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ORIGINAL PAPER

Taguchi and utility based concept for determining optimal process parameters of cold sprayed coatings for multiple responses

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Abstract Most of the existing multi-response optimization approaches focus on subjective and practical know how of the process. As a result some confusions and uncertainties are introduced in overall decision making process. In this investigation, an approach based on a Utility theory and Taguchi quality loss function has been applied to low-pressure cold spray process to deposit copper coatings, for simultaneous optimization of more than one response characteristics. In the present paper, three potential response parameters i.e. coating density, surface roughness and Micro hardness have been selected. Utility values based upon these response parameters have been analyzed for optimization by using Taguchi approach. The selected input parameters of powder feeding arrangement, substrate material, air stagnation pressure, air stagnation temperature and stand-off distance significantly improves the Utility function (raw data) comprising of quality characteristics (coating density, surface roughness and micro hardness). The percentage contribution of the parameters to achieve a higher value of utility function is: substrate material (64.59%), air stagnation pressure (16.35%), powder feeding arrangement (6.92%), air stagnation temperature (6.49%) and stand-off distance (1.84%) respectively.

Keywords Cold spray (CS) · Optimization · Taguchi method · Utility concept

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1 Introduction

There are many coating deposition techniques available, and choosing the best process depends on the functional requirements, adaptability of the coating material to the technique intended, level of adhesion required, size, shape, and metallurgy of the substrate, and availability and cost of the equipment. Goyal et al. [3] enlisted the commonly employed coating deposition techniques in Fig. 1.

In the early nineteen hundreds, a young Swiss inventor named Dr. Max Schoop invented thermal spraying, after watching his son playing with his toy cannon. Dr. Schoop observed that the hot lead shots that were projected out of the cannon, stuck to almost any surface, the result of which gave him the idea that if metal could be melted and projected in a spray like manner, then a surface could be built up with that material.

Knotek [12] explained that the technology continued, but expanded in the 70s due to development of the thermal plasmas and the increasing demand of high-temperature and wear resistant materials and coating systems. Marceau et al. [15], Groshart [8] and Ishikawa et al. [11] found that Thermal spraying is one of the most versatile hard facing techniques available for the application of coating materials used to protect components from abrasive wear, adhesive wear, erosive wear or surface fatigue and corrosion (such as that caused by oxidation or seawater).

CS is a process of applying coatings by exposing a metallic or dielectric substrate to a high velocity (300–1200 m/s) jet of small (1–50 μm) particles accelerated by a supersonic jet of compressed gas. The two main clear cut distinctions of the Low Pressure Cold Gas Dynamic Spray (LPCGDS) system from the High Pressure Cold Gas Dynamic Spray (HPCGDS) system are: the utilization of low pressure gas (5–10 bars instead of 25–30 bars) and the radial injection of

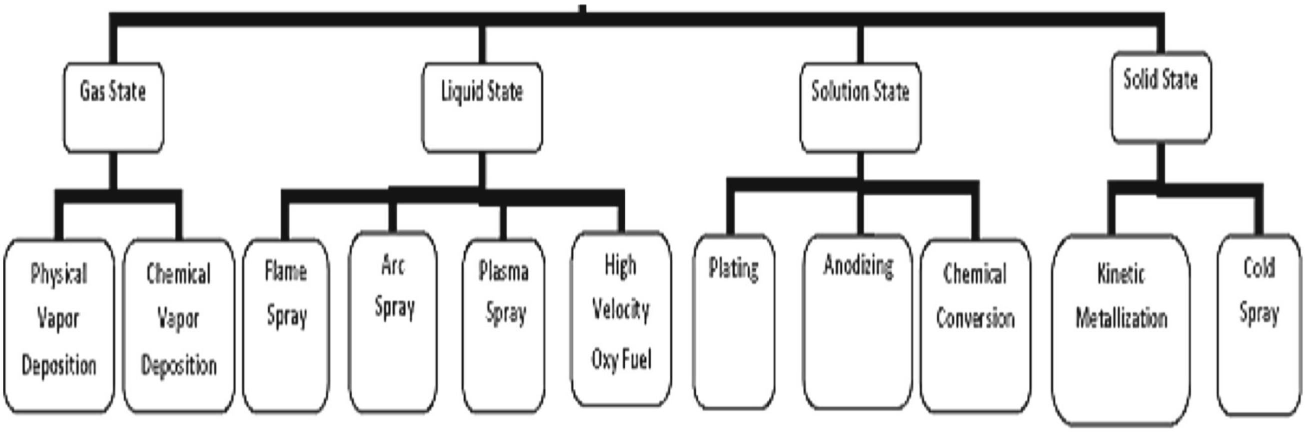

Fig. 1 Various coating deposition processes in commercial use

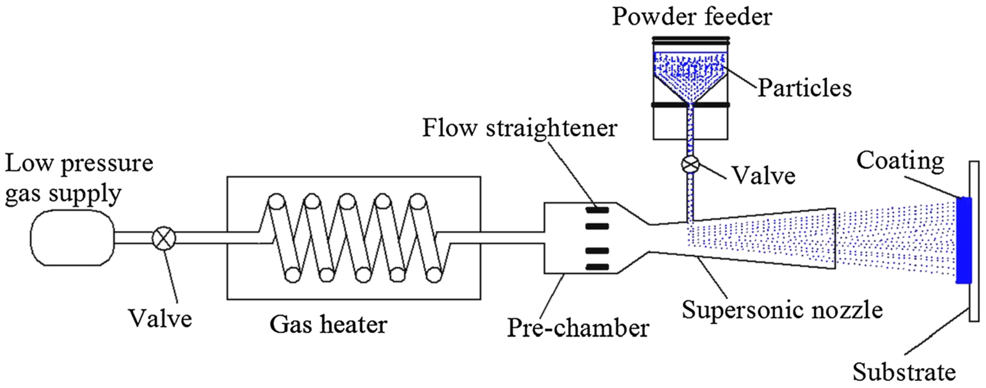

Fig. 2 A typical LPCGDS device

powder instead of axial injection. The accelerating gas (usually air or N_2) is injected at low pressure (5–10 bars) and preheated within the gas heater to temperatures up to about 400°C to optimize its aerodynamic properties. Solid powder particles are radially introduced downstream of the throat section of the supersonic nozzle thus eliminating the need for a high pressure delivery system, which increases system portability, operational safety and significantly reduces spraying costs. Maev and Leshchynsky [14] discovered that within the nozzle, static pressure is maintained below the atmospheric pressure ensuring that feedstock particles are effectively drawn in from the powder feeder by Venturi effect. Grujicic et al. [9] shows a schematic of the LPCGDS system in Fig. 2.

To obtain good quality coatings, these spray parameters should be selected carefully and then optimized. In the process of optimization of process parameters, it is seen that one particular setting of input parameters for a response characteristics may not be suitable for other characteristics of the process/product. In most of the manufacturing processes, more than one quality characteristics has to be considered for optimization of process parameters making it necessary that several response characteristics have to be simultaneously optimized. Based on the foregoing discussions, in this paper, Taguchi method is briefly reviewed for the multi-response optimization. The multi-response optimization of the response parameters of Low Pressure Cold Spray (LPCS) process is presented by using the experimental data. Optimization models have been developed by combination of Taguchi Method and the Utility concept. The multi-response optimization of quality characteristics i.e. coating density, surface roughness and micro hardness of LPCS has been carried.

2 Experimental procedure

2.1 Development of coatings

Substrate material

The substrate materials selected were Al (ASTM B221), Brass (ASTM B36) and Ni (ASTM B435) in the rolled sheet form. The substrate materials selected for the study finds application in the manufacture of electrical contact points, fuse element of electric mains plug, battery terminals,

Table 1 Nominal chemical composition of the substrate materials chosen

Nominal Chemical composition of ASTM B 221 (Al alloy)

%Si	%Fe	%Cu	%Mn	%Mg	%Cr	%Zn	%Ti	%Others	%Al
0.4–0.8	0.7	0.15–0.40	0.15	0.8–1.2	0.04–0.35	0.25	0.15	0.15	Rem.

Nominal Chemical composition of ASTM B 36 (Brass)

%Cu	%Pb	%Fe	%Zn
64–68.5	0.15	0.05	Remainder

Nominal Chemical composition of ASTM B 435 (Ni alloy)

%Fe	%Ni	%Co	%Cr	%Mo	%W	%Mn	%Si	%Ta	%Al	%C	%N	%Zr	%La
31	20	18	22	3	2.5	1	0.4	0.6	0.2	0.1	0.2	0.02	0.02

Table 2 Process parameters and their range

Symbol	Process parameters	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	104–120 psi	104	112	120
D	Stagnation temperature	350–400 °C	350	375	400
E	Stand-off distance	2.5–7.5 mm	2.5	5.0	7.5

Nozzle type: Converging-diverging, Carrier gas: Air, Powder size: <45 µm

bimetallic joints, heat sinks, waste incinerators, gas turbines, brazing and soldering alloys and many more. The nominal chemical composition of the substrate material used in the study is mentioned in Table 1. The samples were cut from the alloy sheet to form approximately 25 mm × 15 mm × 5 mm sized specimens. The specimens were polished and grit blasted with alumina powders (grit 60) before being cold sprayed.

Coating formulation

The coating powder selected was commercially available Copper (less than 45 microns diameter; spherical morphology) obtained from Centreline (Windsor), Ltd (Windsor, ON, Canada) (material ID- 440-00251 and Catalogue Number-SST-C5001). The carrier gas used in the system was compressed air. The coating deposition was done at Surface and Coatings Laboratory, University of Alberta, Edmonton, Canada using Low-Pressure Cold Spray Equipment-SST LPCS Model # SSM-P3800-001, produced by Centreline Windsor, Canada. Table 2 show the process parameters that were identified as potential important in affecting the quality characteristics of the LPCS process under consideration. The process parameters, their designated symbols and ranges are also given in Table 2.

Taguchi's mixed level design was selected as it was decided to keep two levels of powder feeding arrangement. The rest four parameters were studied at three levels. The effect of selected process parameters was studied on the following response characteristics of LPCS process:

a. Coating density (CD)
b. Surface Roughness (SR)
c. Micro hardness (MH)

Coating density and micro hardness are "higher the better" whereas surface roughness is "lower the better" type of quality characteristics.

The coating density was calculated by measuring coating thickness for the samples using digital Micrometer, Mitutoyo, Japan make for an accuracy of 0.0254 mm (0.0001 inch) [4,5]. Goyal et al. [4,5] measured the surface roughness of the samples with the help of Surface Roughness Tester, Mitutoyo, Japan make, Model SJ 400 for a resolution of 0.000125 µm and maximum measuring range of 800 µm. Goyal et al. [6] measured the micro hardness of the coating by Metco's Micro-hardness Tester. A load of 300 g (2.94 N) was provided to the needle for penetration; the loading time was selected as 18 s, and hardness value was based on the relation $Hv = 1854.4\,(F)/d^2$ (where F is the load in grams and d is the mean penetrated diameter in µm).

Goyal et al. [7] used a simplified multi-criterion methodology based on Taguchi's approach and utility concept (given below) to achieve the objective of this study. The observed values of response parameters are given in Table 3.

2.2 Utility concept

Utility can be defined as the usefulness of a product or a process in reference to the expectations of the users. The overall usefulness of a process/product can be represented by a unified index termed as *Utility* which is the sum of the individual utilities of various quality characteristics of the process/product. The methodological basis for Utility approach is to transform the estimated response of each quality characteristic into a common index.

Derek [2] explained that if X_i is the measure of effectiveness of an attribute (or quality characteristic) i and there are n attributes evaluating the outcome space, then the joint Utility function can be expressed as:

$$\mathrm{U}\left(\mathrm{X}_1, \mathrm{X}_2, \ldots \mathrm{X}_\mathrm{n}\right) = \mathrm{f}\left(\mathrm{U}_1(\mathrm{X}_1), \mathrm{U}_2(\mathrm{X}_2) \ldots . \mathrm{U}_\mathrm{n}(\mathrm{X}_\mathrm{n})\right) \quad (1)$$

where $\mathrm{U_i(X_i)}$ is the utility of the ith attribute.

The overall Utility function is the sum of individual utilities if the attributes are independent, and is given as follows:

$$\mathrm{U}\left(\mathrm{X}_1, \mathrm{X}_2, \ldots \mathrm{X}_\mathrm{n}\right) = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{U_i(X_i)} \quad (2)$$

The attributes may be assigned weights depending upon the relative importance or priorities of the characteristics. The overall utility function after assigning weights to the attributes can be expressed as:

$$\mathrm{U}\left(\mathrm{X}_1, \mathrm{X}_2, \ldots \mathrm{X}_\mathrm{n}\right) = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{W_i U_i(X_i)} \quad (3)$$

where $\mathrm{W_i}$ is the weight assigned to the attribute i, the sum of the weights for all the attributes must be equal to 1.

2.3 Determination of utility value

A preference scale for each quality characteristic is constructed for determining its utility value. Two arbitrary numerical values (preference number) 0 and 9 are assigned to the just acceptable and the best value of the quality characteristic respectively. Gupta and Murthy [10,13] proposed that the preference number ($\mathrm{P_i}$) can be expressed on a logarithmic scale as follows:

$$P_i = A \times \log\left(\frac{X_i}{X_i'}\right) \quad (4)$$

where $\mathrm{X_i}$ = value of any quality characteristic or attribute i

X_i' = just acceptable value of quality characteristic or attribute i

A = constant

The value of A can be found by the condition that if $\mathrm{X_i} = \mathrm{X^*}$ (where $\mathrm{X^*}$ is the optimal or best value), then $\mathrm{P_i} = 9$

Therefore, $A = \frac{9}{\log \frac{X^*}{X_i'}}$

The overall utility can be calculated as follows:

$$\mathrm{U} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{W_i P_i} \quad (5)$$

subject to the condition: $\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{W_i} = 1$

Among various quality characteristics type viz. smaller the better, higher the better, and nominal the better, suggested by Taguchi, the Utility function would be higher the better type. Therefore, if the Utility function is maximized, the quality characteristics considered for its evaluation will automatically be optimized (maximized or minimized as the case may be).

3 Analysis and discussions

Based upon the methodology developed in the previous section, following case have been considered to obtain the optimal settings of the process parameters of LPCS for predicting the optimal values of combined responses. Three quality characteristics i.e. Coating density, Surface Roughness and Micro hardness have been included in utility response.

Roy [16] explained Taguchi $\mathrm{L_{18}}$ orthogonal array (OA) which has been adopted for conducting the experiments. Powder feeding arrangement (A), Substrate material (B), air stagnation pressure (C), air stagnation temperature (D), and stand-off distance (E) were selected as input parameters. Response parameters (quality characteristics) were coating density, surface roughness and micro hardness, when they are optimized individually; the summary of results is produced in Table 4.

Following is the stepwise procedure for transforming experimental data into utility data.

3.1 Construction of preference scales

(a) Preference scale for CD (P_{CD}):

$\mathrm{X^*}$ = Optimal value of CD = 27,584.59 (refer Table 4)

X_i' = Just acceptable value of CD = 2700 (All the observed values of CD are greater than 2700)

Following equation is obtained from Eq. 4:

$$P_{CD} = 8.91 \times \log\left(\frac{X_{CD}}{2700}\right) \quad (6)$$

Table 3 Experimental results of various response characteristics

Exp. No.	Coating density (kg/m^3) CD			S/N ratio (dB)	Surface roughness (μm) SR			S/N ratio (dB)	Micro hardness ($H_{v0.3}$) MH			S/N ratio (dB)
	R1	R2	R3		R1	R2	R3		R1	R2	R3	
1	4654.4	4623.6	4593.2	73.29	13.56	13.71	13.83	−22.73	122	126	124	41.86
2	3128.5	3157.9	3116.9	69.92	10.87	10.91	10.36	−20.60	134	129	132	42.38
3	5012.1	5034.4	4997.4	74.00	8.05	7.81	7.73	−17.91	131	132	122	42.15
4	4638.1	4654.1	4614.4	73.32	9.2	10.04	10.68	−19.99	126	128	124	42.00
5	6229.5	6169.3	6125.0	75.81	8.17	8.02	10.23	−18.95	124	125	128	41.98
6	9016.9	8992.2	9021.0	79.09	8.7	7.5	8.6	−18.36	126	127	128	42.07
7	27354.5	27106.4	27500.7	88.72	11.17	11.22	11.56	−21.07	129	131	132	42.32
8	8948.0	8887.9	8877.1	78.99	6.69	6.68	7.35	−16.79	137	133	134	42.58
9	9440.4	9442.0	9474.6	79.51	6.89	6.97	7.02	−16.85	134	135	139	42.66
10	3075.1	3111.0	3084.0	69.79	8.31	8.26	9.59	−18.83	123	118	111	41.36
11	3259.0	3211.9	3245.9	70.20	9.24	9.6	9.52	−19.51	119	115	117	41.36
12	3422.3	3457.9	3437.5	70.72	8.42	8.29	8.92	−18.63	126	131	129	42.18
13	5273.6	5261.5	5225.3	74.40	9.04	9.78	9.62	−19.54	125	121	122	41.77
14	5206.4	5299.1	5216.8	74.38	7.19	7.79	7.82	−17.62	110	119	113	41.12
15	2741.4	2758.3	2749.8	68.78	6.18	6.97	6.39	−16.28	122	120	124	41.72
16	8615.5	8628.4	8671.6	78.72	7.94	8.13	8.15	−18.14	129	125	127	42.07
17	5796.5	5874.8	5818.7	75.31	7.19	8.62	7.34	−17.77	125	127	128	42.05
18	30161.0	30513.7	30244.6	89.63	7.94	7.11	7.84	−17.66	123	128	132	42.11
Total	145973.1	146184.4	146014.3	1364.67	154.75	157.41	162.55	−337.23	2265	2270	2266	755.80
	$\bar{T}D$ = overall mean of CD = 8114.29				$\bar{T}_{SR}$ = overall mean of SR = 8.79				$\bar{T}_{MH}$ = overall mean of MH = 125.94			

Table 4 Optimal setting and values of process parameters

Response characteristics	Optimal level of process parameters	Significant process parameters	Predicted optimal value of quality characteristics
CD	A1, B3, C3, D2, E1	A, B, C, D, E	27584.59 kg/m^3
SR	A2, B3, C3, D3, E3	A, B, C, D, E	4.92 μm
MH	A1, B3, C3, D2, E2	A, B, C, D, E	138.36 $H_{v0.3}$

(b) Preference scale for SR (P_{SR}):
X^* = Optimal value of SR = 4.92 (refer Table 4)
X_i' = Just acceptable value of SR = 14 (All the observed values of SR are lesser than 14)
Following equation is obtained from Eq. 4:

$$P_{SR} = -19.81 \times \log\left(\frac{X_{SR}}{14}\right) \tag{7}$$

(c) Preference scale for MH (P_{MH}):
X^* = Optimal value of MH = 138.36 (refer Table 4)
X_i' = Just acceptable value of MH = 110 (All the observed values of MH are greater than 110)
Following equation is obtained from Eq. 4:

$$P_{MH} = 90.34 \times \log\left(\frac{X_{MH}}{110}\right) \tag{8}$$

3.2 Calculation of utility value

Equal weights (1/3 each) have been assigned to the selected quality characteristics assuming all the quality characteristics, are equally important. However, these weights can be varied depending upon the case or user requirements, if any.

The following relation was used to calculate the utility function based upon the experimental trials:

$$\begin{aligned} U(n, r) = {} & P_{CD}(n, r) \times W_{CD} + P_{SR}(n, r) \times W_{SR} \\ & + P_{MH}(n, r) \times W_{MH} \end{aligned} \tag{9}$$

where $W_{CD} = \frac{1}{3}$; $W_{SR} = \frac{1}{3}$; $W_{MH} = \frac{1}{3}$
n is the trial number ($n = 1, 2, 3, \ldots, 18$) and r is the repetition number (r = 1,2,3). The calculated Utility values are shown in Table 5.

Table 5 Calculated utility data based on responses CD, SR and MH

Trial number	Utility values			S/N ratio (dB)
	R1	R2	R3	
1	2.15	2.53	2.29	9.26
2	3.50	3.00	3.43	10.34
3	4.67	4.86	3.85	12.85
4	3.68	3.64	3.04	10.66
5	4.19	4.34	3.94	12.35
6	4.70	5.22	4.94	13.87
7	5.72	5.90	5.93	15.34
8	6.54	6.14	5.97	15.85
9	6.23	6.30	6.66	16.11
10	3.13	2.61	2.38	8.48
11	1.96	1.89	2.05	5.86
12	3.54	4.11	3.69	11.50
13	3.79	3.14	3.28	10.56
14	2.76	3.58	2.87	9.58
15	3.72	3.17	3.84	10.97
16	4.21	4.73	4.94	13.24
17	4.57	4.27	4.83	13.14
18	6.20	7.06	7.17	16.60

R1, R2, R3 = repetitions of experiments against each of the trial conditions

3.3 Analysis of utility data for optimal settings of process parameters

Roy [16] found that Taguchi suggests two different routes to carry out the complete analysis of the experiments. First the standard approach, where the results of a single run or the average of the repetitive runs are processed through main effect and ANOVA analysis (Raw data analysis). The second approach which Taguchi strongly recommends for multiple runs is to use signal-to-noise (S/N) ratio for the same steps in the analysis. The S/N ratio is a concurrent quality metric linked to the loss function. By maximizing the S/N ratio, the loss associated can be minimized. The S/N ratio determines the most robust set of operating conditions from variation within the results. The S/N ratio is treated as a response parameter (transform of raw data) of the experiment. Byrne and Taguchi [1] gave S/N ratio for a “higher the better” type of quality characteristic by:

$$(S/N)_{HB} = -10\log(MSD_{HB})$$

where $MSD_{HB} = \frac{1}{R}\sum_{j=1}^{R}(1/y_j^2)$
where, MSD denotes mean square deviation, which presents the average of squares of all deviations from the target value rather than around the average value.

The average and main response in terms of Utility values and S/N ratio (Tables 6, 7) are plotted in Fig. 3. It can be observed from Fig. 3(i)–(v) that the 1st level of powder feed

Table 6 Average and main Effects (raw data: CD, SR and MH)

Process parameter designation	Average utility values			Main effects		Difference
	L1	L2	L3	L2–L1	L3–L2	(L3–L2) – (L2–L1)
A	4.57	3.83	–	−0.74	–	−0.74
B	3.09	3.77	5.74	0.68	1.97	1.29
C	3.73	3.88	5	0.15	1.12	0.97
D	3.71	4.55	4.34	0.84	−0.21	−1.05
E	4.16	4.16	4.28	0	0.12	0.12

L1, L2 and L3 represents average values of raw data of corresponding parameters at levels 1, 2 and 3 respectively. L2–L1 is the average main effect when the corresponding parameter changes from level 1 to level 2. L3-L2 is average main effect when the corresponding parameter changes from level 2 to level 3. A-Powder feed arrangement, B- Substrate material, C-air stagnation pressure, D-air stagnation temperature, E-stand-off distance

Table 7 Average S/N values and main effects (raw data: CD, SR and MH)

Process parameter designation	S/N Average values			Main effects (dB)		Difference
	L1	L2	L3	L2–L1	L3-L2	(L3-L2)-(L2-L1)
A	12.74	11.1	–	−1.63	–	−1.63
B	9.38	11.33	15.05	1.95	3.72	1.77
C	10.92	11.19	13.65	0.26	2.46	2.2
D	10.67	12.78	12.31	2.11	−0.47	−2.58
E	11.42	12.09	12.25	0.67	0.16	−0.51

L1, L2 and L3 represents average values of S/N data of corresponding parameters at levels 1, 2 and 3 respectively. L2–L1 is the average main effect when the corresponding parameter changes from level 1 to level 2. L3–L2 is average main effect when the corresponding parameter changes from level 2 to level 3. A-Powder feed arrangement, B- Substrate material, C-air stagnation pressure, D-air stagnation temperature, E-stand-off distance

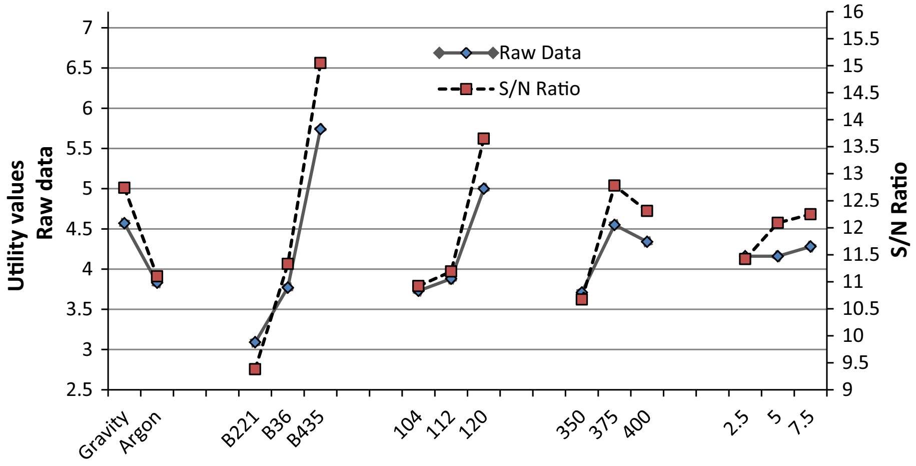

Fig. 3 Average and main response in terms of Utility values and S/N ratio

arrangement (A 1), 3rd level of substrate material (B 3), 3rd level of air stagnation pressure (C 3), 2nd level of air stagnation temperature (D 2) and 3rd level stand-off distance (E 3) are expected to yield a maximum values of the utility and S/N ratio within the experimental space.

The pooled version of ANOVA for utility data and S/N ratio are given in Tables 8 and 9 respectively. It can be noticed from Table 8 that all the input parameters have significant effect (at 95% confidence level) on the utility function. Similarly, it had been found from Table 9 that all the chosen parameters in study have significant effect on the S/N ratio of utility function.

3.4 Optimal values of quality characteristics (predicted means)

The average values of all the response characteristics at the optimum levels of significant parameters with respect to Utility function are recorded in Table 10.

Table 8 Pooled ANOVA (raw Data: CD, SR and MH)

Source	SS	DOF	V	F-Ratio	SS′	P %
A	7.31	1	7.31	79.81*	7.22	6.92
B	68.28	2	34.14	372.72*	68.10	64.59
C	17.28	2	8.64	64.27*	17.10	16.34
D	6.86	2	3.43	79.81*	6.68	6.49
E	1.95	2	0.97	10.64*	1.77	1.84
E (Pooled)	4.03	44	0.09	–	4.85	3.81
Total (T)	105.72	53	–	–	105.72	100

* Significant at 95% confidence level
SS sum of Squares, *DOF* degree of freedom, *V* variance, *SS*′ pure sum of squares

Table 9 S/N pooled ANOVA (raw data: CD, SR and MH)

Source	SS	DOF	V	F-Ratio	SS′	P %
A	11.99	1	11.99	54.40*	11.77	7.61
B	99.44	2	49.72	225.53*	99.00	63.13
C	27.19	2	13.59	61.66*	26.74	17.26
D	14.81	2	7.40	33.58*	14.37	9.40
E	2.32	2	1.16	5.27*	1.88	1.48
E (Pooled)	1.76	8	0.22	–	3.75	1.12
Total (T)	157.51	17	–	–	157.51	100

* Significant at 95% confidence level
SS sum of Squares, *DOF* degree of freedom, *V* variance, *SS*′ pure sum of squares

Table 10 Average values of various responses at optimal levels

Levels	Coating density, CD (kg/m^3)	Surface roughness, SR (μm)	Micro hardness, MH (Hv$_{0.3}$)
A1	8696.68	9.390	129.33
B3	15075.3	8.101	130.44
C3	9995.41	7.629	128.28
D2	12604.7	9.415	127.83
E3	5802.51	8.258	126.11

The above average values are taken from experimental data

The optimal values of the predicted means (μ) of different response characteristics can be obtained from the following equation:

$$\mu = A1 + B3 + C3 + D2 + E3 - 4T \tag{10}$$

where, A1-First level of powder feed arrangement, B3-Third level of substrate material, C3-Third level of air stagnation pressure, D2-Second level of air stagnation temperature and E3-Third level of stand-off distance.

Roy [16] described that the 95% confidence interval of confirmation experiments (CI$_{CE}$) can be computed by using the following equation:

$$\mathrm{CI_{CE}} = \sqrt{\mathrm{F_\alpha(1,f_e)V_e}\left[\frac{1}{\mathrm{n_{eff}}} + \frac{1}{\mathrm{R}}\right]} \tag{11}$$

where, $\mathrm{F_\alpha(1, f_e)}$ = The F-ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom $\mathrm{f_e}$, R = Sample size for conformation experiments, $\mathrm{V_e}$ = Error variance, $\mathrm{n_{eff}} = \frac{\mathrm{N}}{1+\mathrm{DOF}}$, N= total number of trials, and DOF= Total degrees of freedom associated in the estimate of mean response.

(a) For Coating density (CD)

$$\mu_{CD} = A1 + B3 + C3 + D2 + E3 - 4T_{CD} = 19717.44$$

where A1 = 8696.68, B3 = 15075.3, C3 = 9995.41, D2 = 12604.7, E3 = 5802.51 (Table 10):
$\mathrm{T_{CD}} = 8114.29$ (Table 3)
The following values have been obtained by the ANOVA:
$\mathrm{N = 54,\ f_e = 44;\ v_e = 4349657.9,\ n_{eff} = 5.4,\ R = 3,}$
$\mathrm{F_{0.05}(1, 44) = 4.064}$
From Eq. 11, $\mathrm{CI_{CE}} = \pm 3027.52$
The predicted optimal range (for conformation runs of three experiments) for CD is given by
$\mathrm{CI_{CE}} : 16689.92 < \mu_{CD} < 22744.96$

(b) For Surface Roughness (SR)

$$\mu_{SR} = A1 + B3 + C3 + D2 + E3 - 4T_{SR} = 7.633$$

where A1 = 9.390, B3 = 8.101, C3 = 7.629, D2 = 9.415, E3 = 8.258, (Table 10):
$\mathrm{T_{SR}} = 8.79$ (Table 3)
The following values have been obtained by the ANOVA:
$\mathrm{N = 54,\ f_e = 44;\ v_e = .000387079,\ n_{eff} = 5.4,\ R = 3,}$
$\mathrm{F_{0.05}(1, 44) = 4.064}$
From Eq. 11, $\mathrm{CI_{CE}} = \pm 0.02856$
The predicted optimal range (for conformation runs of three experiments) for SR is given by
$\mathrm{CI_{CE}} : 7.60444 < \mu_{SR} < 7.66156$

(c) For Micro hardness (MH)

$$\mu_{MH} = A1 + B3 + C3 + D2 + E3 - 4T_{MH} = 138.23$$

where A1 = 129.33, B3 = 130.44, C3 = 128.28, D2 = 127.83, E3 = 126.11, (Table 10):
$\mathrm{T_{MH}} = 125.94$ (Table 3)
The following values have been obtained by the ANOVA:
$\mathrm{N = 54,\ f_e = 44;\ v_e = 19.77,\ n_{eff} = 5.4,\ R = 3,}$
$\mathrm{F_{0.05}(1, 44) = 4.064}$
From Eq. 10, $\mathrm{CI_{CE}} = \pm 6.45$
The predicted optimal range (for conformation runs of three experiments) for MH is given by
$\mathrm{CI_{CE}} : 131.77 < \mu_{MH} < 144.68$

Table 11 Observed values of quality characteristics (Confirmation experiment)

Exp. no.	CD (kg/m^3)			SR (μm)			MH (Hv$_{0.3}$)		
	r$_1$	r$_2$	r$_3$	r$_1$	r$_2$	r$_3$	r$_1$	r$_2$	r$_3$
1	18798.5	19765.6	20987.5	7.62	7.63	7.65	135	139	137
2	19682.8	21942.8	20736.4	7.64	7.65	7.62	134	137	138
3	18952.7	19428.9	21659.3	7.61	7.64	7.63	142	142	141
Overall average	20217.2			7.63			138.336		

3.5 Confirmation experiment

For confirmation of experimental results, three experiments were performed at optimal settings as suggested by Taguchi analysis of Utility data. The observed values of various response characteristics have been given in Table 11. It can be noticed that overall average of the observed values of the response characteristics fall well within the 95% $\mathrm{CI_{CE}}$ of the optimal range of the respective response characteristics.

4 Conclusions

A simplified model based on the Taguchi method and Utility concept was used to analyze the multi-response optimization of Low-pressure cold spray process. Following conclusions can be drawn from this study:

- All the input parameter significantly improves the Utility function comprising of three quality characteristics (coating density, surface roughness and micro hardness). All the chosen process parameters are found to have significant effect on the S/N ratio of Utility function.
- The optimal setting of the process parameters were predicted for optimization of coating density, surface roughness and micro hardness using the model. The optimal settings were A1- First level of powder feed arrangement, B3-Third level of substrate material, C3-Third level of air stagnation pressure, D2-Second level of air stagnation temperature and E2-Third level of stand-off distance.
- The decreasing order of percentage contribution of the parameters to achieve a higher value of utility function is: substrate material (64.59%), air stagnation pressure (16.34%), stand-off distance (6.92%), air stagnation temperature (6.49%) and powder feeding arrangement (1.84%) respectively.
- The overall average of quality characteristics was found to be 20, 217.2 kg/m^3 for coating density, 7.63 μm for surface roughness and 138.34 $\mathrm{H_{v0.3}}$ for micro hardness which falls well within the 95% $\mathrm{CI_{CE}}$ of the optimal range of the respective response characteristics.

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