting of noisy experimental data [16]. Consequently, it is predominantly employed in pure statistical data analysis rather than physical engineering kinematics. In contrast, the skew-normal distribution is widely applied in engineering fields and originates directly from the normal distribution family. This foundational link is highly advantageous, as it naturally builds upon and transitions from the established Gaussian-based thickness modeling frameworks that are extensively utilized in thermal spraying [17,18]. By modulating a standard Gaussian baseline with a single skewness parameter, it avoids severe parameter instability. Taking all these factors into consideration, the skew-normal distribution is highly suitable for fitting the asymmetric coating profiles generated in non-orthogonal spraying applications, such as internal diameter plasma spraying.

As industrial applications shifted toward components with more complex geometries, mathematical models based on coating thickness were further extended to specific surfaces. For instance, Ahmadkhaniha et al. [19] used finite element simulations to optimize thickness distributions on complex workpieces, highlighting the need to consider deposition kinematics and geometric feedback. For regular curved geometries, Zhang et al. [20] established a coating thickness model for external cylindrical surfaces, while another thickness model was developed for spherical surfaces [21]. To bridge theoretical modeling and industrial implementation, Deng et al. [22] and Chen et al. [10] integrated thickness distribution algorithms into offline programming software to improve automated path generation. Furthermore, Wu et al. [23] proposed a boundary fitting approach for robotic path planning on arbitrary topologies. However, the inherent geometric constraints of internal diameter spraying can induce shadowing effects and jet deflection, making symmetric distribution assumptions inadequate for predicting asymmetric coating profiles. Related studies have shown that non-orthogonal spraying strongly affects coating microstructure

and profile characteristics [24], while multivariate models considering asymmetric powder distribution have also been proposed [25]. Despite these advances, an analytical framework capable of predicting asymmetric thickness evolution during inclined ID-APS remains insufficiently developed.

Current scholarly discourse regarding internal diameter coatings remains heavily weighted toward the empirical optimization of processing parameters and the metallurgical development of advanced feedstock materials [26–28]. For instance, researchers have extensively investigated the effects of particle regulation [29], spray distance [30], and powder materials [8] on the resulting coating microstructure and mechanical integrity. Furthermore, advanced composite systems, such as carbon nanotube-reinforced coatings, have been developed and applied to internal surfaces to enhance their operational performance and extend their service limits [31]. Parallel to material advancements, recent research has pivoted toward enhancing system intelligence and automated trajectory optimization. To improve process adaptability, Bocklisch et al. [32] introduced a hybrid decision-making framework that enables effective human–machine teaming in APS operations. Regarding the geometric challenges of complex surfaces, Ding et al. [33] developed localized corner path planning strategies to balance high precision with machining efficiency. Additionally, advanced optimization techniques, such as Bayesian optimization combined with ant colony algorithms [34], have been implemented to automate the generation of efficient spray paths. However, the development of robust thickness prediction models specifically for internal cylindrical geometries has received comparatively limited attention. This research gap is primarily attributed to the stringent spatial constraints within narrow bores, which preclude the integration of bulky in situ diagnostic instrumentation [35]. Moreover, the inherent complexities of the internal diameter spraying system—such as the restricted kinematics of miniaturized torches and the resultant non-orthogonal spray trajectories—create a unique deposition environment that traditional modeling frameworks fail to accommodate.

In this study, a kinematic-based thickness modeling framework is developed for ID-APS under inclined deposition conditions. First, experimentally measured single-path coating profiles are described using a skew-normal formulation to capture the asymmetric cross-sectional profile induced by non-orthogonal plasma jet impingement. Subsequently, a thickness superposition model is established to correlate process kinematics and workpiece geometric characteristics with key coating quality metrics, including mean thickness, profile uniformity, flatness, and lateral distance. Moreover, a simulation procedure based on internal cylindrical surface meshing and thickness mapping is established to visualize the spatial evolution of coating thickness. Finally, the predicted thickness distribution is validated at both macroscopic and microscopic scales through surface reconstruction and cross-sectional characterization, demonstrating the applicability of the proposed framework for thickness uniformity control on internal cylindrical surfaces.

2. Modeling Framework

2.1. Single-Path Thickness Profile Model

For conventional APS torches, the jet exit is axisymmetric, yielding an isotropic Gaussian distribution during a fixed-time spot spray when gravitational effects are neglected. However, for internal diameter spray torches, the deposition process often occurs at an inclined angle relative to the substrate due to geometric constraints, jet dynamics, and deposition efficiency limitations. This results in the non-symmetric distribution shown in Figure 1a, where the profile along the X-axis exhibits distinct skewness. As the torch translates along the Y-axis at a constant velocity, a single-path coating track is generated, as illustrated in Figure 1b. Under steady-state conditions, the cross-sectional profile remains

consistent at any point along the Y-axis. By slicing the track at an arbitrary position, the characteristic data distribution shown in Figure 1c is obtained. These distributive features allow for numerical fitting via mathematical expressions, which is essential for investigating coating thickness superposition.

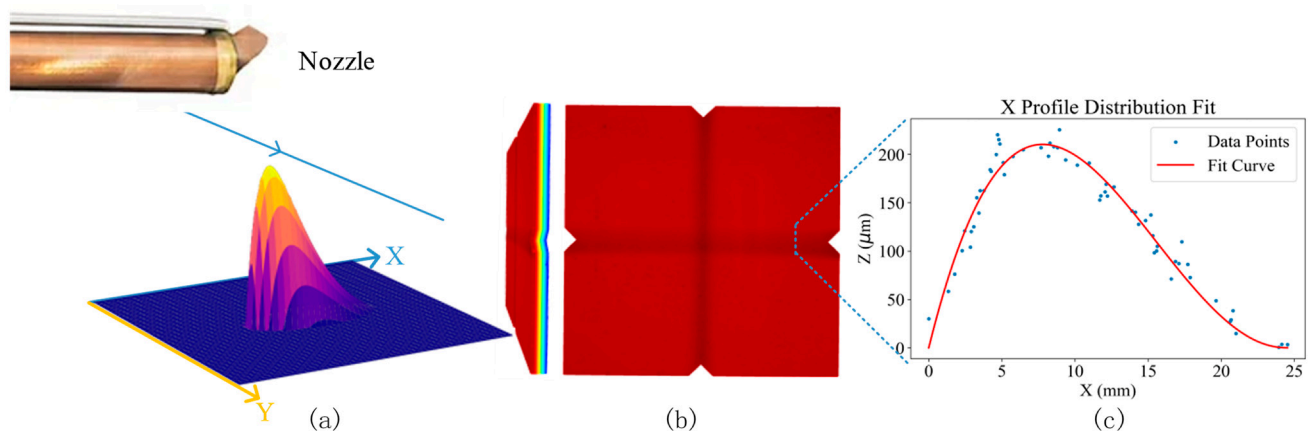


Figure 1. Schematic evolution and numerical modeling of the coating deposition process: (a) non-symmetric spot distribution formed by a fixed-time spot spray at an inclined angle, with the X-axis and Y-axis indicating profile skewness and spray torch translation directions, respectively; (b) formation of a single-path coating track during constant velocity scanning along the Y-axis; (c) cross-sectional profile data and the corresponding numerical fitting based on the skew-normal engineering model.

To quantitatively capture this physical asymmetry, the skew-normal distribution is an ideal candidate [36], with its general probability density function defined as

$$H(x) = A \cdot \frac{2}{\omega} \cdot \phi\left(\frac{x - x_0}{\omega}\right) \cdot \Phi\left(\alpha \cdot \left(\frac{x - x_0}{\omega}\right)\right) \quad (1)$$

In this expression, A controls the overall magnitude of the distribution rather than representing a probability. Φ denotes the cumulative distribution function of the normal distribution, and ϕ represents its probability density function. x_0 is the location parameter representing the horizontal displacement, ω is the scale parameter reflecting the spreading width of the spray jet, and α is the skewness parameter that controls the degree and direction of asymmetry in the coating thickness profile. When α approaches zero, the skew-normal distribution degenerates into a symmetric Gaussian-like distribution, indicating that the coating thickness profile exhibits little directional bias. As the absolute value of α increases, the deviation from symmetry becomes more pronounced, and the coating profile develops a longer tail on one side. Physically, this tail elongation is directly linked to the spatial gradient in the standoff distance across the deposition footprint, which is inherently induced by the nozzle inclination: the region of the substrate further away from the nozzle exit experiences wider spatial spreading, resulting in an extended tail. The sign of α determines the direction of this tail elongation, thereby indicating the orientation of the asymmetric deposition profile. In the context of ID-APS, this parameter provides a concise mathematical representation of the profile distortion associated with the intrinsic angular configuration of the internal diameter nozzle. While this formulation modulates the standard normal distribution through α , the strong coupling between the scale parameter ω and the peak amplitude in engineering practice complicates the direct analysis of the influence of process parameters on coating thickness. Consequently, by introducing the

error function erf and reconfiguring the parameters, a more physically intuitive engineering expression is derived:

$$H(x) = K \cdot \exp\left(-\frac{(x - x_0)^2}{2\sigma^2}\right) \cdot \left[1 + \operatorname{erf}\left(\frac{\alpha \cdot (x - x_0)}{\sqrt{2}\sigma}\right)\right] \quad (2)$$

Within this model, the deposition intensity K , scale parameter σ , and skewness parameter α are mathematically decoupled. This formulation explicitly reflects the synergistic effects of kinematic variables and geometric constraints on the coating profile, providing a solid theoretical basis for the study of coating thickness superposition on confined internal curved surfaces.

Figure 2 illustrates the influence of individual parameters on the cross-sectional distribution of the coating profile, as described by Equation (2). By comparing the baseline with the modified profiles, the distinct physical role of each parameter is clearly demonstrated. Impact of deposition intensity (K): As shown by the blue dotted line, K acts as a linear scaling factor. Increasing K elevates the overall coating thickness without altering the transverse spreading width. Impact of Scale Parameter (σ): The green dash-dotted line demonstrates that σ governs the footprint of the spray jet. An increase in σ leads to a wider distribution of the deposited material. For a constant overall deposition level, this transverse expansion results in a compensatory reduction in peak height, reflecting the lateral energy dissipation of the plasma jet. This indicates that the reconfigured engineering expression successfully achieves the mathematical decoupling of deposition intensity from spatial dispersion. Impact of Skewness Parameter (α): The red dashed line captures the profile distortion characteristic of inclined internal diameter spraying. Increasing α enhances the profile asymmetry—exhibited by a steeper leading edge and a prolonged tail—while simultaneously inducing a localized elevation of the peak height. This phenomenon accurately represents the preferential deposition toward the primary impingement direction. The synergy of these three independent parameters allows the proposed model to flexibly and accurately characterize the complex non-symmetric profiles encountered in practical engineering applications.

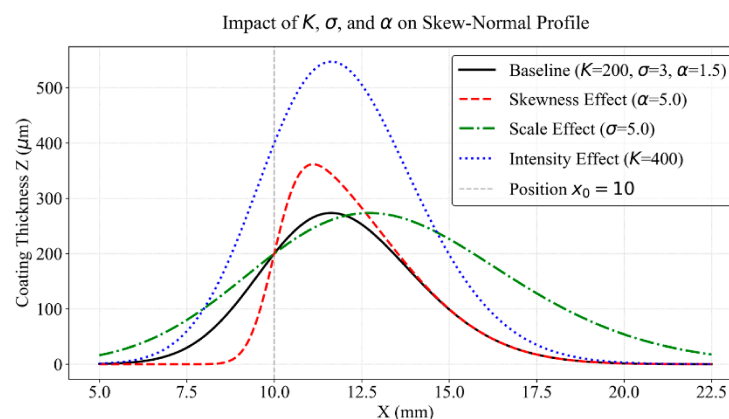


Figure 2. Influence of model parameters on the single-path cross-sectional profile, where K reflects deposition intensity, σ represents jet dispersion, and α characterizes the impingement angle induced distortion.

For the systematic characterization of ID-APS, Figure 3 illustrates the kinematic variables and geometric parameters that govern the resulting coating thickness. In a typical internal diameter thermal spray process, the nozzle is integrated into a specialized spray torch designed to extend into the cylindrical cavity of the workpieces with different radius. The fundamental motion is defined by a synchronized combination of rotation and

translation: the nozzle (or the workpiece) rotates at a specific angular velocity to establish the circumferential scanning velocity, while simultaneously advancing along the longitudinal axis, defined as the spray torch movement direction. This coordinated kinematic relationship generates a continuous helical spray path on the internal surface. Rather than being a discrete increment, the step between adjacent paths is precisely regulated by the velocity ratio between the longitudinal translation and the circumferential scanning speed. To achieve the target specifications, the process is repeated for a designated number of the number of spray times. Furthermore, a lead-in lateral distance and lead-out lateral distance are incorporated to allow the spray torch to reach a steady-state velocity before and after the effective coating zone, thereby ensuring a uniform deposition thickness throughout the functional area of the workpiece. The specific definitions of the variables illustrated are summarized as Table 1.

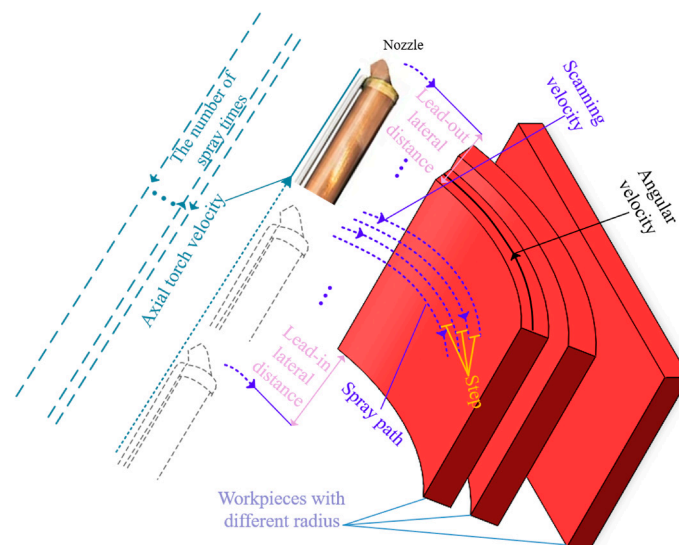


Figure 3. Schematic of the kinematic variables and geometric parameters for ID-APS.

Table 1. Key parameters determining the coating deposition and trajectory in internal diameter spraying.

Parameter	Symbol	Definition/Description
Angular velocity	ω_r	The rotational speed of the nozzle or the workpiece, which scales the linear scanning speed
Axial torch velocity	v_m	The torch velocity along the axial direction of the workpiece
Scanning velocity	v_s	The circumferential velocity of the plasma jet relative to the internal surface, determined by the angular velocity and the workpiece radius
Spray path	p	The equivalent plasma jet trajectory on the internal wall of the workpiece, representing the effective path of material accumulation.
The number of spray times	N	The total number of completed deposition cycles
Step	d_{step}	The axial spacing between adjacent helical spray paths is determined by the ratio of the axial scanning velocity to the rotational frequency
Lead-in/Lead-out lateral distance	d_{in}/d_{out}	Buffer zones located at both ends of the effective coating area to ensure kinematic stability and uniform thickness distribution at the boundaries
Workpieces with different radius	R	Workpiece radius dictates the scanning velocity and fundamentally shapes the resultant deposition thickness and distribution

2.2. Kinematic Superposition Model

To bridge the gap between the kinematic variables of a recurrent single spray path and the resulting skew-normal distribution of the coating, a functional mapping is defined to account for the underlying deposition physics. This relationship is formally expressed as a vector-valued mapping from the kinematic parameter space to the characteristic space of the deposition profile:

$$[K, \alpha, \sigma]^T = \mathcal{F}([N, v_s, R]^T) \quad (3)$$

where the input vector comprises the primary operational variables and the output vector represents the fundamental coefficients governing the deposition. The establishment of this mapping, which is detailed in Sections 4.1 and 4.2, is essential for decoupling the geometric constraints of the substrate curvature from the spray kinematics. This provides a deterministic framework for predicting the thickness distribution and ensuring coating uniformity throughout the functional area.

In the context of ID-APS, when the radius of the workpiece approaches infinity, the deposition kinematics effectively converges to a planar spraying process. Consequently, characterizing the superposition effect of single-path profiles on planar substrates serves as a fundamental benchmark for understanding confined internal geometries. To achieve uniform coverage across the entire functional surface, the spray torch typically executes a zig-zag scanning path [18,37] with a prescribed step (d_{step}), leading to the linear accumulation of the coating thickness. Figure 4 illustrates the evolution of coating uniformity and cumulative thickness as a function of d_{step} , which can be mathematically described as

$$T(x) = \sum_{i=1}^n H_i(x) = \sum_{i=1}^n K \cdot \exp\left(-\frac{(x-x_i)^2}{2\sigma^2}\right) \cdot \left[1 + \operatorname{erf}\left(\frac{\alpha \cdot (x-x_i)}{\sqrt{2}\sigma}\right)\right] \quad (4)$$

where n denotes the number of spray paths. Given the equidistant nature of the deposition process, the position of each path x_i is defined by

$$x_i = x_0 + i \cdot d_{step} \quad (5)$$

The evolution of the coating profile as a function of the lateral step is illustrated in Figure 4a–c. At a relatively large d_{step} , as shown in Figure 4a, the individual spray paths remain spatially isolated with no significant kinematic interference between adjacent paths. As d_{step} decreases in Figure 4b, the superposition sum increases in magnitude; however, the profile exhibits distinct topographical fluctuations, indicating that the overlap is insufficient to achieve a smooth surface finish. With a further reduction in d_{step} in Figure 4c, a stable and smooth effective zone is successfully established in the central region, forming a uniform plateau. This plateau is flanked by transition regions, defined as the lateral distance, where the deposition thickness gradually tapers off due to the termination of the spray sequence at the boundaries.

To quantitatively evaluate the impact of d_{step} on the coating quality, three metrics are defined: Mean Thickness (T_{mean}), representing the average value within the effective zone; Flatness (T_{flat}), defined as the ratio of the minimum to the maximum thickness within the same zone; and Lateral Rate, which is the ratio of the lateral distance to the total span (the sum of the effective zone and lateral distance). Figure 4d presents a sensitivity analysis illustrating the response of these variables to changes in d_{step} . It is evident that increasing d_{step} leads to a gradual reduction in the Mean Thickness. Simultaneously, Flatness transitions from a stable 100% to lower values, indicating a loss of surface uniformity. In contrast, the lateral distance remains relatively stable, fluctuating within a narrow range of less than 20% of the total span (approximately 8 mm).

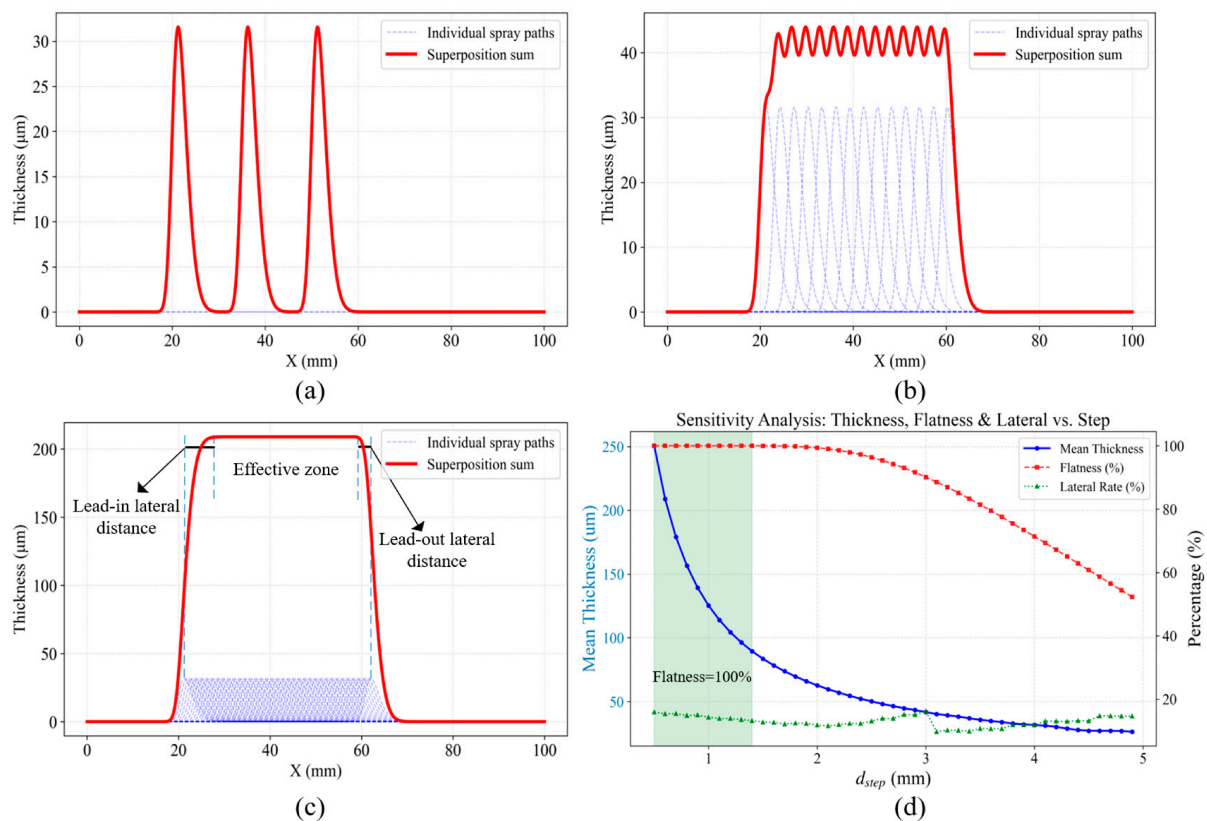


Figure 4. Investigation of coating deposition characteristics and parameter sensitivity: (a) Individual spray paths at a large step with negligible overlap; (b) topographical fluctuations in the cumulative thickness profile due to a moderate step; (c) formation of a stable effective zone and the definition of lateral distance at a further reduced step; (d) quantitative impact of step on the Mean Thickness, Flatness, and Lateral Rate.

In ID-APS of internal cylindrical channels, such as combustion chambers, the spray angle is largely dictated by the confined component geometry and the structural configuration of the internal diameter torch, rather than being an independently adjustable process variable as in conventional external spraying. Consequently, the impingement-induced asymmetry is an inherent characteristic of the hardware setup, and the skewness and scale parameters of the coating thickness profiles are expected to vary only slightly with changes in torch kinematics and substrate geometry. To systematically investigate the effects of α and σ on lateral distance, this study assumes a skewed distribution and varies the parameters within the ranges of $[0, 4]$ for α and $[1, 5]$ for σ . Figure 5 displays the response surfaces of the lateral distances on both sides. As shown in Figure 5a, the lead-in lateral distance (d_{in}) is primarily governed by σ , increasing significantly as σ expands. Figure 5b clearly demonstrates that the lead-out lateral distance (d_{out}) reaches its maximum when α is small and σ is large; conversely, a smaller d_{out} is obtained as α increases and σ decreases. In practical operations, a minimized total lateral distance is generally preferred. Thus, Figure 5c illustrates the sum of both distances ($d_{in} + d_{out}$). It is observed that when α is large (greater than 1), its impact on the total lateral distance becomes negligible; however, as σ increases, the lateral distance grows rapidly.

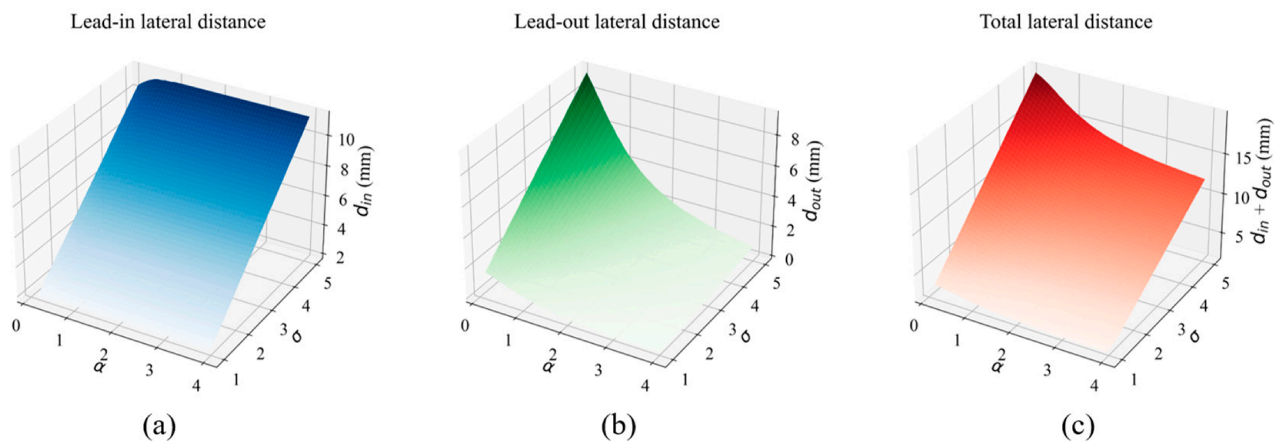


Figure 5. Response surfaces of lateral distances under varying skewness α and scale σ parameters: (a) Lead-in lateral distance d_{in} ; (b) Lead-out lateral distance d_{out} ; (c) Total lateral distance ($d_{in} + d_{out}$).

The mechanism of thickness accumulation described above elucidates the inherent coupling between the fundamental deposition mapping and the resulting macroscopic profile. This synthesis forms the basis of the kinematic-based superposition thickness model, which establishes a deterministic link:

$$\begin{bmatrix} T_{mean}, T_{flat}, d_{in}, d_{out} \end{bmatrix}^T \leftarrow [\mathcal{F}, d_{step}]^T \quad (6)$$

Within this framework, the mapping $\mathcal{F}$ characterizes the intrinsic distribution physics, while the lateral step d_{step} serves as the primary kinematic control variable for spatial accumulation. By integrating these parameters, the model enables the accurate prediction of the cumulative thickness profile and provides a quantitative mechanism for defining the transition regions. This kinematic-based approach facilitates the deterministic optimization of the spray trajectory, ensuring the formation of a stable thickness plateau across the functional surface.

2.3. Trajectory Planning and Thickness Prediction

To facilitate the migration of the kinematic model to practical industrial conditions, this study investigates the thickness performance of ID-APS based on an internal cylindrical surface geometry. The hierarchical relationships and governing factors within the operational environment are systematically organized in Figure 6. In the established framework, the thickness performance is characterized by four primary metrics: T_{mean} , T_{flat} , d_{in} , d_{out} . These outcomes are determined by the interplay between the kinematic step and the fundamental mapping $\mathcal{F}$. Specifically, the step is synthesized from the axial torch velocity and angular velocity. Concurrently, the mapping $\mathcal{F}$ encapsulates the combined influence of the number of spray times and the scanning velocity, the latter of which is also a function of the rotational kinematics (angular velocity and substrate inner radius). By elucidating these interdependencies, the model provides a comprehensive predictive pathway from machine-set parameters to the final coating profile on cylindrical workpieces.

As illustrated in the flowchart in Figure 7, this study establishes a systematic framework to transform fundamental kinematic parameters into a practical spray trajectory. The process encompasses the methodology for thickness prediction and the deployment of the real-world operational trajectory. The primary raw input parameters within this framework include the number of spray times, scanning velocity, radius of the workpiece, and the step. Initially, the first three parameters undergo high-precision curve fitting to derive the specific skew-normal distribution coefficients for the given operational conditions [38]. Subsequently, this distribution, along with all input parameters, is integrated into a sys-

temic correlation solver. This solver derives the corresponding control parameters for both the simulation environment and practical spraying scenarios; specifically, it outputs the axial torch velocity, lateral distances, mean thickness, and angular velocity. Following the derivation of these control parameters, the trajectory is visualized and rendered within a simulation environment to evaluate whether the equivalent trajectory intervals and predicted thickness values align with the thickness expectations. If the results are suboptimal, the raw input parameters are iteratively adjusted to modify the coating distribution. Once the requirements are satisfied, the validated trajectory and its associated control parameters are deployed for real-world operational spraying.

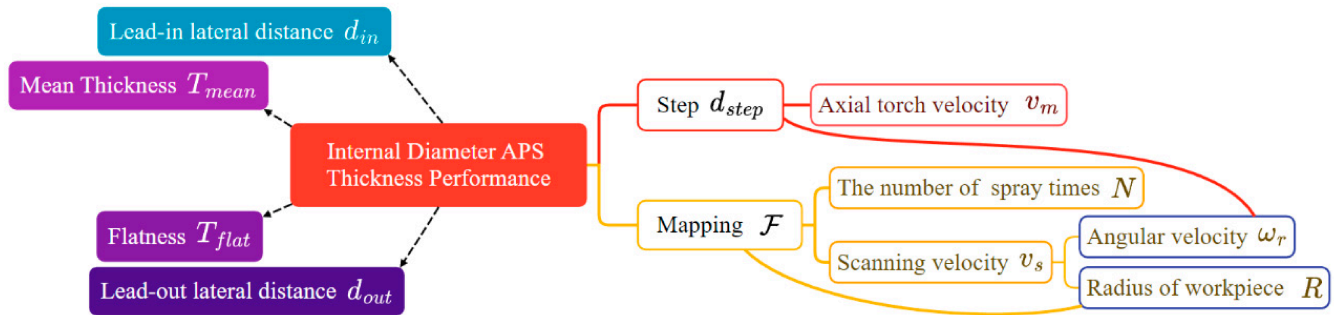


Figure 6. Hierarchical structure of the kinematic-based superposition thickness model illustrating the interdependencies between operational parameters and coating performance.

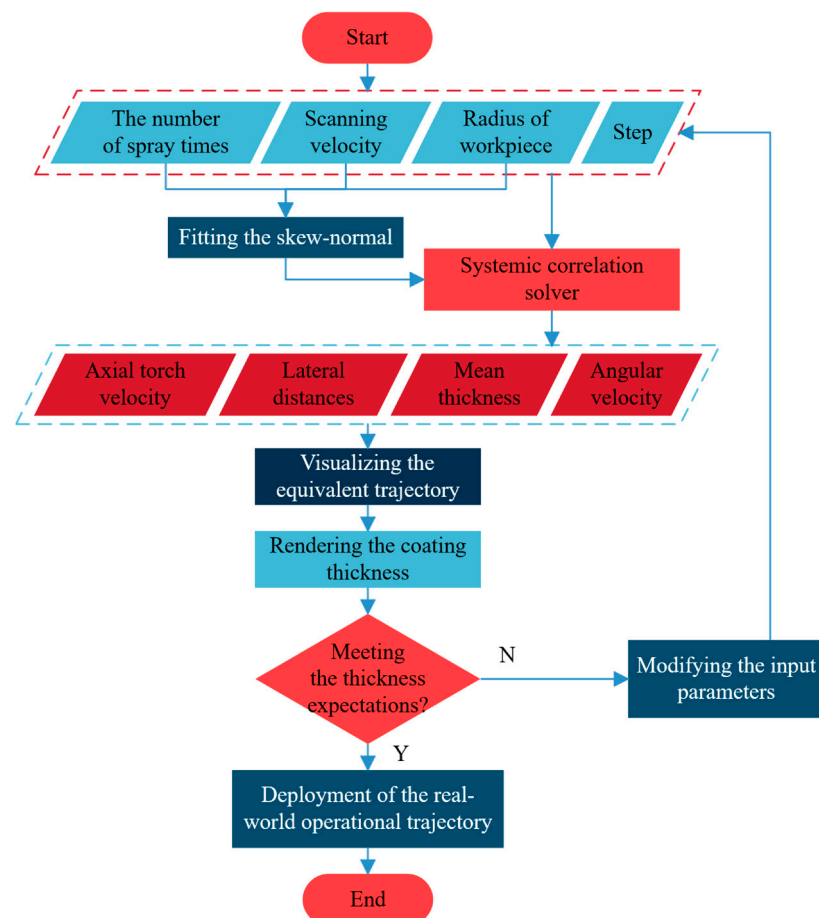


Figure 7. Flowchart of the systematic framework for trajectory planning and real-world deployment based on the predictive thickness model.

The pseudocode for the systemic correlation solver is detailed in Table 2. The derivation of control parameters is executed through a three-step computational process. Step 1: The solver calculates a smooth effective zone based on the superposition thickness model and the comprehensive set of input parameters. This allows the user to select an optimal step (d_{step}), during which the flatness (T_{flat}) is automatically computed. Once the d_{step} is finalized, the lateral distances (comprising d_{in} and d_{out}) are concurrently determined to ensure boundary coverage. Step 2: Based on the kinematic algebraic relationships, the solver derives the axial torch velocity (v_m) and angular velocity (ω_r) from the scanning (v_s) and radius of workpiece (R) velocity. Step 3: The mean thickness (T_{mean}) is obtained by integrating the coating thickness profile across the established effective zone. The solver's optimization logic guarantees that the resulting deposition profile achieves superior uniformity and reaches the necessary coverage extent mandated by standard spraying protocols.

Table 2. Systemic Correlation Solver for Trajectory Planning.

Input:
Raw input parameters: N, v_s, R
Define $\mathcal{F}$, get skew-normal K, α, σ of single spray paths
Step 1: Select d_{step}
for $d_{step} = 0$ to 3σ do
$(d_{in}, d_{out}) \leftarrow$ Superposition thickness model(α, σ, d_{step})
Calculate the effective zone ($x_{effective\ zone}$) of the cumulative coating profile
Compute the flatness $T_{flat} = T_{min}/T_{max}$ within effective zone
Determine the zone of flatness based on the criteria (e.g., $T_{flat} \geq 98\%$)
end for
Select d_{step} from the zone of flatness
Step 2: Get ω_r and v_m
$\omega_r = v_s/R$
$v_m = d_{step} \cdot \omega_r / 2\pi$
Step 3: Get T_{mean}
$T_{mean} = \int T(x)dx / x_{effective\ zone}$
Output:
$\omega_r, v_m, d_{in}, d_{out}, T_{mean}$

Figure 8 presents the numerical simulation results of the proposed equivalent trajectory within the cylindrical bore, as generated by the visualization system. The simulation environment integrates the structural boundary of the workpiece, represented by the translucent light blue bore surface, with the dynamic spray process. To precisely describe the spatial attitude of the deposition process, a local coordinate system $O_g - X_g Y_g Z_g$ is established at the spray torch nozzle. As illustrated, the primary spray axis Z_g in dark blue maintains a specific inclination angle relative to the surface normal, while the auxiliary axes X_g in light blue define the orientation of the spray deposition fan. This fan-shaped region, highlighted by the red shaded areas, represents the coverage area of the spray beam on the internal curved surface during the trajectory movement, directly determining the spatial distribution of the deposition thickness. The calculated kinematic path, shown as the red helical line, demonstrates that the axial torch velocity (v_m) and angular velocity (ω_r) results in a uniform scanning pattern across the internal surface. The scanning direction, indicated by the dark red arrows, confirms the continuity of the process from the lead-in (d_{in}) to the lead-out (d_{out}) zones, ensuring that the steady-state deposition phase fully covers the effective coating area. This simulation-based approach offers a significant advantage by enabling the iterative optimization of process parameters within a virtual environment. By preemptively identifying the conditions for achieving a homogeneous coating thickness, this method substantially reduces the necessity for extensive physical “trial-and-error”

experiments, thereby minimizing material waste and shortening the development cycle for complex bore coating applications.

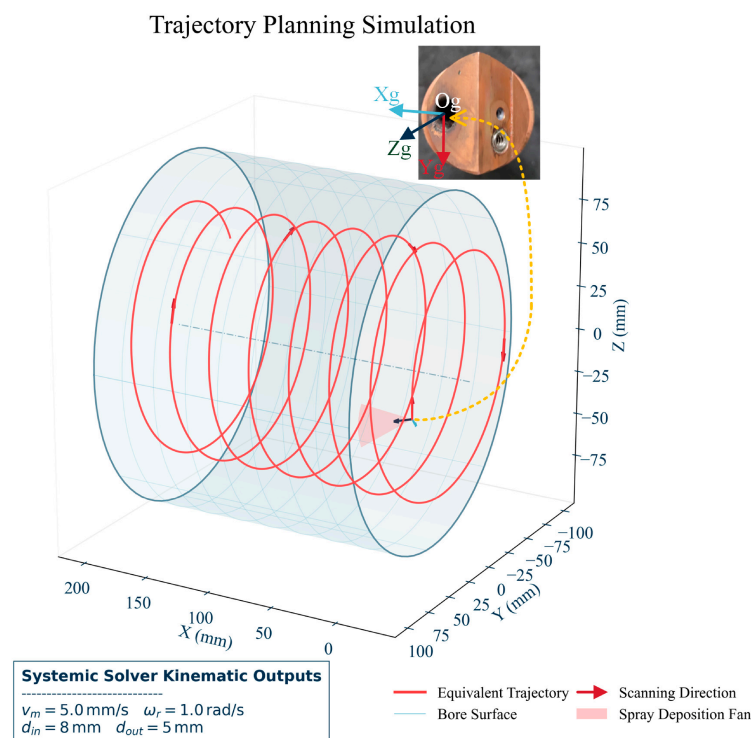


Figure 8. Numerical simulation and kinematic visualization of the equivalent trajectory for the internal bore coating process.

3. Experiments

3.1. Experimental Setup

The experiments focused on the APS bond coat deposition within the internal diameter of the base, utilizing a CoNiCrAlY alloy [39]. The chemical composition of the feedstock powder is detailed in Table 3. The spraying process was performed using an Oerlikon Metco UnicoatPro™ system (Oerlikon Metco, Wohlen, Switzerland) equipped with a Praxair 2086A plasma torch (Praxair Surface Technologies, Indianapolis, IN, USA). All experiments were conducted at a constant standoff distance of 55 mm, with the specific process parameters summarized in Table 4.

Table 3. Chemical composition of the CoNiCrAlY bond coat powder (wt.%).

Composition	Co	Ni	Cr	Al	Y
Percent	37.02	31.97	21.78	8.60	0.51

Table 4. Spray process parameters for the deposition of the coating.

Spray Parameters	Ar Flow (NLPM)	He Flow (NLPM)	Current (A)	Powder Feed (g/min)	Carrier Gas Flow (NLPM)
Value	55	20	560	30	7

3.2. Data Acquisition and Processing

Prior to thermal spraying, the substrate surfaces were grit-blasted using white fused alumina to generate an anchor profile with an average surface roughness (R_a) of 4–6 μm .

Given that the final coating thickness in this study is on the order of several hundred micrometers, a clear separation of length scales exists between the initial surface topography and the macroscopic coating build-up. The influence of the anchor profile is therefore primarily confined to the first-stage particle impingement and local valley filling, which may introduce a small effective initial offset in thickness. However, this effect is not expected to significantly affect the subsequent coating growth governed by the kinematic deposition model, nor does it significantly modify the spatial distribution shape of the coating profile. Consequently, the anchor profile is not explicitly included in the macroscopic thickness prediction model, except as an implicit contribution to the initial condition.

The spraying process is schematically illustrated in Figure 9. To accurately quantify coating thickness variations induced by diverse kinematic parameters, both planar and curved substrates were employed, each integrated with specific fixtures to facilitate precise alignment. Figure 9a depicts the relative positioning of the planar substrate with respect to the spray torch, where the deposition process was primarily executed through the translational motion of the torch along the Y-axis. In contrast, Figure 9b demonstrates the mounting configuration for curved substrates. By utilizing custom-designed fixtures to accommodate substrates with varying curvatures and securing them onto a rotary table, the actual internal diameter spraying environment was effectively simulated. This setup enabled the acquisition of internal surface coating samples under realistic operational conditions, providing a robust basis for the subsequent thickness modeling.

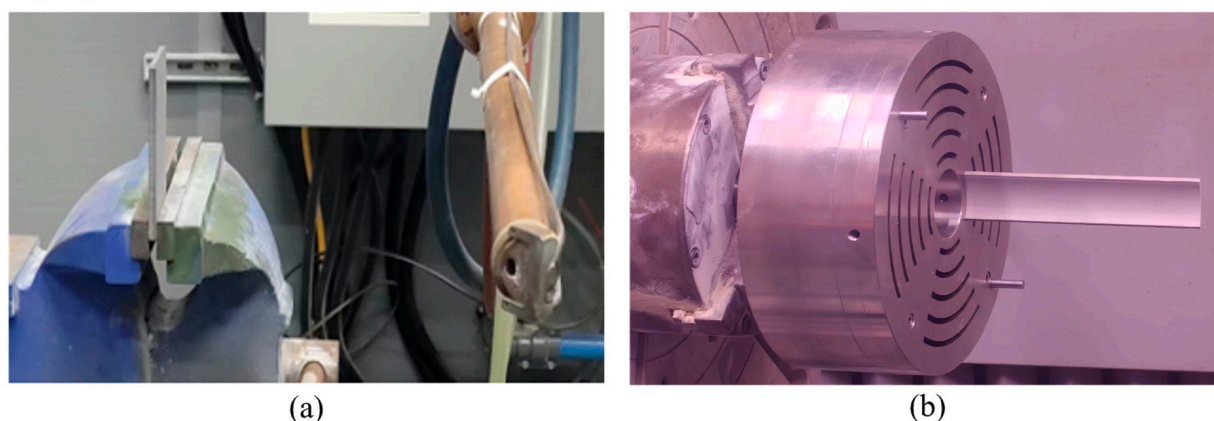


Figure 9. Schematic of the experimental configurations and substrate mounting for planar and internal diameter spraying: (a) Planar substrate setup for Y-axis translational spraying; (b) Curved substrate mounting for rotational internal diameter spraying.

Following the acquisition of sample data, a five-step data preprocessing phase was implemented to refine the raw measurements. In steps 1 through 3, the specimen coated via ID-APS, as depicted in Figure 10a, was digitized using the profile scanner shown in Figure 10b. Prior to the scanning procedure, the profile scanner was configured to the continuous trigger mode illustrated in Figure 10c to verify that the topographical height range of the coated surface was entirely encompassed within the sensor's acquisition window. Subsequently, the complete point cloud data of the sprayed surface was captured through the integration of the scanner's encoder model. In the succeeding steps 4 and 5, the acquired point cloud was processed to extract the axial data distribution along the X-axis. First, a spatial slice of the point cloud was obtained along the center of the Y-axis, as shown in Figure 10d. To compensate for minor structural deformations and angular inclinations occurring during the acquisition process, a linear regression analysis was performed on the data points within the unsprayed regions (Figure 10e) to establish a baseline, indicated by the red reference line. Based on this baseline, a rotational transformation defined by

the angle θ , together with translational shifts along the X- and Y-directions, was applied to obtain the normalized scatter distribution shown in Figure 10f. Finally, the processed data points were characterized using a skew-normal distribution to fit the final profile curve of the deposition. By relying on direct measurements of the final coating profiles, the proposed thickness modeling framework is formulated as a data-driven phenomenological approach. In actual ID-APS operations, variations in kinematic parameters influence the local thermal history, including substrate temperature fluctuations, which may in turn affect particle flattening behavior and deposition efficiency. However, because the deposition intensity, skewness, and scale parameters of the skew-normal distribution are extracted directly from experimentally scanned topographies, these coupled thermal and kinematic effects are implicitly embedded in the measured profiles [20,40].

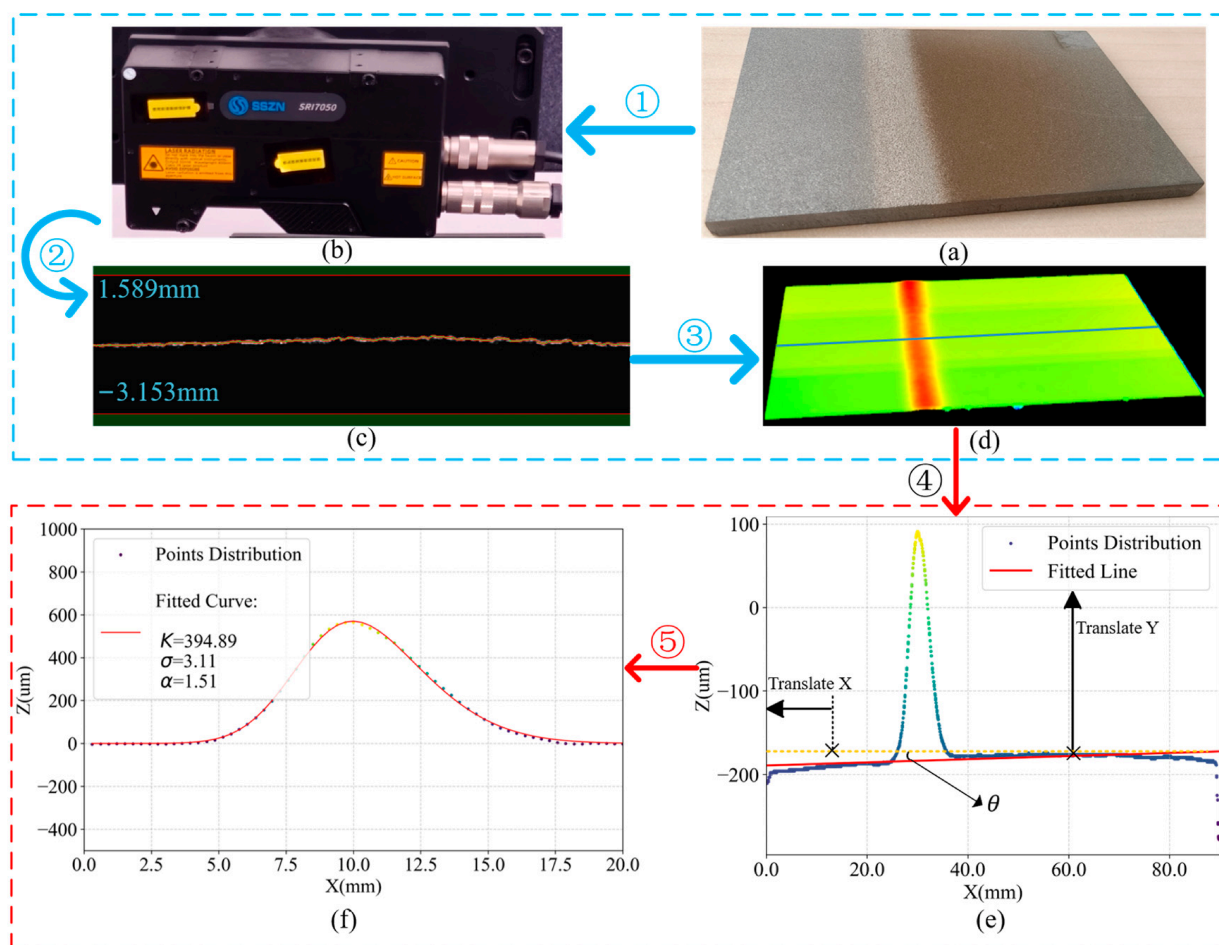


Figure 10. Schematic of the data preprocessing workflow for extracting the deposition profile from ID-APS coated samples. (a) As-sprayed surface. (b) Profile scanner. (c) Data acquisition window in continuous trigger mode. (d) Point cloud cross-sectional slicing. (e) Linear baseline correction, with the red reference line indicating the established baseline and θ representing the rotational transformation angle. (f) Normalized profile for skew-normal fitting.

In the numerical simulation, the curved workpiece was meshed using ANSYS 2025 R1 [41]. The skew-normal distribution was mapped onto the internal curved surface, with the thickness distribution sampled at the mesh nodes. The resulting coating thickness was then rendered directly onto these nodes, as illustrated in Figure 11, providing an intuitive visualization of the coating thickness evolution during the thermal spray process.

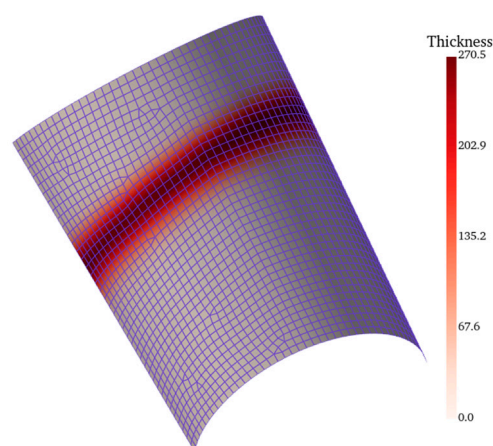


Figure 11. Coating thickness simulation on the internal curved surface using mesh-node sampling and skew-normal modeling.

4. Results and Discussion

4.1. Model Fitting

As presented in Table 5, recurrent single-path spraying experiments were first conducted on planar substrates, which were treated as a special case of infinite radius ($R \rightarrow \infty$). These tests aimed to quantify the effects of scanning velocity and the number of spray times (N) on the deposition thickness. Subsequently, experiments on curved substrates were performed (Table 6) to investigate the influence of curvature on the thickness distribution. The number of spray times was precisely governed by the spraying time using the algorithm described in Table 2. Following the spraying process, profile data were collected and pre-processed to characterize the coating distribution.

Table 5. Parameter configurations for scanning velocity and the number of spray times on planar substrates.

No.	v_s (mm/s)	R (mm)	N
1–5		∞	6
6–10	200/300/400/	∞	12
11–15	500/600	∞	18
16–20		∞	24

Table 6. Experimental parameters for curved substrates with varying radii of curvature.

No.	v_s (mm/s)	R (mm)	t (s)	ω ($^\circ$ /s)
1–4	400	40	7.54/11.31	572.94
	600		5.03/7.54	859.41
5–8	400	60	11.31/16.97	381.96
	600		7.54/11.31	572.94
9–12	400	80	15.08/22.62	286.47
	600		10.05/15.08	429.71
13–16	400	100	18.85/28.27	229.20
	600		12.57/18.85	343.80
17–20	400	120	22.62/33.93	190.98
	600		15.08/22.62	286.47

To evaluate the fitting accuracy of the skew-normal distribution for the coating profile of recurrent single-path spraying on planar substrates, the Mean Absolute Error (MAE) was employed [42]:

$$MAE = \frac{1}{n} \sum_{i=1}^n |h_{pred,i} - h_{true,i}| \quad (7)$$

where $h_{pred,i}$ and $h_{true,i}$ represent the predicted thickness from the fitting curve and the experimentally measured thickness at each data point, respectively. Figure 12 illustrates the maximum thickness and the corresponding MAE under various parameter configurations. Generally, a higher scanning velocity leads to a reduction in the maximum thickness, while an increase in the number of spray times results in a higher maximum thickness. This phenomenon is primarily attributable to the influence of scanning velocity and the number of spray times on the mapping parameters defined in Equation (3), a response mechanism that will be elaborated upon in the subsequent sections. Notably, since the number of data points in each measured slice remains constant, the calculated MAE is intrinsically sensitive to the overall coating thickness. As the thickness increases, the deviations from a few outliers are proportionally magnified. Nevertheless, in this study, all MAE values remained below 7 μm , even under conditions of reduced scanning velocity and increased spray passes. This consistently low error margin validates the robustness of the skew-normal model in accurately describing the coating profile across varying process intensities.

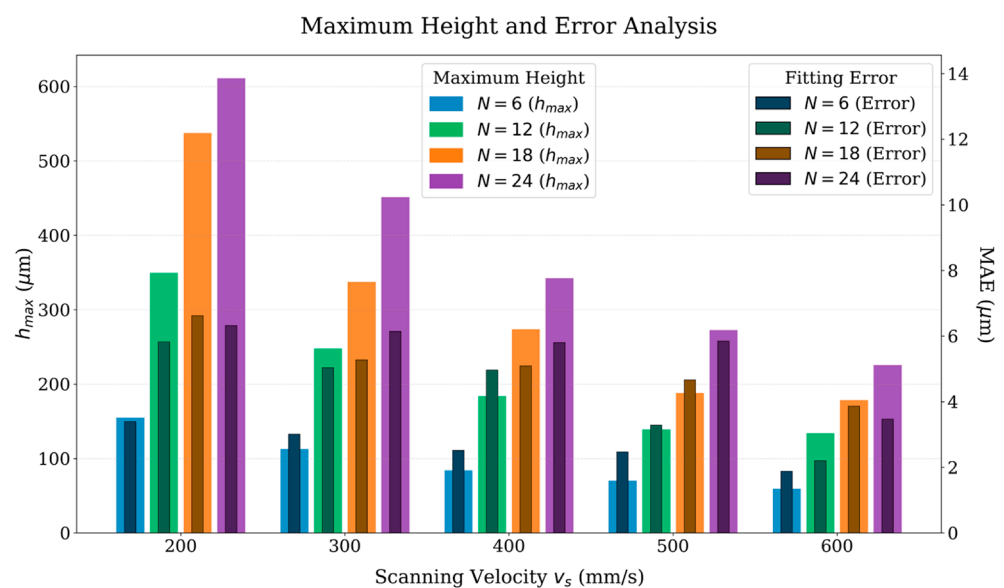


Figure 12. Maximum coating thickness and Mean Absolute Error (MAE) under different scanning velocities and numbers of spray passes.

4.2. Effects of Kinematic and Geometric Parameters

To systematically investigate the effects of kinematic and geometric parameters on the final coating profile, the experimental operating window was strictly defined in accordance with the hardware specifications of the internal diameter spray torch and established industrial norms. Confining the study within this regulated domain guarantees that the resulting phenomenological models remain physically realistic and practically applicable. Operating within these strict boundaries, all essential mathematical parameters used for thickness prediction, including the skewness parameter, the scale parameter and the deposition intensity, were extracted directly from experimentally measured profiles under their corresponding operating conditions.

To establish the mapping relationship defined in Equation (3), the influences of varying kinematic parameters on α and σ were investigated based on the experimentally fitted

single-path deposition profiles. The resulting scatter distribution is shown in Figure 13. As the substrate geometry gradually changes from a curved surface to a planar surface, which corresponds to an increasing radius of curvature, α generally decreases while σ increases. This indicates that the fitted deposition profile evolves from a relatively narrow and asymmetric distribution to a broader and more symmetric distribution. In this study, α and σ are used as empirical fitting parameters to quantify the shape characteristics of the measured deposition profile. Specifically, σ describes the effective spreading width of the fitted profile, while α characterizes the degree of profile asymmetry. Therefore, the decrease in α and increase in σ with increasing radius of curvature indicate that the curvature-dependent deposition behavior can be represented by a systematic change in the fitted profile shape. This parameter evolution provides the basis for selecting appropriate lateral distances in the subsequent trajectory planning process.

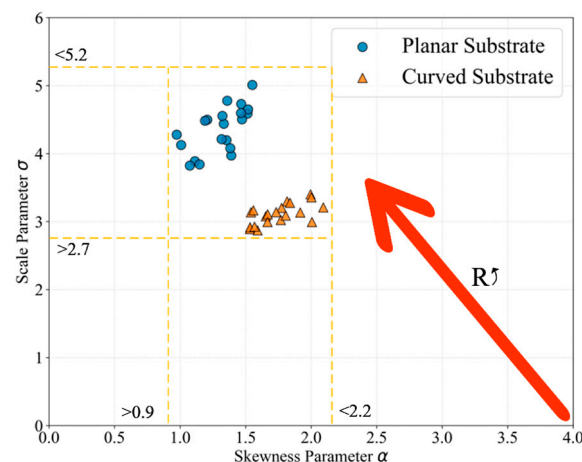


Figure 13. Evolution of fitting skewness, and scale parameters under different substrate curvatures. The red arrow indicates the evolutionary trend of the skewness and scale parameters as the substrate's radius of curvature increases. The yellow dashed lines define the boundary ranges within which all experimental results are concentrated.

Ultimately, all experimental results are concentrated within the range of $\alpha \in [0.9, 2.2]$, $\sigma \in [2.7, 5.2]$. Figure 5 indicates that, by using a smaller α and a larger σ within an appropriate range determined by the radius of curvature, the lateral distance can be maintained with an adequate redundancy margin.

Subsequently, the influence of key variables on deposition intensity K was analyzed. Given the physical characteristics of the coating process, the effects of scanning velocity v_s and the number of spray times N on the peak thickness were first investigated using planar samples. A smooth 3D surface plot was fitted, as shown in Figure 14a, which clearly illustrates the contribution of v_s and N to the deposition intensity under different parameter configurations. It can be observed that K increases as v_s decreases or N increases. Notably, the impact of N on K exhibits a strictly linear superposition, whereas the scanning velocity v_s demonstrates a pronounced non-linear relationship with the deposition intensity. This linear behavior of N is primarily attributed to the constant powder feed rate and plasma power; each pass delivers a consistent mass of material and heat input. Once a thermal steady state is reached, the boundary conditions for the N -th and $(N + 1)$ -th passes become identical, ensuring an additive deposition process. In contrast, at a fixed feed rate and number of passes, the number of particles intercepted per unit area follows an inversely proportional relationship with the scanning velocity.

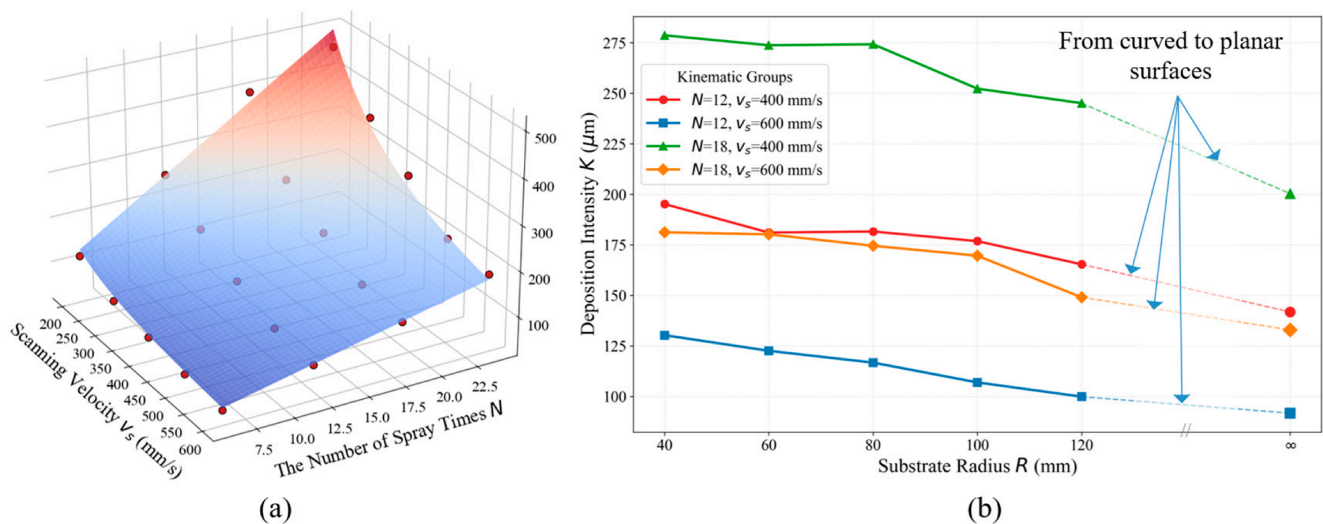


Figure 14. Analysis of deposition intensity patterns: (a) 3D response surface showing the combined effects of scanning velocity and the number of spray times on planar substrates; (b) Variation in deposition intensity as a function of curvature radius across different experimental groups.

Figure 14b depicts the variation in intensity as a function of curvature across various scanning velocities and numbers of spray times. All curves exhibit a downward trend as the radius of curvature increases, and this attenuation phenomenon becomes particularly pronounced at higher deposition intensities. This clearly demonstrates that the geometric curvature exerts a non-negligible influence on the final coating thickness. Although its impact may appear secondary to the kinematic parameters when the difference in curvature radius is minimal, its cumulative effect becomes highly significant in practical ID-APS applications.

4.3. Thickness Measurement and Verification

Fundamentally, spatial fluctuations in the coating distribution serve as a physical manifestation of temporal process instabilities. Consequently, to evaluate the practical efficacy of the proposed modeling approach, this study acquired thickness profiles at various cross-sections through both macroscopic digital slicing and microscopic physical sectioning. As illustrated in Figure 15, the substrates utilized throughout these experiments consisted of 60° partial cylindrical surfaces. The left side designates the clamping area required for securing the substrate during the spraying process, whereas the right side indicates the spraying area. The effective spraying area is strictly bounded between d_{in} and d_{out} . By sampling the coating thickness data strictly within this area, macroscopic spatial variations were extracted by digitally slicing the left-view cross-section at discrete angular intervals γ . Concurrently, physical cross-sections were cut at predetermined intervals L along the effective spraying area to facilitate high-resolution microscopic thickness measurements via SEM observation at distinct locations.

As shown in Figure 16, the workpiece was scanned before and after spraying using a profile scanner. The upper and lower images on the far right display the sandblasted substrate and the coating, respectively. The blue dashed line distinguishes the clamping area from the spraying area. In the point cloud visualization, blue points represent the initial substrate surface, while red points denote the surface after spraying. To align the datasets, manual feature matching was first performed in the clamping area of scanner images. Since the scanner images correspond directly to the point cloud data, this allowed for coarse registration. Finally, a multi-scale Iterative Closest Point (ICP) algorithm [43] was applied to the clamping area to achieve fine registration. To establish a rigorous metrological basis for

evaluating the model accuracy, the uncertainty associated with the thickness measurement procedure was assessed. The profile scanner employed in this work has a nominal accuracy of $\pm 3.2 \mu\text{m}$. To further evaluate the fidelity of the point-cloud alignment used for thickness extraction, the result of the ICP-based registration was evaluated within the rigid clamping region, yielding a residual RMSE of $16.5 \mu\text{m}$. As the aligned point clouds were acquired using the same scanning system, this residual error represents the cumulative effect of scanner noise, slight clamping-induced deformation, and registration uncertainty.

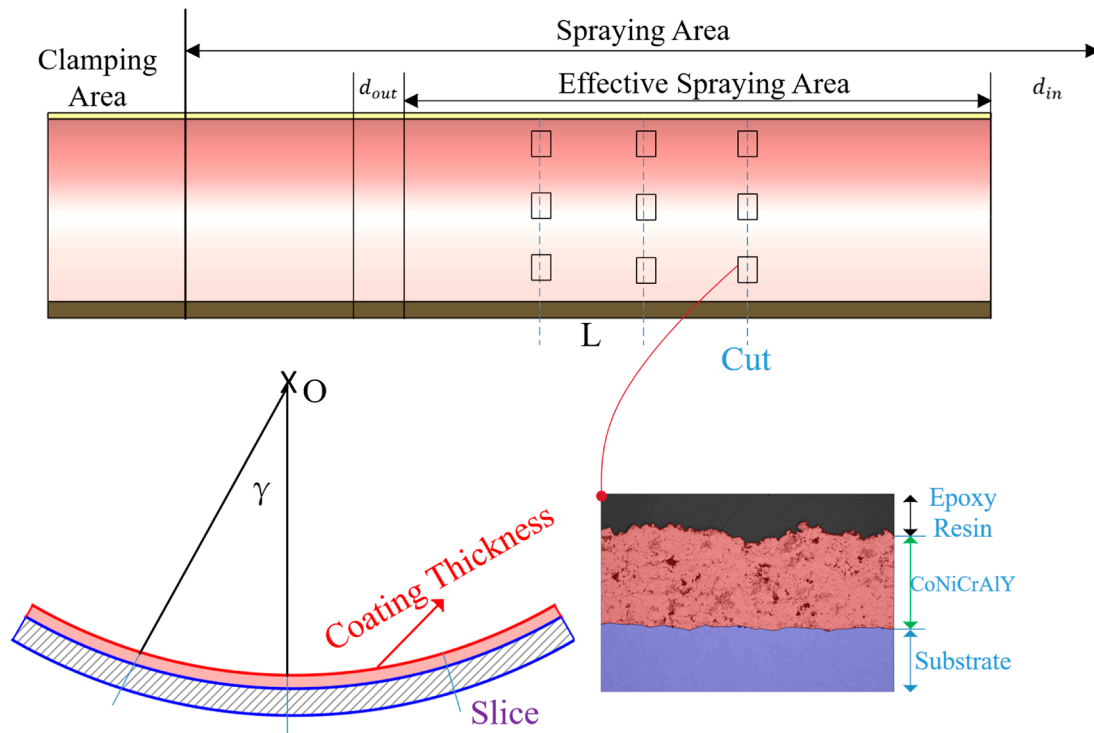


Figure 15. Schematic of the macroscopic digital slicing and microscopic physical sectioning procedures for coating thickness evaluation.

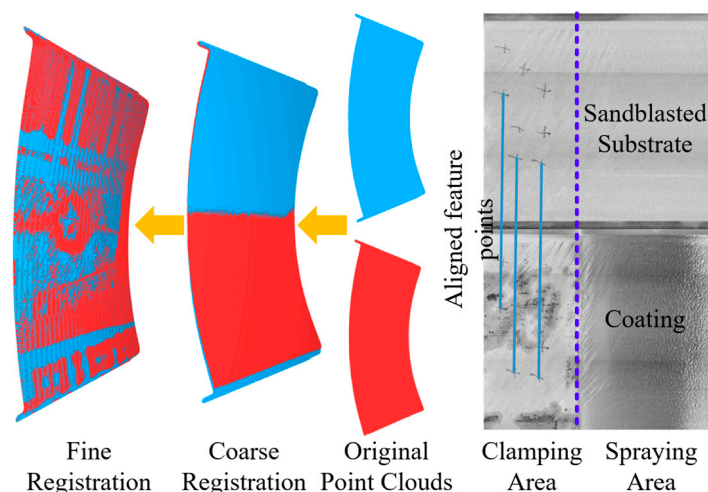


Figure 16. Point cloud registration based on the clamping area for the internal cylindrical workpiece before and after spraying. In the point cloud models, the blue and red points represent the initial substrate surface and the as-sprayed surface, respectively. In the rightmost images, the blue dashed line distinguishes the clamping area from the spraying area, and the solid blue lines indicate the aligned feature points used for registration.

Upon completing the fine registration of the point clouds in the clamping area, a visualization of the global point clouds was generated, as shown in Figure 17a. In the spraying area, the red point cloud (post-spraying) completely covers the initial blue point cloud (pre-spraying). Figure 17b illustrates the calculated coating thickness distribution, where the dark red regions signify greater thickness. To further analyze the profile, the 3D point cloud was sliced along the horizontal direction to obtain cross-sectional contours before and after spraying, as presented in Figure 17c. The transition from the clamping area on the left to the spraying area on the right shows a progressively more pronounced change in thickness. Correspondingly, Figure 17d displays the thickness variation at the same position as Figure 17c, consistent with the overall trend observed in Figure 17b. The coating thickness within the sprayed area is uniformly distributed, exhibiting a distinct step-change compared to the unsprayed area.

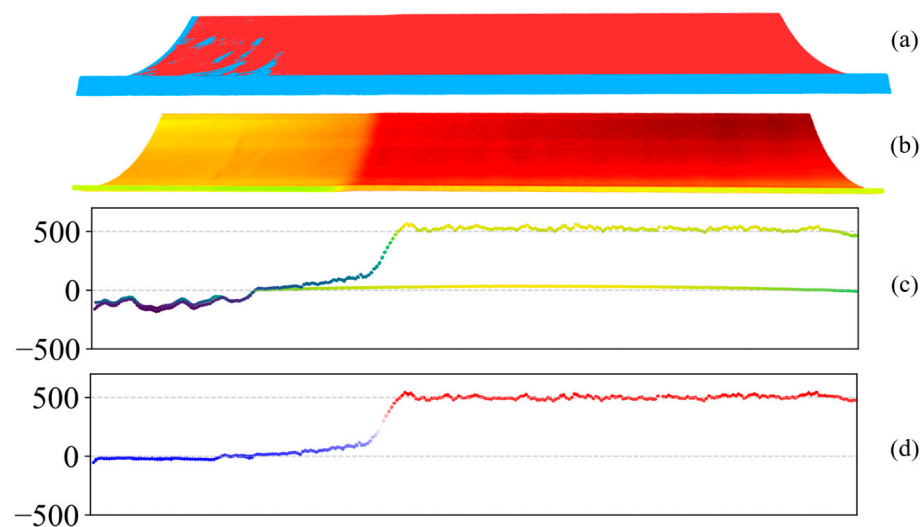


Figure 17. Visualization and quantitative characterization of the coating thickness distribution: (a) Global point cloud overlay of the red (post-spraying) and blue (pre-spraying) datasets; (b) 3D thickness distribution map showing the coating depth variations; (c) Horizontal cross-sectional profiles across clamping and spraying areas, where the upper and lower lines represent the post-spraying and pre-spraying profiles, respectively; (d) Thickness variation curve corresponding to the cross-sectional profile, with the color transition from blue to red highlighting the progression from the unsprayed clamping area to the fully sprayed area.

Figure 18 presents microscopic images acquired from three representative locations along a single cut. The coating–substrate interface and the outer coating surface can be clearly distinguished, enabling direct thickness measurement from the cross-sectional morphology. Compared with the macroscopic profile scanning method, microscopic observation provides a higher spatial resolution and allows the local coating morphology, including surface roughness and interlamellar stacking features, to be examined simultaneously. The measured coating thicknesses across these different selected sampling locations remain within a consistent range, indicating good local thickness uniformity along the examined cut.

To simulate and validate the thickness prediction performance of the model over the entire sprayed surface, the mapping relationship defined in Equation (6) was established following the flowchart presented in Figure 7. Table 7 details the six distinct experimental cases utilized for coating thickness evaluation. To ensure rigorous cross-scale validation, two independent replicate spray runs were executed for each configuration: the first run was dedicated to macroscopic profile scanning, while the second was reserved for microscopic image measurement. The parameters R , N , v_s listed in the table were derived from

the mathematical fitting of the recurrent single-path spray profile deposited on a curved surface. Furthermore, d_{step} was strictly selected according to the procedure outlined in Table 2, ensuring that the coating flatness achieved the optimal 100%. Based on these designated inputs, the actual operational parameters, ω_r and v_m , were calculated. Concurrently, $d_{in} = 7$ mm and $d_{out} = 2.5$ mm were defined according to the data distribution illustrated in Figure 13. Ultimately, the uniform coating thickness T_{mean} across the internal cylindrical surface was successfully predicted through this comprehensive simulation framework.

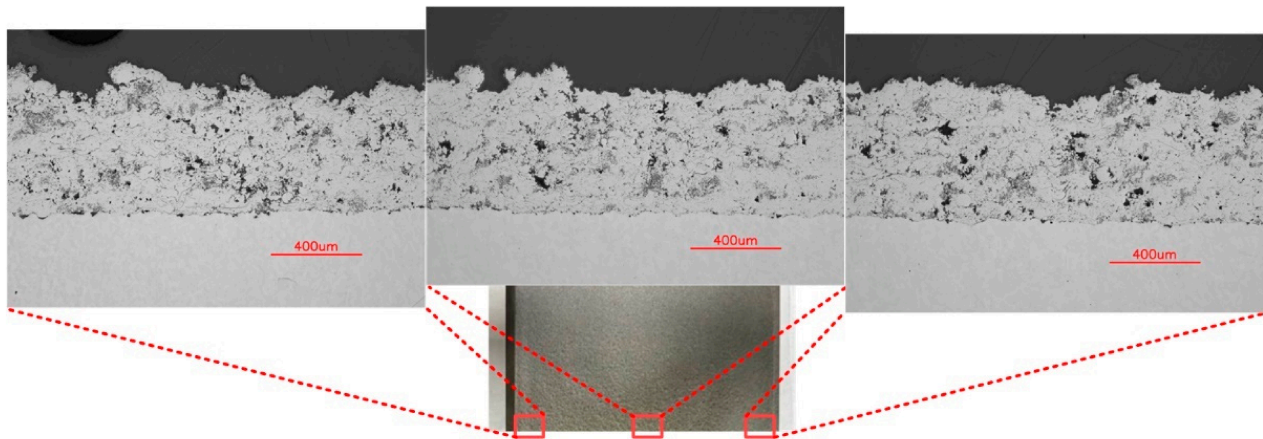


Figure 18. SEM micrographs of coating cross-sections at different locations for thickness uniformity verification.

Table 7. Experimental cases and corresponding predicted thicknesses for coating evaluation.

No.	R (mm)	N	v_s (mm/s)	d_{step} (mm)	ω_r (°/s)	v_m (mm/s)	T_{mean} (µm)
1	40	12	600	1.8	859.44	4.30	493.57
2	60	12	600	1.8	572.96	2.87	472.10
3	60	18	400	2.8	381.97	2.97	780.54
4	80	12	400	2.8	286.48	2.23	459.45
5	100	18	600	1.8	343.77	1.72	708.81
6	120	12	600	1.8	286.48	1.43	407.02

Figure 19 presents the cross-scale verification results of the thickness prediction model for all experimental cases listed in Table 7. Specifically, for the macroscopic profile measurement, a predefined sampling protocol was used to ensure consistency among all experimental cases. Five profile lines were extracted from the central region of the reconstructed cross-sectional profile at an angular interval of $\gamma = 5^\circ$. The edge regions were excluded to minimize the influence of boundary effects, overspray accumulation, and possible profile distortion during reconstruction. For the microscopic thickness evaluation, cuts were made within the same central effective spraying area. The spacing between adjacent cuts was set to $L = 6$ mm. For each cut, at least three non-overlapping fields of view were selected for high-resolution microscopic imaging, resulting in at least nine microscopic images for each experimental case. The microscopic thickness values were then averaged to obtain a representative local thickness, while the standard deviation was used to characterize local thickness variation within the examined region. As shown in Figure 19a, the standard deviations of the microscopic measurements are generally smaller than those of the macroscopic measurements. This difference can be attributed to the different spatial scales and uncertainty sources involved in the two measurement methods. The macroscopic profile measurements include not only local thickness variations, but

also global process fluctuations along the scanning trajectory, instrumental noise from the scanner, and registration errors introduced during point-cloud alignment. In contrast, the microscopic measurements were obtained from multiple discrete cross-sectional fields of view at different positions. Therefore, their standard deviations mainly represent thickness variations among the sampled local regions, rather than the continuous global thickness fluctuations captured by macroscopic profile scanning. To further quantify the predictive accuracy, Figure 19b shows a parity plot with a $\pm 12\%$ error band. The measured thickness values obtained from both macroscopic and microscopic methods are in good agreement with the predicted values, with all data points located within the shaded tolerance band. The macroscopic measurements yield an MAE of $34.83\ \mu\text{m}$ and a mean relative error (MRE) of 6.39% , while the microscopic measurements show a lower MAE of $20.17\ \mu\text{m}$ and an MRE of 3.47% . These results indicate that the proposed thickness prediction model can provide reliable thickness estimates across the investigated spraying conditions.

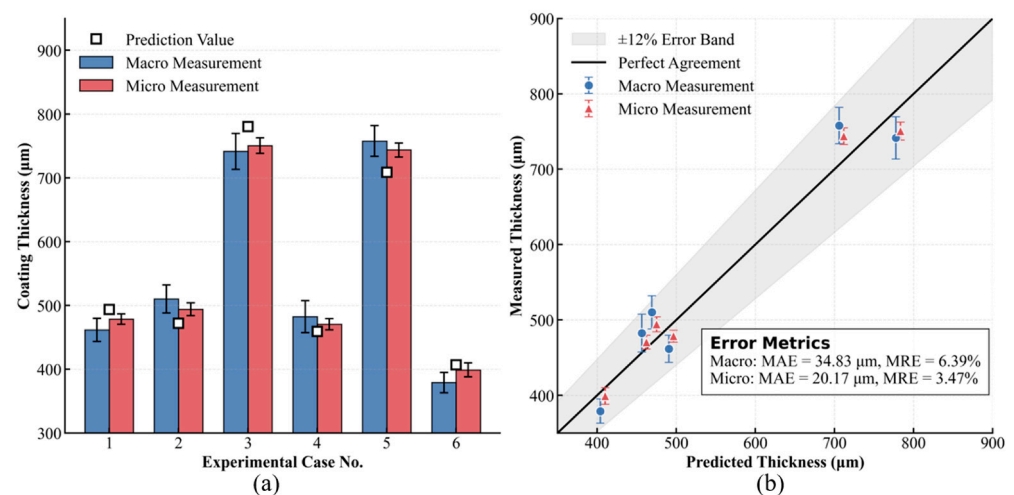


Figure 19. Quantitative cross-scale validation of the thickness prediction model: (a) Comparison of predicted values with macroscopic and microscopic measurements across six experimental cases; (b) Parity plot demonstrating the overall predictive accuracy with a $\pm 12\%$ error band and inset error metrics.

5. Conclusions and Outlook

In this study, a kinematic-based thickness prediction and uniformity control framework was developed for ID-APS on internal cylindrical surfaces. To describe the asymmetric deposition profile caused by inclined spraying, a skew-normal model was introduced to fit the single-path thickness profile. Based on this profile representation, a superposition model was established to connect the single-path deposition behavior with process kinematics and cylindrical geometric constraints.

Single-path experimental results demonstrate that the skew-normal formulation can effectively characterize the asymmetric coating profiles produced by ID-APS. Deposition intensity increased with the number of spray times and decreased with increasing scanning velocity, whereas the radius of curvature affected profile skewness and spreading width, thereby affecting the lateral distance. As the key parameter governing the transition from single-path deposition to surface coverage, the step size ultimately determined the uniformity and flatness of the cumulative coating thickness, making it critical for trajectory planning and quality control.

The proposed thickness prediction model was implemented in a prediction workflow for internal cylindrical surfaces and evaluated under representative ID-APS conditions. A cross-scale validation strategy combining macroscopic surface reconstruction and mi-

croscopic cross-sectional imaging showed good agreement between the predicted and experimentally measured mean thickness values. The measured mean thickness values generally remained within the engineering error band, and the microscopic measurements exhibited smaller deviations than the macroscopic measurements. These results indicate that the proposed framework can provide reliable thickness estimates for ID-APS trajectory design and coating uniformity control on internal cylindrical surfaces, thereby reducing the reliance on extensive empirical parameter tuning for confined internal geometries.

While the current study demonstrates the effectiveness of the proposed framework for internal cylindrical surfaces, future work will focus on expanding its applicability to a broader range of engineering scenarios. Since the skewness and scale parameters of the mathematical model are currently calibrated for a specific coating material, subsequent research will systematically investigate the framework's adaptability to alternative materials with varying powder properties. This could be efficiently facilitated by developing rapid calibration methodologies, such as spot spraying experiments, to swiftly extract the appropriate mathematical model parameters for different material systems. Furthermore, to address more complex internal geometrical configurations, such as variable-diameter bores or non-uniform transitions, future efforts will extend the current kinematic superposition algorithms. This will involve developing advanced geometric mapping strategies to continuously capture the geometric distortion of the thickness profile under varying surface curvatures and dynamically shifting kinematic constraints. Concurrently, to directly substantiate the physical mechanisms underlying these curvature effects, future investigations will integrate computational fluid dynamics simulations with advanced in-flight diagnostics. Such a multiphysics approach will provide empirical insights into the aerodynamic confinement phenomena. These future developments will further generalize the proposed approach, providing a universal trajectory planning and thickness control tool for complex internal coating applications.

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