APPLICATION OF TAGUCHI-PARETO-DEMATEL METHOD TO OPTIMIZE THE THERMAL SPRAY HIGH-VELOCITY OXY-FUEL (HVOF) PROCESS PARAMETERS USING 67NI18CR5SI4B COATING

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ABSTRACT: In contemporary technology, for the parameter of corrosion erosive wear, the responses of metal-based coatings such as FeCrCoAlTiB, FeCrNiSiB and 67Ni18Cr5Si4B among others, in high-velocity oxy-fuel spraying, have been investigated from both optimization and X-ray photo-electron spectroscopic perspectives. Notwithstanding, the expected utility of these perspectives, the interaction among the parameters of the spraying process is unexplored. Using data from the literature, this study presents a new method, the Taguchi-Pareto-DEMATEL method to capture interaction among the three key parameters of spray distance, velocity of spray and powder flow rate. The results show that the Taguchi-Pareto method exhibited an optimal parametric setting of $S_3V_1P_3$, indicating 0.3 m of spray distance, 800 m/s of the velocity of spray and 50 g/min of powder flow rate. There is a concurrence of ranking in 33.3% of the instance where our ranks and Dinh *et al*.'s ranks conflicts as (2,1,3) and (2,3,1) for spray distance, the velocity of spray and powder flow rate, respectively. Furthermore, our results show that S, V and P are neutral along the net effect perspective. They are all equal from the prominence viewpoint. The contribution of this study is the exploration of parametric prioritization in combination with a method of analyzing the interdependence of the high-velocity oxy-fuel spraying parameters for the 67Ni28Cr5Si4B coating.

KEYWORDS: *Surface coating, optimization, Taguchi method, thermal spraying*

1.0 INTRODUCTION

For several decades, materials made of metals have been used for structural development, equipment build-up and component manufacture [1]. Unarguably, they form a huge part of industrial activities and infrastructural development, whose economy is important to nations [3]. However, it was soon realized that the surfaces of these materials often wear off easily and hence threaten the lifespan and durability of the structures, equipment and components that these materials are made up of. This stimulated intense research, which brought about the solutions to the reduction of surface wear, using coating materials [2, 3]. For instance, to protect steel, elements such as aluminum, zinc, and to some extent cadmium have been used for coating where they are used as sacrificial anodes at sites of discontinuity, leading to the cathodic protection of the metal. Accordingly, surface coating of metal has become of huge interest among material scientists and engineers striving to lengthen the lives of structures. Moreover, surface coating is a medium for protecting nanomaterial and structures by modifying the adverse influence of ultraviolet radiation, corrosion and weathering on them. Such protection has been experienced in water treatment plants, highway bridges, marine structures and particular emphasis is on the mechanical elements of the structures.

The advantages of surface coatings, which make them attractive to researchers are hardness, protection, corrosion resistance, aesthetics, minimum maintenance requirement for the products, environmentally-friendliness, durability, cost-savings, and wear resistance, among others [2]. Notwithstanding, several factors can compromise the performance of coatings such as permeability. For instance, thermal spray coatings could easily crack due to weak bond strength, which excludes them from use in internal protection to essential equipment. Moreover, in sealed environments, thermal spray coatings are difficult or impossible to operate due to their higher temperature requirement. These challenges therefore call for optimization efforts the reduce their effects on the process or eliminate them. For parts, more importantly, are the industrial coatings through the thermal spray coatings developed to protect mechanical components against corrosion (chemical) and weather conditions. Examples of coating, materials include titanium oxide, brass Inconel, zinc aluminium, Babbitt, nickel, cermet, aluminum, 300 and 400 series stainless steel, high carbon steel, and tungsten [4]. Moreover, despite the potential of surface coatings being cost savings, the recent worldwide trend in economic decline reveals that an extra attempt at the cost-effectiveness of coating operations is necessary. However, cost-effectiveness may be achieved if resources are optimally utilized. The parameters of the surface coating process should be used at the optimal levels; sub-optimal thresholds should be avoided and the application of intuition or experience of the engineer during the coating process should be downplayed. Furthermore, it was found that the cost of coating has risen due to the increasing labor, material, equipment and energy costs. In the midst of this, the manufacturer is limited in not being allowed to increase its product prices (for coated materials) given the control agency that regulates the prices of coated products.

Thus, the manufacturers are in a dilemma on how to solve this rising cost problem. After extensive interactions of manufacturers with researchers, it was soon realized that the optimization of resources is a viable option to tackle this problem. Therefore, efforts are made in the present study to optimize the parameters of the coating process involving the high-velocity oxy-fuel (HVOF) coating process. In this work, Taguchi-Pareto is combined with the DEMATEL method to illustrate how the parameters of the coating process can be optimized and the interaction among the parameters measured.

Moreover, the environmental impact of coatings is negative and arises from waste generation, resource consumption and the release of pollutants to the environment. This aspect is the traditional coating. However, for the optimized process proposed in this study, the system no more utilizes sub-optimal quantities but optimal thresholds of resources. For example, the required quantity of raw materials, used optimally will generate less waste, use less amount of energy, less labor hours to do transformation of the raw materials into coatings and less transportation. The reduction of all these is the optimization active for the parameters. Furthermore, there are several cases of real-world examples where optimization could lead to substantial benefits for the organization. A case in point is the production of film-coating tablets in the pharmaceutical industry. Within this industry, the surface of a tablet is often surrounded by film coatings due to the action of a thin, even and continuous film on the tablet.

The objective of this study contributes to research and development in the area of surface coating and expand the analysis already reported in the surface coating area of research, introducing an optimization viewpoint into the surface coating arena. It also fills the gap in the operational knowledge of surface coating, aiming to declare the impacts of variables to avoid sub-optimal tasks, which is expensive in the overall perspective. Finally, this work brings about a social contribution in that due to the reduction of resources, usage, energy usage is reduced. This interprets the reduction of environmental influences as a result of the extra energy usage that is avoided; it has the potential to avoid harm to the environment.

2.0 LITERATURE REVIEW

In the first group, the papers discussed parametric optimization and analysis. The members of this group include Cheng *et al.* [5]. For the second group, HVOF thermal spraying is the main theme of the papers in this category. The associated papers include the following: Ren *et al*. [10], Wilson *et al.* [7] and Kumar *et al*. [8]. In the third group, the focus is on HVOF cavitation silt. Article in this group include the following: Hong *et al*. [4] and Kumar *et al*. [15]. In the fourth group, the heading is known as the gelation-based feedstock technologies for HVOF spray. Members of this group include Russell *et al.* [1]. The fifth group of papers relate to improving wear resistance. Prominent articles in this group include Patel *et al*. [11] and Kumar *et al*. [9]. The six group of articles is known as the modelling of thermal spray coating. It includes Ren *et al*. [6]. Table 1 provides information of the papers reviewed.

Table 1. Literature summary concerning the present study

S/No.	Source	Parameters	Output	Application area	Method used	Limitations	Results
1	Ren *et al*. [25]	Temperature, gas flow rate, spray distance, particle velocity	Particle velocity, porosity	Surface coating technologies Aerospace industry	Closed loop optimization simulation method	CAD is slow and is difficult software to utilize inaccuracies may take place due to simple flow models	The spray coatings improved by taking charge of in-flight particle action.
2	Cheng *et al*. [20]	Temperature, pressure, spray distance	Porosity, Hardness	Marine engineering, Thermal spraying, technologies	Taguchi optimization method	Copper alloy undergoes intense localized corrosion in severe marine surroundings	It was found that in corrosion tests, optimized coating showed better corrosion resistance concerning other coating

3	Russell *et al.* [2]	Feed rate, spray distance	Elastic modulus porosity, hardness	Ocean power generation, hydraulic machinery	Coating manufacturing method, microstructure analysis	The powder manufacturing for HVOF applications is often prolonged, expensive and rigorous	Spherical particles have proved to enhance flight within the HWF process gas stream
4	Patel *et al.* [11]	Hardness, toughness	Temperature wear rate	Wear resistant coatings, corrosion-resistant coatings	Thermocals predictions	Fabricating HEA is challenging due to their complicated compositions	High entropy Alloys (HEA) showed enormous promise for engineering
5	Ren *et al.* [34]	Temperature, porosity, stress	Stress	Coating material development process optimization of spraying guns	Response surface methodology (RSM)	Feature-based modelling is complex and has the potential for increased file sizes	Traditional simulation model lacks knowledge about real-time physical properties involved in manufacturing
6	Kumar *et al.* [29]	Densify, corrosion rate	Density	Maritime applications	SEM (Scanning Electron Microscopy)	cavitation-corrosion analysis of HVOF spray involves complex analysis.	WC-10Co-4Cr + 2% graphene has superior cavitation

2.1 Observations from the papers

The following are observations related to the reviewed articles:

i. Spray parametric optimization is important to achieve efficient and effective spraying in applications like painting (surface coating).
ii. It is a characteristic of the high-velocity oxy-fuel (HVOF) thermal spraying to apply coatings with high bond strength as well as low porosity.
iii. Cavitation leads to erosion of coatings and substrate. When bubbles accumulate, they can mechanically damage the coating surface.
iv. The establishment of component coating procedures (i.e. joining hydroxyapatites and other materials such as ceramics) aids in the improvement of the wear resistance of coatings.
v. There is a high correlation between the choice of coating materials and the performance of the thermal spray coatings.
vi. Diverse materials exhibit a wide range of hardness and thermal conductivities and these properties impact the effectiveness of coatings.
vii. If surface coatings are adequately designed, there is a high tendency to reduce friction between interacting components.
viii. The microstructures of dense coatings are closely packed thereby minimizing porosity. However, highly textured coatings exhibit various crystallographic orientations, which lead to anisotropic material characteristics.

The above-listed points show some interesting insight into the literature on HVOF coating. However, to show the direction of investigation in this work, the essential gaps noted in the literature review are highlighted subsequently.

2.2 Gaps in the literature

Concerning the papers reviewed, certain gaps were observed, including the following:

i. A crucial limitation is the changes that in environmental factors such as wind speed, temperature variations with consequential impact on spray effectiveness.
ii. Accurate estimations of residual stresses in thermal spray coatings are difficult.
iii. In practice, diverse applications exist where multiple coatings are required.
iv. The discussion on the Taguchi ABC and Taguchi Pareto optimization of process parameters in HVOF coating application is missing in the literature.

From the literature review, observations and gaps it was found that the issue concerning optimization to 67Ni18Cr5Si4B coating by HVOF spray has been attempted by Dinh *et al*. [11]. Although the Taguchi-OEC technique has been used, the application of the combinational methods of Taguchi-Pareto and Taguchi-ABC has not been made. Thus, given the urgent need for resource conservation, through its efficient resource usage, and the need for plant performance improvement, the present study focuses on the application of combined Taguchi-Pareto and DEMATEL (DEcision-MAking Trial and Elimination) method to the 67Ni18Cr5o4B coating by the HVOF spray method.

3.0 METHODS

3.1 Procedure to implement the Taguchi-Pareto DEMATEL method

The steps for the implementation of the Taguchi-Pareto-DEMATEL method are found in two articles, namely, Abayomi and Oke [12] and Maduekwe and Oke [14], and are repeated hereunder.

Step 1: Establishment of possible parameters and shortlisting to key parameters: Given the problem description given in an earlier section of this article, several parameters could be extracted to represent the spray process. Consider parameters as follows: Density of coatings, and adhesive properties such as adhesive index. Others are the porosity of the coated material, velocity of coating, spray distance, powder flow rate, impingement angle, erodent size and many more. However, depending on the material to be coated and the resources available, the choice of the key parameters may differ from one situation to another. Therefore, the engineer decides through a discussion with experts in the area which key parameters to focus on. As in the case study, where the material for analysis is 67Ni18Cr5Si4B, the principal parameters of interest are the spray distance, velocity of spray and powder flow rate.

Step 2: Compute the results of the Taguchi method using any of the criteria including lower the better, higher the better and the nominal-the best (Equations (1) to (3)) [12,14]. The signal-to-noise ratio calculated according to the three criteria should be clearly stated.

Larger the better = $-10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}$ (1)

Smaller the better = $-10\log_{10}\frac{1}{n}\sum_{i=1}^{n}y_i^2$ (2)

Nominal the best = $10\log_{10}\frac{1}{s^2}$ (3)

where y_i may be taken as the attribute of the performance that is evaluated for the i^{th} observed value, n represents the experimental trial number and s^2 represents the variance of observations

Step 3: Use the Pareto 80-20 rule on the data: Here, the signal-to-noise ratios are attached to experimental trials. They are ordered in descending order of value. Then the percentage of each signal-to-noise ratio out of 100 is calculated. They are added to one another in another column as a cumulative issue. Then, the closest number to 80% is chosen as the cut-off mark if 80% is not available.

Step 4: Develop the response table: This is the average of the signal-to-noise ratio but discarding the entries of the experimental trials, which fall into the 81-100% cumulative value for the signal-to-noise ratio.

Step 5: Develop the DEMATEL matrix: Based on the researcher's experience or the judgement of experts, the table of interrelationship of one parameter against the other is utilized to form the matrix.

Step 6: Normalize the matrix formed in step 5 [12,14].
The calculation of the normalized direct-relation matrix using the direct-relation matrix may be achieved using Equations (4) and (5)

$$X = S \times Z \quad (4)$$

$$S = \frac{1}{\max_{1\le i\le n}\sum_{j=1}^{n} Z_{ij}};\ i, j = 1, 2, 3, \ldots, n \quad (5)$$

This is done by introducing an extra column and then picking the highest value of the sum for each parameter along the vertical route. This is used to divide each entry in the matrix and the result is the desired output.

Step 7: Develop the total relation matrix [12,14]:
Derivation of the total Matrix T: The total matrix is obtainable using Equation (6). Here, the sum of the row and the column of the total matrix are evaluated and may be designated as S_r and S_c, respectively.

$$T = X(1-X)^{-1} \quad (6)$$

Here, the identity matrix is introduced and used to multiply the matrix initially developed.

Step 8: Extract the parameters of the net effect and dominance measures: This is obtained by obtaining (S_r-S_c) and (S_r+S_c).

Step 9: Decide on the outcome in step 8 (a) what parameters are the receiver, givers or neutral based on the (S_r-S_c) measure and (b) what parameters are the most influential and the least influential on other parameters.

4.0 RESULTS AND DISCUSSION

The analysis of the data prescribed in Dinh *et al*. [11] using the proposed Taguchi-Pareto-DEMATEL method was conducted by extracting data from Table 3 of the article. The purpose of the L9 orthogonal array (Table 3 in Dinh *et al*. [11]) is to assist the researcher in examining the diverse parameters (notably the spray distance, velocity of spray and powder flow rate). It aids in understanding their interactions and proceeds in explaining the likely combination the parameters may have in experimental trials. All these efforts are implemented while reducing the number of test cases.

4.1 Taguchi-Pareto method

Thus, the commencement of analysis of Table 3 in Dinh *et al*. [11] focuses on the last column, S/N ratio dB. This has the values of experimental trails 1 to 9 as 1.064, 1.858, -3.098, 3.783, 2.321, 1.330, 3.370, 3.463 and 2.064. By recording these experimental trials based on a descending order then, the new arrangement will be experimental trials 4, 8, 7, 5, 9, 2, 6, 1 and 3 with the corresponding experimental values of 3.783, 3.463, 3.370, 2.321, 2.064, 1.858, 1.330, 1.064 and -3.098. Notice that -3.098 is placed last because it is a negative value while others are positive values. In applying the Pareto principle, the researchers need to establish a cut-off point for experimental trials. In this instance, after obtaining the percentage cumulative for the experimental trials, a target of 80%, corresponding to the 80-20 rule is pursued. In practice, it may not be feasible to obtain the 80% as related to a specific experimental trial, an approximation to the 80% is taken. In this case of the 67Nil8Cr5Si4B coating process, 81.38% (experimental trial 6) and 5.43% (experimental trial 2) were obtained to be close to 80%. However, 75.43% is roughly 4% away from 80% while 81.38% is about 1% away from 80%. Hence, the latter is chosen as the cut-off point (i.e. 81.38%). Notwithstanding, to arrive at this point, the researcher needs to first obtain the percentage of each experimental value relative to the total value and also calculate the cumulative value. In doing so, consider the first value of 3.783 (experimental trial 4) and the sum of values of all experimental values as 22.351. The proportion of 3.783 to 22.351 is 0.1693, which is converted to a percentage of 16.93%. Next is experimental trial 8, which has a value of 3.463 out of a total of 22.357 and gives a proportion of 15.49%. However, in finding the cumulative figure, 16.93% is taken as the first value, and 15.49% is added to it to obtain 32.42%. Subsequent addition along the cumulative path gives 47.50% (experimental trial 7). Such a procedure is followed to obtain 57.88%, 67.12%, 75.43%, 81.38%, 86.14% and finally 100% for experimental trials 5, 9, 2, 6, 1 and 3. Now, in further computations, experimental trials 1 and 3 are discarded as it is known that their contributions are insignificant and relevant to the goal of the HVOF coating process since they exceed the 80% mark of the 80-20 rule for Pareto analysis. In the next stage of analysis, reference is made to the L9 orthogonal array which has arrays for 9 experiments. However, notice that experimental trials 1 and 3 are omitted from the regular L9 orthogonal array and the researcher is left with experimental trials 4, 8, 7, 5, 9, 2 and 6. The revised L9 orthogonal array is obtained as mentioned earlier where experimental trial 4 is mentioned first with orthogonal entries of 2, 1, 2 under spray distance, velocity of spray and powder flow rate, respectively. With this same arrangement of parameters, the orthogonal entries for other experimental trials are obtained as follows: experimental trial 8 as 3, 2, 1, experimental trial 7 as 3, 1, 3, experimental trial 5 as 2, 2, 3; experimental trial 9 as 3, 3, 2; experimental trial 2 as 1, 2, 2; and experimental trial 6 as 2, 3, 1. Now, a piece of additional information required is the distribution of the factors and levels. Interestingly, data from Dinh *et al*. [11] reveals the following: For spray distance, levels 1, 2 and 3 are 0.1m, 0.2m and 0.3m, respectively. For velocity of spray, levels 1, 2 and 3 are 800 m/s, 900 m/s and 1000 m/s, respectively. However, for the powder flow rate, levels 1, 2 and 3 give 30g/min, 40g/min and 50g/min, respectively. To obtain the translated array, these values are converted from the orthogonal entries of 1, 2 and 3 to their respective values. Then the revised average signal-to-noise ratios are computed to obtain the delta values, ranks and optimal parametric settings (Table 2).

Table 2. Revised average signal-to-noise ratios [11]

Level	Spray distance	Velocity of spray	Powder flow rate
1	1.858	3.577*	2.397
2	2.478	2.547	2.568
3	2.966*	1.697	2.846*
Delta	1.108	1.88	0.449
Ranks	2	1	3

*Optimal parametric setting is $S_3V_1P_3$

At this point, a discussion of the practical implications of spray distance's influence on the HVOF spraying process is important. HVOF spraying requires a line of sight to the surface being sprayed and a spray distance of 0.3m was obtained in the revised response table calculated for the Taguchi-Pareto method in the present study. The obtained distance through the optimization ensures that even if a second layer of coating is to be applied it does not get dried before it is applied. Notwithstanding, it is difficult and somewhat impossible to deposit coatings on internal surfaces or surfaces that have restricted areas if the minimum distance of spraying is not maintained. Furthermore, Table 2, which is a matrix to be produced, is a 3 x 3 matrix, which excludes the experimental trials 1 and 3 from the parametric averages to be obtained from the signal-to-noise ratios. Now, we start with the entry at the intersection of spray distance, which is indicated as 1. However, the researcher is interested in the average of the associated signal-to-noise ratio, which is 1.858. Therefore, the value in the cell where level 1 and spray distance join are 1.858. Further down, the value at the confluence of spray distance and level 2 is the average of 3.783, 2.321 and 1.33, which is 2.478. Then, the value at the confluence of spray distance with level 3 is the average of 3.463, 3.37 and 2064, which is 2.966. Now, the computation shifts to the parameter named velocity of spray. Here, the starting point is the evaluation of the cell of velocity of spray and its association with level 1. The average of the following is found; 3.783, and 3.37, which is 3.577. Next, the researcher computes the value of the cell at the intersection of the velocity of spray and level 2. This is the average of 3.463, 2.321 and 18.58, which is 2.547. Then, the intersection of the parameter named velocity of spray and level 3 will produce the needed average from 2.064 and 1.33, which is 1.697. Now, moving to the last parameter in the matrix, which is powder flow rate, the starting point is level 1. Here, the average of the intersection of the powder flow rate and level 1 is first obtained from 3.463 and 1.33 as 2.397. For the intersection of powder flow rate and level 2, the average required is from 3.783, 2.064 and 1.858 as 2.568. Next is the intersection of the powder flow rate and level 3, which provides an average of 3.37, 2.321 as 2.846. Then, the results are summarized in Table 2. The next step is to compute the delta value, which is the difference between the highest and lowest value within a column, obtained as 1.108, 1.88 and 0.449, respectively. Based on the magnitudes of these values, the parameters are ranked. However, the delta value of the velocity of the spray parameter (i.e. 1.88) is greater than that of the spray distance (i.e. 1.108), which is greater than the powder flow rate (i.e. 0.449). This can be expressed as the velocity of spray delta (i.e. 1.88) > Spray distance delta (i.e. 1.108) > Powder flow rate delta (i.e. 0.449). Then the ranks are given according to the decreasing value. Thus, the velocity of the spray parameter is ranked first, spray distance is ranked second and the powder flow rate is ranked third. Next is the computation of the parametric values for the process. Notice that signal-to-noise ratios are the basis for the computation of the average signal-to-noise ratios on which the delta values, ranks and optimal parametric values are determined. This implies that higher values are desired as a high value of the signal to a low value of noise is shown in the overall computations of the signal-to-noise ratios. Therefore, to determine the optimal parametric setting, along each column, the highest average signal-to-noise ratio is searched for and located as levels 3, 1 and 3 for the spray distance (i.e. 2.966), velocity of spray (i.e. 3.577) and powder flow rate (i.e. 2.846), respectively. If the first letters of each of these parameters are used to represent them, then it will make sense to state the optimal parametric settings as $S_3V_1P_3$. The above procedure is the first step in the evaluation of the data on the HVOF spray of 67Ni18Cr5Si4B using the Taguchi-Pareto-DEMATEL approach. Then the next phase is to apply the DEMATEL approach (see the procedure in section 3). Notice that the data being examined is on the 67Nil8Cr5Si4B coating where the HVOF spray system is utilized.

To sum up, spray parametric optimization was achieved by the usage of the input resources, including, spray distance, velocity of spray and powder flow rate. Optimization was achieved in a stepwise concern involving the establishment of the goal, analyzing the process, developing, testing, implementing and evaluating the process. Accordingly, optimization was achieved. The process of doing this describes the contribution of the present study as stated in the latter part of section one.

4.2 DEMATEL method

The full meaning of DEMATEL is the Decision-Making Trial and Elimination method to examine the 67Ni18Cr5Si4B coating process data. To proceed, the research identifies three parameters of interest in the application of the DEMATEL method. These are the spray distance, velocity of spray and powder flow rate. Table 1 shows all the parameters of the coating process. This is the raw data subjected to analysis in the present scheme of analysis. The first note to take is to establish a comparison of the degree of influence of the parameters one on another. This degree of influence could be analyzed by a group or the researcher. However, in the present case, the researcher adopts the experience gained in the manufacturing industry to evaluate the parameters. The result of the evaluation is presented in Table 3.

Table 3. DEMATEL influence table

Parameter	S	V	P	Summation
S	0	4	4	8
V	1/4	0	3	3.25
P	1/4	1/3	0	0.68

Here, the degree of influence of the spray distance against the velocity of the spray is to be determined. However, according to Katranidis *et al*. [2], it was asserted that the standoff distance (implying spray distance in this work) is a great determinant of the velocity of spray. This means that from the definition of 0, 1, 2, 3 and 4 as Absence of influence, low influence, intermediate influence, elevated influence and extremely high influence, the last rating, which is extremely high influence is chosen (i.e. 4). Then stand-off distance against the powder flow rate is 4. Then velocity of the spray against the powder flow rate is 3, the powder flow rate against spray distance is ¼, powder flow rate against the velocity of the spray is 1/3. Meanwhile, a parameter against itself is 0. Thus Table 3 is completed with this information.

Step 2 of the Taguchi-Pareto DEMATEL method is the parametric normalization. In any situation where the researcher attempts to analyze a process, parametric normalization is used for ease of analysis. Thus, the spray distance is denoted by S, the velocity of spray is denoted by V and the powder flow rate is denoted by P. Step 3, presentation in Table 3 is the normalization of direct relations matrix Q. This involves finding the horizontal summation of the parameters. Thus, for the first row, which is S row, the summation is 0+4+4, which is 8. For the V row, the summation is 3.25 while for the P row, the summation is 0.25 + 0.33, which is 0.68. This is presented in the last column of Table 3. The result of normalizing direct relation matrix Q is given as normalization direct relation matrix Y. This is achieved when all the entries in the matrix are divided by the highest summation in the normalized direct relation matrix Q. Here, the highest figure in the matrix is 8. Thus, all the elements of the matrix are divided by 8, which is the highest summation in the normalized direct relation matrix. The results obtained thereof are called normalized direct relation matrix Y as presented in Table 4.

Table 4. Normalized results, Identity matrix I and total relation matrix computation

	Normalized results (Y)			Identity matrix I			Matrix I-Y			Total relation matrix T = Y(I-Y)^-1		
Parameter	S	V	P	S	V	P	S	V	P	S	V	P
S	0.00	0.29	0.29	1.00	0.00	0.00	1.00	-0.29	-0.29	0.00	-1.00	-1.00
V	3235.36	0.00	0.21	0.00	1.00	0.00	-3235.36	1.00	-0.21	-1.00	0.00	-1.00
P	3235.36	3235.29	0.00	0.00	0.00	1.00	-3235.36	-3235.29	1.00	-1.00	-1.00	0.00

Table 5. Cause and effect group table

Parameter	S_r	S_c	S_r - S_c	S_r + S_c	S_r - S_c	S_r + S_c
S	-2.00	-2.00	0.00	-4.00	neutral	All criteria are equally important
V	-2.00	-2.00	0.00	-4.00	neutral	All criteria are equally important
P	-2.00	-2.00	0.00	-4.00	neutral	All criteria are equally important

Step 4 is to calculate the total relation matrix T, given by T = Y $(I-Y)^{-1}$, where I is the identity matrix. This step 4 can be broken down into four steps. The first part of step 4 is to draw up the identity matrix I, which is a 3 x 3 matrix in line with the number of parameters being considered. This is presented in Table. The second step under step 4 is step 4.2, which is to subtract matrix Y from the identity matrix I, i.e. identity matrix I minus the normalized matrix Y. This is presented in Table 5. The vertical sum of the parameters of the coating process is denoted as S_c while the horizontal sum is shown as S_r as presented in Table 4. Step 5 is presented in Table 4, which is to determine the causal and effect group. Table 5 interprets the results in Table 4. So, the S_r is the second column, and S_c is the third column. Then S_r-S_c will be expressed as the fourth column and S_r+S_c will be the fifth column. Then the interpretation of the result is contained in the last two columns, S_r-S_c which is negative implies a receiver. However, there is no situation like this in the results obtained as all the parameters namely S, V and P should be neutral, which means that they are neither receivers nor givers. Notice that *a* S_r-S_c that is negative implies that the criterion is influenced by others. Whereas, S_r-S_c which is positive implies that the criterion is a causal parameter, which means that such a criterion influences other criteria. For the S_r+S_c the parameter that gives the highest value is the most important criterion, which exhibits maximum influence on other criteria. However, S_r+S_c which has the lowest value is the least important criterion. Nonetheless, the parameters S, V and P do not fall into either case as their values are equal at -4.00, implying that all criteria are equally important. Thus, there are no causal groups for the problem and also no effect group for the problem analyzed. S_r+S_c is called the prominence measure, which means being well-known and important. In the context of the DEMATEL application, S_r+S_c indicates that attention should be given to the fact or with high S_r+S_c while low prominence should be given to the parameter with the low S_r+S_c value.

Furthermore, an article on wind turbine parametric analysis using the Taguchi-Pareto-DEMATEL method [12] was compared with the present results obtained in this article. The basis of comparison is the net effect and prominence criteria. The parameters of interest in Abayomi and Oke [12] are truck gap, height, effective length, pressure and blower distance while in the present study, the key parameters analyzed are the spray distance, velocity of spray and powder flow rate. For the net effect, Abayomi and Oke [42] reported that D-R (equivalent to S_r-S_c in the present situation) for pressure and height having values of -1.004 and -0.994, respectively are receivers. Also, the parameters blower distance, effective length and truck gap, which have positive D-R values of 1.229, 0.4 and 0.223 are givers. The results are contrary to the obtained values for the current study in which all the parameters of spray distance, velocity of spray and powder flow rate are neutral. It implies that they are neither receivers nor givers. There are differences in results also when the criterion of prominence is considered. For Abayomi and Oke [12], the most important parameter is the height (i.e. 0.382) which exhibits the highest value. It has the greatest influence on all other parameters. The least important parameter is the blower distance (-2.168). However, these results are contrary to what was obtained in the current study where all the parameters are equally important (-4.00) based on the prominence criterion. Though the outcome of our study and Abayomi and Oke [12] show the feasibility of applying the Taguchi-Pareto-DEMATEL method, it does not show concurrence.

4.3 Taguchi-Pareto DEMATEL method

The sections on the Taguchi-Pareto method and DEMATEL method in this result section have independently applied the 67Ni18Cr5Si4B coating data to obtain different results. However, to have the joint Taguchi-Pareto DEMATEL method, there is a need to couple the results of the Taguchi–Pareto method and the DEMATEL method. The point of coupling in this work is the response table values of the Taguchi-Pareto method being multiplied by the normalized values. In this particular case, to obtain a table called response table-normalized table, which is the multiplication of each of the entries of the response table with those of the normalized table, the following results are obtained for the S row, the value at level 1 row of the average signal to noise ratios are 1.858, 3.577 and 2.397 for S, V and P, respectively. The corresponding values from the normalized results along the S row are 0.00., 0.29, and 0.29. As 1.858 is multiplied by 0.00, the result is 0.00. Then, 3.577 is multiplied by 0.29 to give 1.02 while 2.397 from the response table is multiplied by 0.29 of the normalized result to give 0.68. Then, the computation is done for the V row of the response table-normalized results to obtain 8017.22, 0.00 and 0.55, respectively in intersection with the S, V and P cells. Next, the results for the P row of the response table-normalized results in intersection with the S, V, and P parameters give 9596.07, 5490.28 and 0.00, respectively. The summary of these computations is shown in Table 6.

Table 6. Response table-normalized results

Parameters	S	V	P
S	0.00	1.02	0.68
V	8017.22	0.00	0.55
P	9596.07	5490.28	0.00

Then, the remaining procedure conducted under the DEMATEL method's analysis (section 4.2) is followed, which includes obtaining the identity matrix I, calculating the matrix I- Y, matrix $(I - Y)^{-1}$, and the total relation matrix $T = Y (1- Y)^{-1}$, the final computation is shown as the cause and effect group table in Table 5. From Table 5, S_r-S_c is neither positive nor negative but of value zero, implying that the three parameters of S, V and P are neutral. This is the same result as using the DEMATEL method only as indicated in a previous section. For the S_r+$S_{c'}$ there is no highest or lowest value as the value obtained, -4.00 for all the parameters is the same. It implies that there is no most important criterion which has a maximum relationship with other parameters. Also, there is no parameter with the least value, which can be identified as the least important criterion, which has a minimum relationship with other criteria. The implication is that all the criteria (parameters) can be described as most important and least important accordingly. Notice that since the results obtained in the implementation of the Taguchi-Pareto DEMATEL method and only the DEMATEL method gives the same results as in Table 5, the repetition of the results is not necessary.

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4.4 Taguchi- Pareto versus Taguchi Method

Taguchi Pareto has been applied in the present study with results obtained for delta values, ranks and parametric settings. However, a re-computation of the results of Dinh *et al*. [11] was made using the Taguchi method and the mentioned measures were also obtained. Notwithstanding, it is interesting to compare the results of the two methods graphically as shown in Figures 1a and 1b. it can be observed from Figure 1a that the Taguchi method gave the values of 1.5, 1.27 and 1.69 for the spray distance velocity of spray and powder flow rate, respectively, keeping in mind that delta values show the difference of the lowest average response from the highest, the interpretation of the result is accordingly along this understanding. The Taguchi-Pareto method, by revealing a value of 1.88 for the velocity of spray against 1.27 for the Taguchi method shows that the comparative effect of the velocity of spray on the response is more. However, considering the spray distance and powder flow rate, the Taguchi method (Dinh *et al*. [11]) shows that the effects of the two parameters are more compared to the revelation by the Taguchi-Pareto method. This is shown in Figure 1a. In Figure 1b, the optimal parametric settings are shown as $S_{2.96}V_{3.58}P_{2.85}$ for the Taguchi Pareto method against $S_{2.96}V_{2.54}P_{2.54}$ for the Pareto method.

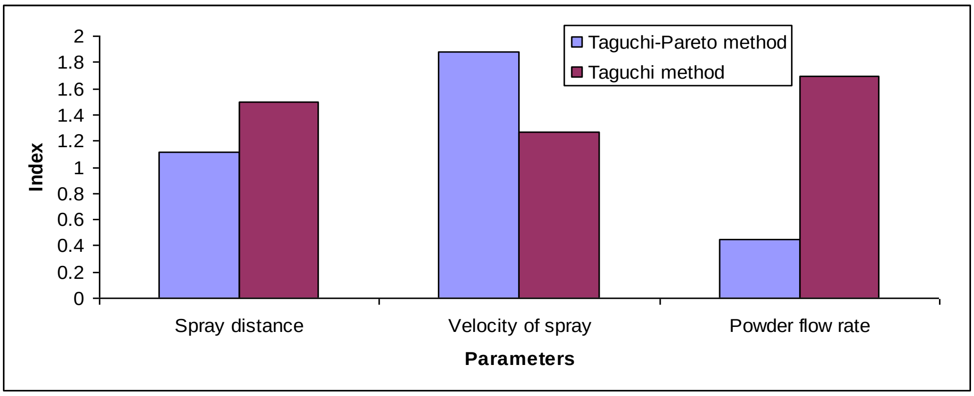

Figure 1a. Comparison of delta values for the Taguchi-Pareto and Taguchi methods

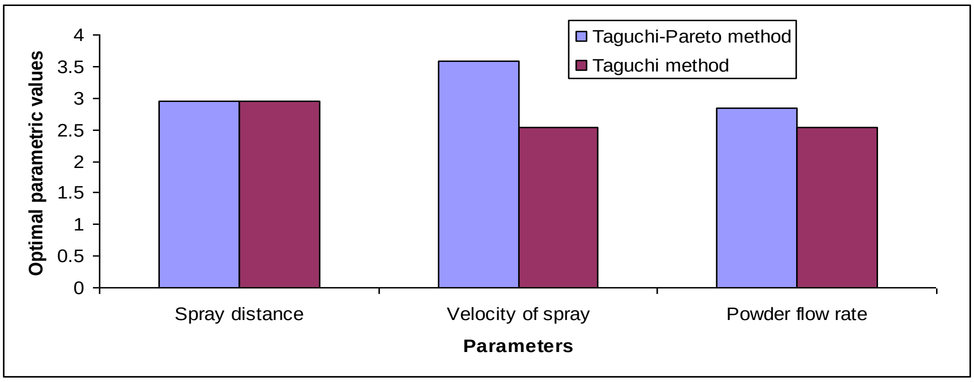

Figure 1b. Optimal parametric settings for the 67Ni18Cr5Si4B coating process parameters

The implication is that the Taguchi-Pareto method has more potential to reduce the experimental cost and improve quality than the Taguchi method since the averages are 3.0987 and 2.6532, respectively. On individual analysis, the velocity of spray is the greatest contributor to the Taguchi-Pareto method with a value of 3.58.

Notwithstanding, for the Taguchi method, spray distance is the greatest contributor to the performance of the system with a value of 2.96.

4.5 Validation of the Taguchi-Pareto DEMATEL method using Kumar *et al.* [15]

In this section, the process of systematically comparing the results of the application of the Taguchi-Pareto DEMATEL method on Dinh *et al.*'s [11] data with Kumar *et al.* [15] was achieved. The latter is independent real-world data whose results confirm the appropriate use of the proposed method in practical real-world situations. First, the Taguchi Pareto method was applied to the data, which is a relatively new version of the Taguchi method. Taguchi-Pareto is different from the Taguchi method applied by Kumar *et al.* [15]. It differs in that while it proclaims discrimination, the Taguchi method does not. The Taguchi-Pareto method has its main framework in the 80-20 rule, where 805 of the experimental trials are considered most relevant and dictate the quality of the results. In the case of Kumar *et al.* [15], the orthogonal array is first extracted from the L16 orthogonal array used by the author. Since four control factors are involved in the analysis. The chief measure in this circumstance is the signal-to-noise ratios, which were assumed as the smaller the better criterion for all the control factors used in the case study, namely, the erodent size, impingement angle, impact velocity and erodent feed rate. Then to commence the analysis, Equation (2) is used on all the factors symbolically represented as Iv, Ia, Efr and Es for the respective control parameters of impact velocity, impingement angle, erodent feed rate, and erodent size. The analysis produced experimental trials 1 to 16, which vary in signal-to-noise ratios from -12.5871 (lowest) to -11.4387 (highest). These are then ordered from the highest to the lowest value for ease of computation of the cumulative values of the signal-to-noise ratios (Table 7).

Table 7. Orthogonal array, the translated values and the cumulative values of the signal-to-noise ratios for Kumar *et al.* [15]

	Orthogonal array				Translated values							
Exp	I_v	I_a	E_{fr}	E_s	I_v	I_a	E_{fr}	E_s	SNR	Proportion	Cumulative proportion	Cumulative %
1	1	1	1	1	10	30	160	105	-11.4387	0.059156	0.0592	5.92
11	3	3	1	2	30	60	160	125	-11.6504	0.060251	0.1194	11.94
16	4	4	1	3	40	75	160	149	-11.8514	0.06129	0.1807	18.07
2	1	2	2	2	10	45	195	125	-11.8661	0.061366	0.2421	24.21
12	3	4	2	1	30	75	195	105	-11.8622	0.061346	0.3034	30.34
6	2	2	1	4	20	45	160	180	-11.953	0.061816	0.3652	36.52
5	2	1	2	3	20	30	195	149	-11.9726	0.061917	0.4271	42.71
14	4	2	3	1	40	45	230	105	-12.0741	0.062442	0.4896	48.96
8	2	4	3	2	20	75	230	125	-12.1811	0.062995	0.5526	55.26
15	4	3	2	4	40	60	195	180	-12.1967	0.063076	0.6157	61.57
3	1	3	3	3	10	60	230	149	-12.2413	0.063307	0.6790	67.90
7	2	3	4	1	20	60	265	105	-12.3267	0.063748	0.7427	74.27
9	3	1	3	4	30	30	230	180	-12.35	0.063869	0.8066	**80.66**
13	4	1	4	2	40	30	265	125	-12.3655	0.063949	0.8705	87.05
10	3	2	4	3	30	45	265	149	-12.4483	0.064377	0.9349	93.49
4	1	4	4	4	10	75	265	180	-12.5871	0.065095	1.0000	100.00

The average signal-to-noise ratios (i.e. response table) are computed in a revised manner. Its traditional form involves the use of all the experimental trials but the trials that are captured under 80-100% in the cumulative scenario may not be considered for the revised signal-to-noise average ratios. Table 7 shows the cut-off at experimental trial 9 (after ordering), indicating 80.66%) where experimental trials 13, 10 and 4 are disregarded in further computations. In recomputing the average signal-to-noise ratios for parameter Iv, orthogonal array counts 4, 3 and 1 are removed from levels 4, 3 and 1, respectively. Here, the averages to observe then become three orthogonal array counts each, dividing the corresponding values by three. For instance, considering the intersection of Iv and level 1, the value obtained will be 0.33 (-11.4387-12.5871-11.6504), which gives -11.7731. Other values such as those at the intersections of Iv and level 2, Iv and level 3 and Iv and level 4 are calculated accordingly as -12.123, -11.9474. and -12.1674. The same procedure is used to fill Table 8.

Traditionally, the delta values and ranks are calculated. Thus, for the Taguchi -Pareto method, the ranks are 1st, 2nd, 3rd and 4th for I_a (impingement angle), E_{fr} (erodent feed rate), I_v (impact velocity) and E_s (erodent size), respectively. In addition, the optimal parametric setting is $I_{v1}I_{a2}$ $E_{fr4}E_{s1}$, translated as 10m/s of impact velocity, 450 of impingement angle, 265g/min of erodent feed rate and 105/m of erodent size. When the ranks obtained by the Taguchi-Pareto method are compared with the Taguchi method [15], the following is observed. The ranking order of parameters according to Taguchi methods coincides with ¼ parameters, equivalent to 25%. In other words, the impingement angle was first in the Taguchi-Pareto against second in the Taguchi method. Erodent feed rate was second in Taguchi-Pareto against third in the Taguchi method. Impact velocity was third in Taguchi-Pareto against first in the Taguchi method. Furthermore, erodent size was fourth in Taguchi-Pareto against fourth in Taguchi method. This is the first time to use the Taguchi-Pareto method for the problem described by Kumar *et al.* [15].

Table 8. Revised signal-to-noise ratios for Kumar *et al.* [15]

	Parameters				Sum
Level	I_v	I_a	E_{fr}	E_s	
1	-11.7731	-11.9232	-11.8748	-11.8637	-47.4348
2	-12.123	-7.96427	-12.3337	-12.1451	-44.5660
3	-11.9474	-11.9567	-12.1368	-11.9521	-47.9930
4	-12.1674	-12.0661	-11.8622	-12.1331	-48.2287
Delta	0.394223	4.101854	0.471493	0.281398	
Ranks	3	1	2	4	

Optimal parametric setting: $I_{v1}I_{a2}E_{fr4}E_{s1}$

Moreover, to have a joint Taguchi-Pareto and the DEMATEL method, both methods need to be coupled. The point of coupling is the response table being used in multiplication from the revised response table with the entries of the normalized results. First, the normalization of the parameters is pursued in Table 8. The normalized values are extracted from the group decision. Experts are expected to rank these parameters relative to one another on a scale of 0 to 4, notable 0 for the absence of influence between parameters, 1 representing low influence between two parameters, 2 showing intermediate influence between two parameters, 3 indicating elevated influence between parameters and 4 revealing extremely high influence when considering any two parameters at a time. Accordingly, literature was searched for guidance for this rating. However, Kumar *et al*. [15] results which rated impact velocity as the most important, impingement angle as the next important, erodent feed rate as the next important and erodent size as the least important, were reliably used in the DEMATEL evaluation. Here, one of the researchers evaluated while other researchers observed the correctness of the assessment. The results of the DEMATEL importance scale evaluation are shown in Table 9 and the accompanying normalized values are also shown in the same Table 9.

Table 9. DEMATEL influence table and its normalization

	DEMATEL influence table					Normalized results			
Parameters	I_v	I_a	E_{fr}	E_s	Summation	I_v	I_a	E_{fr}	E_s
I_v	0.00	2.00	3.00	4.00	9.00	0.00	0.22	0.33	0.44
I_a	0.50	0.00	2.00	3.00	5.50	0.06	0.00	0.22	0.33
E_{fr}	0.33	0.50	0.00	2.00	2.83	0.04	0.06	0.00	0.22
E_s	0.25	0.33	0.50	0.00	1.08	0.03	0.04	0.06	0.00

For ease of computation, the fractions are converted into decimals. For instance Iv, in comparison to itself is given a value of 0.00. Next, Iv in comparison with Ia is assigned a value of 2.00. Then when Ia is compared with Iv, the reverse of a reciprocal of 2.00 is assigned. The idea is used to fill Table 9. Then along the rows of Table 9, the values are summed as 9.00 for row 1_v, 5.50 for row I_a, 2.83 for row E_{fr} and 1.08 for row E_s, respectively. Since the highest value is 9 for each of the summations (i.e. for the row Iv), it is used to divide all the entries of the cell to obtain the normalized values. These are shown on the right-hand side of Table 9. Furthermore, these normalized values are multiple with the revised signal-to-noise ratios of Kumar *et al*. [15] to achieve a new table called the response table-normalized table (Table 10).

Table 10. Revised response table-normalized table

	Parameters			
Level	Iv	Ia	Efr	Es
1	0.0000	-2.6496	-3.9583	-5.2727
2	-0.6735	0.0000	-2.7408	-4.0484
3	-0.4425	-0.6643	0.0000	-2.6560
4	-0.3380	-0.4469	-0.6590	0.0000

With this new table, an identity matrix I may be used, matrix I-Y is computed and the total relation matrix T is evaluated as previously done (Table 11).

Table 11. Total relation matrix $Y(I-Y)^{-1}$

Parameter	I_v	I_a	E_{fr}	E_s	Sr
I_v	0.0000	-1.0000	-1.0000	-1.0000	-3.0000
I_a	-1.0000	0.0000	-1.0000	-1.0000	-3.0000
E_{fr}	-1.0000	-1.0000	0.0000	-1.0000	-3.0000
E_s	-1.0000	-1.0000	-1.0000	0.0000	-3.0000
Sc	-3.0000	-3.0000	-3.0000	-3.0000	

Moreover, Table 12 shows the causal and effect group, which is an interpretation of the results in Table 11.

Table 12. Cause and effect group table

Parameter	S_r	S_c	S_r - S_c	S_r + S_c	S_r - S_c	S_r + S_c
I_v	-3.0000	-3.0000	0.00	-6.00	neutral	all criteria are equally important
I_a	-3.0000	-3.0000	0.00	-6.00	neutral	all criteria are equally important
E_{fr}	-3.0000	-3.0000	0.00	-6.00	neutral	all criteria are equally important
E_s	-3.0000	-3.0000	0.00	-6.00	neutral	all criteria are equally important

So, in Table 12, Sr is the second column, Sc is the third column, Sr-Sc is the fourth column and Sr+Sc is the fifth column. For the interpretation of the results, it should be noted that considering Sr-Sc, all the parameters are neither receivers nor givers. They are neither negative nor positive but zero, which shows neutrality. In essence I_v, I_a, E_{fr} and E_s are all neutral regarding Sr-Sc. However, considering Sr + Sc, there are most important or least important criteria. Since all the criteria possess the same value, they are all regarded as equally important.

4.6 Similarities and differences between Taguchi and Taguchi-Pareto methods

In the Taguchi-Pareto method and the methodology Taguchi employed by Kumar *et al.* [15], the research has similarities and differences. On the one hand, the similarities include the following: The Taguchi method in both researches obtains the minimum number of experiments that may be performed subject to the limits defined by the factors and their corresponding levels. Moreover, the experimental design that serves as the framework for both studies reduces cost, and enhances the quality of outcomes while providing robust design solutions. Furthermore, in both studies (i.e. the present work and Kumar *et al.* [15]), several factors were simultaneously optimized while it was possible to extract quantitative information from the former experimental runs provided by the Taguchi and Taguchi-Pareto methods implying improved optimized results. However, on the other hand, it is known that the Taguchi-Pareto method offers additional advantages that the Taguchi method alone cannot achieve. In the context of the HVOF coating process, the Taguchi-Pareto shows the capacity to establish what measures to implement to solve the coating optimization problem. Moreover, the Taguchi-Pareto method establishes the root causes of the optimization problem. Furthermore, these problems in high-priority areas could be eliminated and decisions made using the Taguchi-Pareto method could be beneficial. Nevertheless, the Taguchi-Pareto method further enhances the optimization performance over the Taguchi-Pareto by discriminating experimental trials, it is urgent and meaningful to pursue optimization with a Taguchi methodical variant that exhibits additional advantages over the Taguchi method alone. This may explain the present effort and initiative that aims to integrate Taguchi-Pareto into a unified framework with the DEMATEL method to achieve robust optimization as well as interaction evaluation performance.

4.7 Implications of the study

This study recognizes the specific challenges faced in the thermal spray coating process, including permeability and the inability to work in sealed environments given the high-temperature requirements for the process. This acknowledgement highlights the implications of the current study and supports the current trends in the coating industry.

It establishes its practical applicability and significance. From this perspective, the present study provides an important understanding that directly furnishes operations managers with information in their quest to enhance their operational strategies. First, the particular function that DEMATEL can play in enhancing process optimization is outlined in the present study. This practical information directs operation managers to gain insights into where the critical factors of the coating process might fit best within their operational strategies and their value-creation potential. Second, in this study, experimental data obtained from the literature was used as a representation of the real-world case study. It shows how DEMATEL and Taguchi–Pareto can effectively influence the operations manager to make informed decisions. This practical understanding empowers the operations manager with information on the most important parameters in the process and how much they exceed others in importance by using the DEMATEL and Taguchi–Pareto methodical implementation.

5.0 CONCLUSIONS

This study applies the Taguchi-Pareto DEMATEL method to optimize the 67Ni18Cr5Si4B coating using experimental data from the literature. It was found that the approach is feasible. The present work contributes to knowledge of coating parametric assessment. It is the foremost (first) research to build up a combined optimization, prioritization and interaction method and conduct a relationship DEMATEL association which receives inputs from the combined Taguchi method and the Pareto method. It assesses the optimization potential of the coating process. Although causes, as may be established in other studies can assist process engineers and managers to focus on particular parameters for the ultimate performance delivery, the present work is neutral in choosing what parameters aid coating goals. This promotes confidence in providing managers of coating processes with information essential to make informed decisions and then more intelligent decisions may be made as superior quality information on the coating process is provided for them. Moreover, the practical and theoretical implications of this article are immense. It is a foundation for the proliferation of studies to reignite the ideas presented in the present work and introduce concepts never being thought of such as the economics of spraying. Additional future studies may be centered on structural equation modeling and system dynamics to bring the work on the DEMATEL method to a better perspective method.

Moreover, the Taguchi-Pareto-DEMATEL is a novel method aimed at capturing these, issues: optimization, prioritization and interactions among parameters. Optimization implies modifying the high-velocity oxy-fuel spraying process such that favorable outcomes are increased while concurrently reducing the influence of undesirable outcomes. This study on optimization aims to enhance the spraying process performance such that the overall cost of spraying, for instance, in using the 67Ni18Cr5Si4B coating is reduced, the efficiency of the process is enhanced and the quality of results obtained greatly improved. However, while implementing optimization using the Taguchi method, several experimental trials are involved. It is also known that not all these experimental trials are equally important to the attainment of the coating process. Therefore, focusing on the important experimental trial by eliminating others could be rewarding as more resources are allocated to the essential parameters. This motivation has brought about the idea of prioritization. However, prioritization is the attempt at ordering the experimental trials in order of importance. With prioritization, aid is given on priorities where the most important experimental trials are used for further analysis. Besides optimization and prioritization comes the idea of interdependence analysis. Interdependence is the state of a parameter depending on the other. Studying the interdependence of parameters enhances efficiency and promotes cooperation among workers of the production process that is to man the various units where the parameters are domiciled. In the above discussion, the author has linked the concepts of optimization, prioritization and interdependence of parameters in the spraying process as it relates to the methodology of Taguchi-Pareto-DEMATEL. The Taguchi-Pareto-DEMATEL method has also effectively addressed the challenges of optimizing and prioritizing process parameters in the thermal spray HVOF process by providing verifiable results in an approach to enhance operations in a coating process.

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