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Optimization of Coating Thickness Parameters and Prediction of Optimal Range in the Cold Spray Process

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Abstract

This research investigates the optimization of electro-conductive coatings using the cold spray process, employing a Taguchi L18 experimental design. The study focuses on the influence of various process parameters on coating thickness, including substrate material, powder feeding arrangement, stagnation gas temperature, stagnation gas pressure, and standoff distance. Three levels of each parameter were tested: substrate materials (Aluminum alloy, Brass, and Ni alloy), powder feeding types (Gravity and Argon feeders), stagnation pressures (98, 104, and 108 psi), stagnation temperatures (360°C, 380°C, and 400°C), and standoff distances (2, 4.5, and 7 mm). The results indicate that the optimal coating thickness is achieved with an Argon powder feeder, Aluminum alloy substrate, stagnation pressure of 110 psi, stagnation temperature of 400°C, and a standoff distance of 4.5 mm. The typical coating thickness for the low-pressure cold spray process was found to be 1.63 mm, within the predicted confidence interval. Statistical analysis, including Analysis of Variance (ANOVA) and Signal-to-Noise (S/N) ratio, was performed to identify the significant factors influencing coating thickness. The percentage contribution of each process parameter was determined, revealing that the most influential factors, in decreasing order of importance, are standoff distance, stagnation gas temperature, substrate material, stagnation gas pressure, and powder feeding arrangement. These findings provide valuable insights into optimizing the cold spray process for high-quality electro-conductive coatings.

Keywords
Cold Spray Process, ANOVA, Taguchi L18 Design, Process Optimization, Coating Thickness

1. Introduction
Coating refers to a layer of material, either naturally or artificially applied, to the surface of another material. This layer serves to enhance the surface properties of the base material, providing essential technical or aesthetic benefits. Coatings act as protective barriers, shielding the underlying material from environmental factors, such as corrosion, wear, or temperature extremes, thereby extending the life and performance of the component (Sharun et al. 2022), (Darband, Aliofkhazraei, Khorsand, Sokhanvar, & Kaboli 2020). The process of applying coatings can be achieved through various methods, each with its specific characteristics and applications. In the case of thermal spraying, for example, the thermal or mechanical energy of particulate material is used to deposit coatings on a substrate (Fauchais & Vardelle 2012). However, these methods often involve high temperatures, which can lead to detrimental effects

such as oxidation, degradation, and other harmful alterations in coating quality (Pielichowski, Njuguna, & Majka, 2022). One promising alternative to traditional thermal spraying techniques is the Cold Spray (CS) process, which was first developed in the mid-1980s at the Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences in Novosibirsk. The Cold Spray (CS) process has demonstrated significant success in depositing a diverse range of pure metals, metal alloys, and composite materials onto various substrate surfaces (He, 2023). Unlike conventional thermal spraying, the CS process relies on high-velocity particles, rather than elevated temperatures, to form coatings. This distinction significantly reduces the heat-related detrimental effects commonly seen in traditional spraying processes, making CS an attractive method for producing coatings with improved quality and durability (K. Tan et al. 2021).

Since its inception, significant research has been conducted worldwide to enhance the CS process and expand its potential applications (Vaz, Garfias, Albaladejo, Sanchez, & Cano 2023), (Kumar, Kumar, & Jindal 2020). Despite its progress, the optimization of certain process parameters, such as coating thickness, remains a critical area of study. The ability to predict and control the optimal coating thickness for a given application can directly influence the performance and longevity of the coated material (Moridi, Gangaraj, Vezzu, & Guagliano 2014),(Goyal, Walia, & Sidhu 2012). The research gap addressed by this study lies in the limited optimization of coating thickness parameters in the Cold Spray process, particularly for electro-conductive coatings. While the Cold Spray technique has gained attention for its potential in industrial applications, there remains a lack of systematic analysis of the impact of key process variables—such as substrate material, powder feeding arrangement, stagnation gas temperature, stagnation gas pressure, and standoff distance on coating thickness.

The novelty of this work lies in applying a Taguchi L18 experimental design to systematically optimize these parameters and predict the optimal range for coating thickness, ensuring the desired coating properties and functionality. The findings provide valuable insights into process refinement and highlight the significant factors influencing coating quality, such as standoff distance, stagnation gas temperature, and substrate material, thereby contributing to the enhancement of the Cold Spray technique for industrial and technological applications. By exploring the relationship between process variables and coating thickness, this study seeks to provide valuable insights into the refinement of the Cold Spray technique for industrial and technological applications (Richer, Jodoin, & Ajdelsztajn 2006), (Richer et al. 2006). Figure 1 shows the high-pressure cold spray system and low-pressure cold spray system.

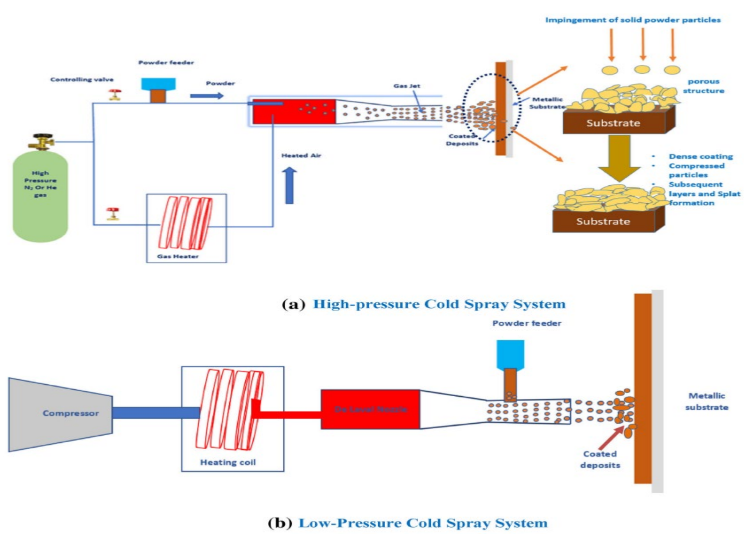

Figure 1. (a) High-pressure cold spray system (b) Low-pressure cold spray system (Kumar, S. & Pandey, S. M., 2022)

1.1 Objectives

The primary aim of this research is to optimize the coating thickness parameters in the cold spray process for electro-conductive coatings. To achieve this, the specific objectives are as follows: (a) to analyze the impact of various process conditions, including substrate material, powder feeding arrangement, stagnation gas temperature, stagnation gas pressure, and standoff distance, on coating thickness; (b) to evaluate the Signal-to-Noise (S/N) ratio to assess the quality characteristics, with a higher S/N ratio indicating better performance; (c) to estimate optimal performance characteristics by applying the Taguchi method for process optimization; and (d) to predict the optimal range for coating thickness, ensuring consistency in the desired coating quality. This research employs a Taguchi L18 experimental design to investigate the relationships between process parameters and coating thickness, providing valuable insights for optimizing the cold spray process and achieving high-quality electro-conductive coatings.

2. Literature Review

Cold spray (CS) technology has emerged as an advanced method for material deposition, offering significant advantages over traditional coating techniques. Unlike high-temperature thermal spray methods, cold spray relies on kinetic energy to accelerate particles, preventing thermal degradation during deposition. This allows for the creation of dense, high-quality coatings with excellent mechanical properties and minimal oxidation (Shao et al. 2023). Cold spray is particularly effective in depositing materials such as copper, titanium, and aluminum, without the thermal stresses that typically occur in other techniques(Adebiyi, Popoola, & Botef 2016). Studies have shown that cold spray coatings exhibit superior wear resistance, thermal conductivity, and corrosion resistance (Silvello et al. 2020). Optimizing the Cold Spray (CS) process is essential for achieving coatings with the desired thickness, surface roughness, and adhesion strength, all of which are critical for ensuring the performance and durability of the coatings. Several key parameters significantly determine the final coating quality, including particle velocity, gas pressure, and spray distance.

Research indicates that higher particle velocities enhance the adhesion between the coating and substrate, resulting in thicker coatings with reduced porosity, thus improving the overall coating performance (Goyal et al. 2012). Additionally, the fine-tuning of process parameters through various optimization techniques, such as Taguchi's method and grey relational analysis, has been widely studied to improve coating properties by identifying the optimal combination of these factors (Kumar et al. 2020). Recent advancements have also focused on enhancing the efficiency of the Cold Spray process, particularly through the improvement of gas heater and powder feeder systems. These developments aim to reduce operational costs while increasing the overall process efficiency and coating quality (A. W.-Y. Tan et al. 2018). Moreover, the selection of suitable materials is a critical factor in ensuring high-quality coatings, as some alloys may experience bonding challenges under specific process conditions, which can affect the final coating properties. This has prompted further research into material optimization to overcome bonding issues and enhance the versatility of the Cold Spray process across different substrate and alloy combinations (Xiong, Zhuang, & Zhang 2015). By addressing these factors, ongoing efforts to optimize the Cold Spray process are expected to lead to improved coatings with enhanced performance for a wide range of industrial applications.

Despite its numerous advantages, Cold Spray (CS) technology faces several challenges that limit its widespread adoption in industrial applications. One of the primary obstacles is the high gas consumption, particularly the use of expensive helium gas, which significantly increases operational costs. Additionally, the processing of certain alloys, especially those that require specialized parameters to achieve optimal bonding, remains a complex task. These difficulties often hinder the ability to produce high-quality coatings across a range of materials consistently. To overcome these challenges, ongoing research is focusing on the development of hybrid coating techniques that combine Cold Spray with other deposition methods, such as laser or plasma spraying, to improve bonding strength and reduce process limitations (Dykhuizen & Neiser 2003).

Furthermore, machine learning and advanced computational techniques are being explored to optimize the selection of process parameters, improving both efficiency and coating quality (Goyal et al. 2012). As part of these efforts, future studies will focus on enhancing the economic feasibility of Cold Spray by developing more efficient systems for gas consumption and improving the performance characteristics of coatings. Innovations such as the use of alternative, more cost-effective gases and the integration of automated control systems for process parameter adjustments are expected to contribute to the widespread commercialization of Cold Spray technology (Jodoin et al.

2006). These advancements hold the potential to expand the applicability of Cold Spray in various industries, further enhancing its role as a versatile and efficient coating deposition method.

3. Methodology

The methodology outlined in this study on optimizing coating thickness parameters for the cold spray process used a structured approach involving Minitab software and Taguchi's design of experiments. The Taguchi method's L18 orthogonal array was employed to assess key parameters feed type, substrate material, air pressure, air temperature, and standoff distance each with mixed levels of influence on coating thickness. The methodology generated response tables for signal-to-noise (S/N) ratio and mean values, which provided insights into how each parameter impacts coating performance. Additionally, the S/N ratio was calculated to understand the variations in coating thickness under different trial conditions. After the data input, analysis was performed in Minitab by selecting Taguchi analysis options and processing response data for S/N ratios and means.

The methodology emphasized "larger is better" criteria for the S/N ratio, optimizing for coating thickness quality. Regression analysis further refined the results by predicting the optimal coating thickness range based on the selected parameters. A regression equation, incorporating factors such as air pressure, temperature, and standoff distance, was derived to estimate the S/N ratio and predict coating thickness.Finally, Analysis of Variance (ANOVA) was used to validate the effects of each parameter on coating thickness. This statistical tool helped isolate the impact of individual factors and allowed for a comprehensive understanding of variance within the data. A Pareto chart visually represented the most influential parameters, with standoff distance and air temperature identified as the most significant. The ANOVA results, alongside regression analysis, offered a robust framework for optimizing coating parameters and predicting the ideal range for achieving the desired coating thickness in the cold spray process.

3.1 Data Collection

Required data have been collected from the recorded data sheet of the company website. As a result, practical solutions may be readily observed within the automotive and electronics industries.The following parameters were selected to investigate their effect on coating thickness in the LPCS (low-pressure cold spray) process: feed type, substrate material, air stagnation pressure, air stagnation temperature, and standoff distance. Table 1 presents the range of process parameters, while Table 2 provides the response data for the study.

Table 1. Process parameters and their range

Symbol	Process Parameter	Range	Level 1	Level 2	Level 3
A	Feed Type	Gravity, Argon	Gravity	Argon	
B	Substrate material	Al alloy, Brass, Ni alloy	Al alloy	Brass	Ni alloy
C	Stagnation Pressure	98-110psi	98	104	110
D	Stagnation Temperature	360-400°C	360	380	400
E	Standoff Distance	2-7mm	2	4.5	7

Table 2, R1, R2, and R3 represent the layer thickness measured with three replicates of each test, recorded using a micrometer to ensure accuracy. The effect of each parameter on the layer is recorded in this datasheet. Calculate the signal-to-noise ratio (S/N) using a regression-based decibel equation to determine the layer thickness conditions.

Table 2. Response data table

R1	R2	R3	S/N ratio
30.0	28.0	26.0	28.75
50.0	52.0	54.0	32.33
76.0	78.0	75.7	36.43
56.4	57.5	58.0	34.23
44.9	44.5	45.2	33.03
25.6	24.4	25.2	28.05
14.2	12.0	13.6	22.35
55.6	55.2	55.4	34.88
56.8	54.2	54.1	34.66
66.9	64.0	69.2	36.56
38.5	38.2	35.7	32.08
58.1	57.2	57.6	35.26
43.4	43.2	43.6	32.72
28.4	27.1	25.4	28.66
64.5	65.3	64.7	36.12
56.5	57.2	58.6	35.15
57.5	56.1	56.5	35.08
17.2	19.2	16.5	24.21

3.2 Coating Formulation

The powder coating used was commercial copper (<45 mm diameter, spherical) obtained from Center Line (Windsor) and deposition was performed at the Surface and Coatings Laboratory at the University of Alberta using an LPCS instrument (model #SSMP3800-001). Carbon monoxide is compressed air and, unlike nozzle type, the working gas (air) and particle size distribution are constant. The major variables affecting the coating were investigated, including feed type, substrate material, air stagnation pressure, air stagnation temperature, and spacing. These variables were tested to varying degrees in experiments designed by Taguchi to improve the quality of the process.

3.3 Working Procedure

This figure 2 shows how to optimize the thickness of a cooling system using Minitab's Taguchi Design. It includes data collection, analysis, and optimization, as well as Pareto charts to visualize values.

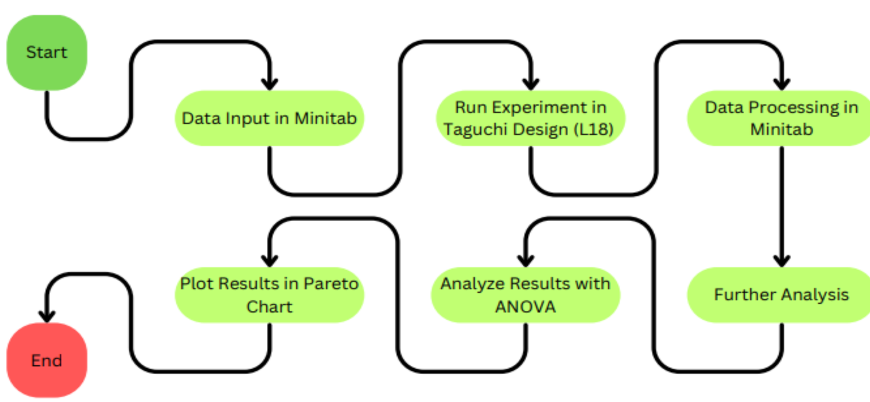

Figure 2. Flow chart of data processing in Minitab by using Taguchi method

The data was generated using the Taguchi method after selecting 3 levels for each measurement of the layer thickness. In the Minitab software, we open DOE and select Taguchi and create a 5-factor mixed model. We select the L18 design and set the parameters for the feed type (gravity and argon feeder), substrate material (aluminum alloy, brass, nickel alloy), stall pressure (98, 104, 108 psi), stall temperature (360, 380, 400 °C) and separation distance (2, 4.5, 7 mm). These settings were used to optimize the coating thickness for the experiment.After the data entry process is completed, the analysis is done using the Taguchi method. In Minitab, we go to DOE, select Taguchi, and then select Analyze Taguchi Design. Select the response data (R1, R2, R3, and signal-to-noise ratio) for analysis. In the display options, we select Signal-to-Noise Ratio and Average. We select the option "bigger is better" to improve the thickness of the layer for signal-to-noise ratio. This approach allows us to analyze the factors affecting the business and determine the level of indicators. Table 3 shows the Orthogonal Array for the Taguchi L18 design with 3 levels. It includes the factor combinations used for the experimental setup.

Table 3. Orthogonal array for Taguchi L18 (levels 03)

Trial No.	**Feed Type**	**Substrate material**	**Air Pressure (psi)**	**Air Temp. (°C)**	**Standoff Distance**
01	GF	Al	98	360	2.0
02	GF	Al	104	380	4.5
03	GF	Al	110	400	7.0
04	GF	Brass	98	360	4.5
05	GF	Brass	104	380	7.0
06	GF	Brass	110	400	2.0
07	GF	Ni	98	380	2.0
08	GF	Ni	104	400	4.5
09	GF	Ni	110	360	7.0
10	AF	Al	98	400	7.0
11	AF	Al	104	360	2.0
12	AF	Al	110	380	4.5
13	AF	Brass	98	380	7.0
14	AF	Brass	104	400	2.0
15	AF	Brass	110	360	4.5
16	AF	Ni	98	400	4.5
17	AF	Ni	104	360	7.0
18	AF	Ni	110	380	2.0

The S/N ratio are calculated by these equations:

$$\mathrm{S/N} = -10\log\left[\frac{1}{R}\sum\frac{1}{\mathrm{Yj2}}\right]$$

Where Yj, j=1, 2... N are the response values under the trial conditions repeated R times.
We also used regression analysis to predict an optimum range of coating thickness mean.
In this method, we also generate an equation to find out the value of the S/N ratio.
Here is the equation:

Regression Equation

S/N = 20.3+ 0.069× (Air Pressure)- 0.0050× (Air Temperature) + 1.479× (Standoff Distance)

3.4 ANOVA Analysis

Analysis of variance (ANOVA) is a method used to analyze differences in data between different groups by dividing the variables into components. Invented by Ronald Fisher in 1918, analysis of variance is a continuation of earlier methods such as the t-test and the z-test. Fisher introduced the term "analysis of variance" in his 1925 book Methods for Scientists, where it gained great popularity, especially in experimental theory and later in many specialized fields. Analysis of variance is often used to compare three or more groups of data to investigate the relationship between success and independence variables. It analyzes between-group and within-group differences by calculating the F statistic (or F ratio). This helps determine if there are significant differences between groups. After performing an analysis of variance, analysts often perform additional tests to examine what factors contribute to the observed variation in the data. These tests further refine the analysis and may include regression modeling to explore relationships in more detail. Overall, ANOVA is an important tool in statistical analysis that allows researchers to compare different groups and understand the factors that influence different data.

4. Results and Discussion

4.1. Taguchi Analysis

Tables 4 and 5 list the average coating thickness and signal-to-noise ratio for each measurement of L1, L2 and L3 and the results are shown in Figures 3 and 4. These figures show the effect of feed preparation and various methods on the coating thickness. The coating thickness is lower when the gravity feeder is used than when the argon feeder is used. Among the substrate materials tested, aluminum alloys showed the best layer thickness at the given parameters, brass showed lower thicknesses and nickel alloys showed the lowest thicknesses. An increase in gas pressure from 98 psi to 104 psi causes an increase in the layer and this increase is further increased when the pressure reaches 110 psi due to the higher inertia of the worm.

Table 4. Response Table for signal-to-noise ratios

Level	**Feed Type**	**Substrate Material**	**Air Pressure (psi)**	**Air Temp. (◦C)**	**Standoff Distance**
1	31.20	32.68	30.97	32.49	27.59
2	31.89	31.50	31.99	29.89	33.59
3		30.46	31.67	32.26	33.45
Delta	0.69	2.23	1.02	2.60	6.00
Rank	5	3	4	2	1

Table 5. Response Table for means

Level	**Feed Type**	**Substrate Material**	**Air pressure (psi)**	**Air Temp. (◦C)**	**`Standoff Distance**
1	41.87	48.19	41.17	45.79	25.39
2	43.95	40.84	42.34	36.10	51.74
3		39.70	45.21	46.84	51.60
Delta	2.08	8.49	4.04	10.74	26.35
Rank	5	3	4	2	1

The coating thickness exhibited a complex relationship with the process parameters, particularly temperature and standoff distance. The highest coating thickness was observed at 400°C, followed by a slight reduction at 380°C, and a slight increase at 360°C, with the thickness at 360°C being very close to that at 400°C. These temperature-dependent variations suggest that while higher temperatures generally enhance particle softening and adhesion, the optimal temperature for maximum coating thickness may lie near the lower end of the tested range. Interestingly, the signal-to-noise (S/N) ratio, which indicates the quality and consistency of the coating, showed a peak at 360°C, decreased at

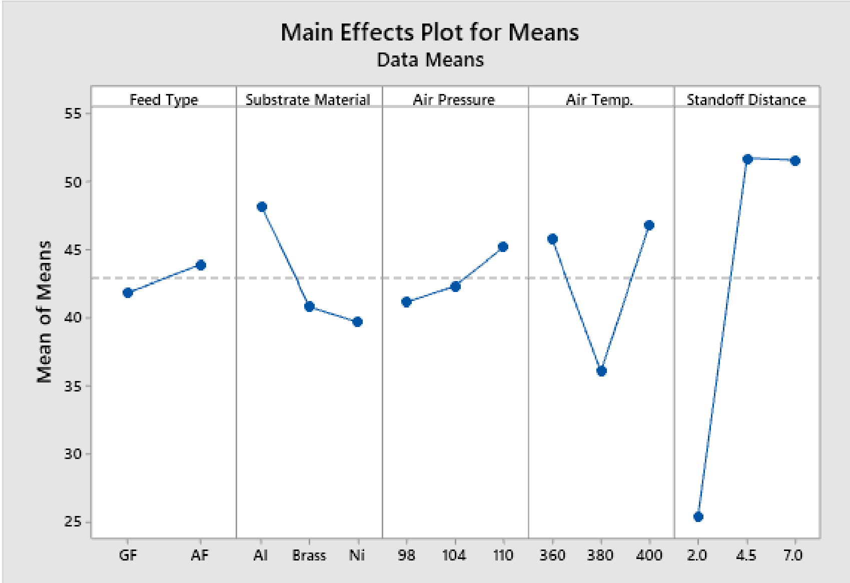

Figure 3. Variation of coating thickness using raw data

380°C, and then increased again at 400°C. This variation in the S/N ratio suggests that coating quality is not solely dependent on temperature but is influenced by the interplay of multiple process factors. Further analysis revealed that standoff distance had a significant effect on the coating thickness. The layer thickness increased with separation distance, reaching its peak at 4.5 mm, and then declined as the distance increased further to 7 mm. This trend highlights the importance of optimizing standoff distance to ensure that the sprayed particles have sufficient kinetic energy for proper bonding while preventing excessive spread that could reduce coating uniformity and adhesion. These findings underscore the critical role of the combination of process parameters including feeder type, gas pressure, temperature, and standoff distance in determining coating quality. Specifically, the use of argon as the powder feed gas demonstrated its effectiveness in enhancing coating adhesion and reducing oxidation. However, the results also highlight the limitations of using argon at higher separation distances, which may reduce the effectiveness of particle impingement and the subsequent coating properties.

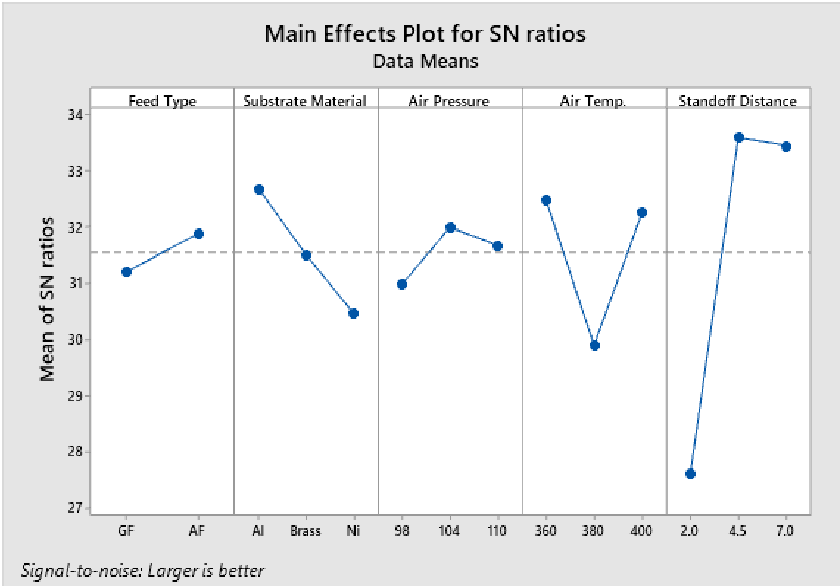

Figure 4. Variation of coating thickness using S/N ratio

The coating thickness reaches a maximum at 400°C, decreases slightly at 380°C, increases at 360°C, and is similar to the thickness at 400°C. The signal-to-noise ratio is the highest. It decreases at 360°C, decreases at 380°C, and increases at 400°C, indicating the effect of temperature on coating quality. The coating thickness also varies with the separation distance, reaching a peak at 4.5 mm and then decreasing to 7 mm. The optimum coating thickness depends on the combination of food, air pressure, temperature, and separation distance. Argon feed equipment gives better results than gravity equipment, while high pressure can improve the process due to higher gas stagnation pressure. These results show the importance of special settings such as the use of argon to ensure gas quality, adjusting to the best and controlling separation, and achieving a good standard in coating. Table 6 presents the average optimal values for different response parameters. These values indicate the most effective conditions for achieving desired outcomes.

Table 6. The average optimum value of various response

Symbol	Process Parameters	The average optimum value of coating thickness (mm)
AF	Argon feeder	43.95
AL	Al alloy	48.19
SP	Stagnation Pressure at 110psi	45.21
ST	Stagnation Temp. at 400°C	46.84
SD	Standoff Distance at 4.5mm	51.74

4.2 Regression Analysis

Regression analysis measures how air pressure, temperature, and separation distance affect the signal-to-noise ratio, providing insight into their impact on coating quality. The results show the extent to which each parameter contributes to the signal-to-mean conversion, allowing fine-tuning of coating performance. This analysis helps create parameter settings that maximize the signal-to-noise ratio, helping to increase process consistency and efficiency in test setups. Table 7 presents the coefficients from the regression analysis, showing each parameter's influence on the response variable. Table 8 provides the Analysis of Variance (ANOVA) results, highlighting the significance of each factor.

Table 7. Coefficients of regression analysis

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	20.3	23.0	0.88	0.392	
Air Pressure	0.069	0.148	0.47	0.649	1.00
Air Temp.	-0.0050	0.0445	-0.11	0.913	1.00
Standoff Distance	1.479	0.356	4.15	0.001	1.00

Table 8. Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	V	P-Value
Regression	3	166.308	55.436	5.83	109.51	0.008
Air Pressure	1	2.058	2.058	0.22	585.68	0.649
Air Temp.	1	0.118	0.118	0.01	89.88	0.913
Standoff Distance	1	164.132	164.132	17.26	949.45	0.001
Error	14	133.136	9.510		3	
Total	17	299.444				

The results of the regression analysis show the effect of various factors on the layer thickness, where the separation distance is significant. The P value is 0.001, which is below the 0.05 significance level, indicating that the distance has a significant effect on the different responses. This is also supported by a T value of 4.15, indicating that the effect of the distance may be significant. The SE air temperature coefficient is 0.0445, indicating that the coefficient of the best is correctly estimated. The R-squared value of 55.54% indicates that the model explains about 55.54% of the coating variance, while the adjusted R-squared value of 46.01% confirms that there is significance in the model due to different coating thicknesses is small.

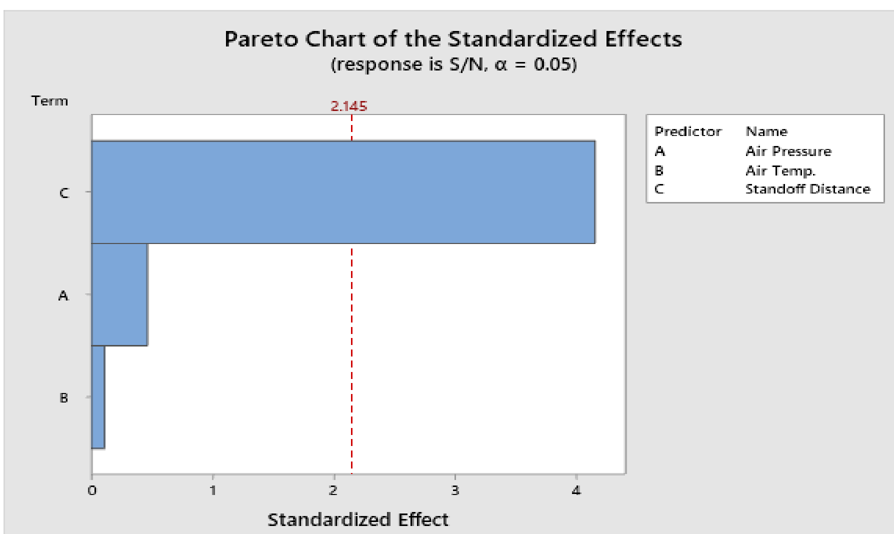

Figure 5. Pareto chart analysis of standardized effect

The Pareto chart analysis of standardized effects figure 5 shows the main factors affecting the different responses. The separation period (C) is particularly important because it crosses the red line on the Pareto chart, indicating that it is critical at the 95% confidence level. This supports the conclusion from the regression analysis that the separation distance plays an important role in determining stratification. The Pareto chart also shows that the most important factors are correctly identified and that the model captures the critical effects of the process with reasonable accuracy.

5. Conclusion

This study on optimizing coating thickness parameters in the low-pressure cold spraying (LPCS) process highlights the significant potential for achieving superior coating thickness compared to traditional thermal spraying methods. The research shows that adjustments in parameters such as powder feeding, carrier gas selection, and standoff distance have a substantial effect on coating thickness and overall quality. Confirmation experiments demonstrated that optimal settings, including the use of an Argon feeder, aluminum alloy substrate, 110 psi stagnation pressure, 400°C air temperature, and a 4.5 mm stand-off distance, resulted in a consistent coating thickness of 1.63 mm, within the predicted confidence interval. These results emphasize the importance of carefully selecting process parameters to achieve high-quality, durable coatings, especially in industries requiring precise performance. Future research should explore further improvements in powder distribution, separation distances, and the integration of advanced process control technologies to refine coating consistency and reduce material waste. Additionally, investigations into alternative gas feeding strategies and the effects of different substrates could expand the versatility of the Cold Spray process. The study also suggests that optimizing stagnation pressure and temperature can enhance particle velocity and softening, improving coating uniformity and adhesion. These findings provide valuable insights for enhancing the economic feasibility, durability, and overall performance of Cold Spray coatings in industrial applications.

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