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Influence of cutting parameters on burr height and burr thickness in drilling of Duplex 2205 using Solid Carbide

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Abstract: Duplex stainless steels are extensively used in chemical industries due to its superior corrosion resistance, high strength and toughness properties after welding. During drilling the degree of burr height and burr thickness of the duplex material plays a significant role, though any irregularities will reduce the final quality of the product. Because deburring processes are not yet well automated, understanding of the burr development in drilling and its principal parameters is important for controlling the burr sized at the fabrication stage itself. Design of experiments, Box-Behnken design have been used to study the effects of the drilling parameters such as spindle speed and feed rate (input data's) used on the prediction of burr height and burr thickness (output response) on drilling Duplex 2205. This work reveals the development of mathematical models to predict the tool exit portion burr height and burr thickness, which were used to determine the characteristics of the material. Experiments were performed under different drilling conditions of spindle speed and feed rate. Residual plots were constructed to analyze the variation between the experimental values and model values. Response contours were constructed to determine the optimum drilling condition for the burr height and burr thickness. The developed model establishes a good correlation between spindle speed and feed rate that influences the burr height and burr thickness. Analysis of Variance (ANOVA) was employed to identify the level of importance in drilling parameters on their performance characteristics. The ANOVA showed better coefficient of determination (R^2) value of 0.8726 and 0.853 for burr height and burr thickness respectively, thus ensuring a satisfactory adjustment of the second order regression model with experimental data. The performance evaluation of the mathematical model was analyzed, ensuring good correlation over the actual data's. The optimum value of cutting parameters is also determined to get minimum values burr height and burr thickness.
Keywords : Duplex, Response Surface Methodology (RSM), Burr height, Burr thickness, Desulfurization.

Introduction

Materials from primary manufacturing processes, further needs a machining to improve its characteristics. Machining is classified as turning, milling, grinding, drilling, etc. Among those, drilling is widely practiced machining process, due to the need for component assembly in mechanical structures. Identification of appropriate input parameters is essential for improving the productivity and quality.

Duplex stainless steels are a family of grades combining good corrosion resistance with high strength and ease of fabrication. Their physical properties are between those of the austenitic and ferritic stainless steels but tend to be closer to those of the ferritics and to carbon steel. Duplex stainless steels are widely used in flue gas desulfurization application, desalination application, oil, gas, biofuel, food, architecture industries due to the enhanced corrosion resistance, and high strength and toughness properties after welding. Duplex 2205 have been used for flue gas desulfurization applications. The chip formed when machining duplex stainless steel is strong and abrasive to tooling, and especially for the most highly alloyed duplex grades. Because the duplex stainless steels are produced with as low as sulfur content as possible, there is little to aid chip breaking. For these reasons duplex stainless steels are typically more difficult to machine than the austenitic stainless steels. Higher cutting forces are required and more rapid tool wear is typical of duplex stainless steel machining[1]. Therefore, it is mandatory to investigate the influences of cutting parameters of Duplex 2205, that this paper reveals the same.

A sharp projection of material on the workpiece edges can be left, and these projection are known as burrs. Burrs can cause troubles with following assembly and handling operations. In practice deburring operation must be used to remove burrs, and the cost of these additional processes can be significant[2]. Burr formed on components lead to many undesirable features in practice, such as improper contact between current carrying members and improper seating of mating surfaces. Burrs are injurious during machining, as they hit the cutting edge and cause the grove wear[3].

Effect of drilling parameters on surface roughness and roundness error were investigated in drilling of Al 6061 alloy using high speed steel (HSS) twist drill by Reddy Sreenivasulu and Srinivasa Rao[4]. The grey relational analysis based on an orthogonal array of the Taguchi methods used to optimize the process parameters in drilling of Al6061 alloy. Integration of fuzzy logic with response surface methodology for thrust force and surface roughness modeling of drilling on titanium alloy were carried out by Suresh kumar and Basker[5]. Researcher developed a mathematical model using fuzzy logic (FL) and fuzzy logic with response surface methodology (FL-RSM); concluded, that hybrid FL-RSM produces the effective output than the FL model. Kannan and Baskar[6] used RSM with genetic algorithm (GA) to optimize the input parameter of face milling operation. Material removal rate and surface roughness considered as responses; when speed, feed and depth of cut were considered as inputs. RSM used to generate the mathematical model and GA used to select the optimal machining parameters. Kasim *et al*[7] investigated the surface roughness in High-speed milling of Inconel 718 under minimum quality lubrication using RSM. The interaction between radial depth of cut and feed rate are the most dominant factor affecting the surface roughness. Prakash S *et al*[8] developed a mathematical model to predict the two surface roughness parameters namely average roughness (R_a) and mean peak to valley height (R_z), which was used to determine the surface characteristics of the panels, considered the cutting conditions spindle speed, feed rate and drill diameter.

Tsao and Hocheng[9] evaluated thrust force and surface roughness in drilling composite materials using Taguchi analysis and neural network; obtained mathematical model using multi-variable regression analysis and radial basis function network (RBFN), while comparing with the experimental results, RBFN is more effective than multi-variable regression analysis. Ramazan Cakıroglu & Adem Acır[10] investigated and optimized the cutting parameters on drill bit temperature in drilling Al7075 work piece using the uncoated and Firex coated carbide drill bits. The factors considered are cutting speed, feed rate and cutting tool. Taguchi method was used to determine the optimum cutting parameters. The drill bit temperature increased with increasing cutting speed whereas, the drill bit temperature decreased with increasing feed rates. Taguchi design method was able to provide the minimum cost and time in the manufacturing engineering applications.

Palanikumar[11] investigated and optimized the input parameters in drilling of glass fiber reinforced polymer (GFRP) composites; the drilling parameters such as spindle speed and feed rate are optimized with consideration of multiple performance characteristics, such as thrust force, work piece surface roughness and delamination factor. The analysis of grey relational grade indicates that the feed rate is more influential parameter than the spindle speed. Turgay Kivak *et al*[12] studied Taguchi method optimization of drilling parameters in AISI 316 steel PVD monolayer and multilayer coated HSS drills. Optimization of drilling parameters using the Taguchi technique to obtain minimum surface roughness and also thrust force were analyzed for AISI 316 stainless steel using uncoated and coated M35 HSS twist drill under dry cutting conditions. A typical burr in a ductile material results in a significant amount of subsurface damage and deformation associated the formation of the burr. Exit burr strongly affects product quality and assembly process. Hence it is essential to understand the factors affecting the formation of exit burr size at the production stage.

This necessitates suitable drill models describing the relation of burr size with process parameters. Here drilling experiment was conducted in a radial drilling machine using 6 mm solid carbide twist drill. The sample work piece of size 150 × 70 × 10 mm was used. The drilling parameters were selected at three levels and the two responses, i.e., the tool exit portion burr height and tool exit portion burr thickness was measured in every run. The assignment of levels to factors is given in table 1.

Table 1 : Factor and their levels

Factors/ Levels	Unit	Low	Middle	High
Spindle speed	rpm	270	350	540
Feed rate	mm/rev	0.038	0.076	0.203

RSM is a combination of mathematical and statistical techniques employed for developing, improving and optimizing the parameters for the required output response. In the present work, an attempt has been made to employ Box-Behnken design using response surface methodology for optimizing the key influencing parameters on the burr height and burr thickness.

Experimental Setup nd Cutting Conditions

The proposed work methodology starts with experimental approach and the experimental data are analyzed with RSM Box-Behnken design. Further, the modeling data are validated with experimental data then optimized input parameters are achieved from the same design. The proposed methodology of this work as follows:

The experiments were carried out in three axes, Vertical Milling Machine as shown in figure 1; the specifications are given in table 2. The 6 mm Solid Carbide twist drill bit was used for this experiment. The digital caliper Mitutoyo CD 6 CS used to measure burr thickness. A dial gauge Mitutoyo 2046 F used to measure the burr height. Both the instruments are capable of producing 0.01 mm fine measurement. The workpiece was prepared by cutting the raw material into smaller sizes of 150 mm × 70 mm × 10 mm for holding in the special fixture. The experiments were carried out as per RSM Box-Behnken experimental design. A set of 17 experiments were conducted for the development of mathematical model for burr height and burr thickness in drilling Duplex 2205 by solid carbide drills.

Figure 1 : Photographic image of vertical milling machine

Table 2 : Specification of Vertical Milling Machine

Model	X 6323
Table dimension Width, Length	230, 1070 mm
Travel x, y, z – axis	610, 350, 380 mm
Head structure	Phased gear head (PGH)
	Vertical steel head (VSH)
	Non-phased head (NPH)
Spindle speed	PGH : 80 – 5400 rpm
	VSH : 80 – 8400 rpm
	NPH : 60 – 4200 rpm
Spindle feed rate	0.038, 0.076, 0.203 mm/rev.
Spindle rotation angle	45°
Motor output	3HP
Ram travel	305 mm
Ram rotation angle	360°
Machine size (L × W × H)	1500 mm × 1530 mm × 2100 mm
Machine load	250 kg

The drilling parameters were selected at three levels (spindle speeds of 270, 350 and 540 rpm and feed rates of 0.038, 0.078 and 0.203 mm/rev.). These parameters were preferred based on tool manufacturer commendation and machine tool competence. The combinations between these two factors were created, and 17 experiments were conducted.

Burr height measured four replicates at various places in the tool exit portion and the average value considered for the further processing. The internal and external distance on the hole measured using digital vernier caliper and the average of the difference considered for further analysis. The measured burr height and burr thickness data are given in table 3.

Table 3 : Response data's

S. No.	Spindle Speed	Feed rate	Burr height	Burr thick
	rpm	mm/rev	mm	mm
1	270	0.038	0.234	0.115
2	270	0.076	0.3425	0.265
3	270	0.076	0.4475	0.2925
4	270	0.203	0.1375	0.365
5	350	0.038	0.08	0.3625
6	350	0.038	0.1825	0.325
7	350	0.076	0.25	0.375
8	350	0.076	0.26	0.355
9	350	0.076	0.2475	0.53
10	350	0.076	0.235	0.435
11	350	0.076	0.2125	0.42
12	350	0.203	0.165	0.2225
13	350	0.203	0.235	0.215
14	540	0.038	0.315	0.385
15	540	0.076	0.4475	0.24
16	540	0.076	0.375	0.2525
17	540	0.203	0.1425	0.27

Anova and Response Plots

The analysis of variance (ANOVA) was applied to study the effect of the input parameters on the output parameters. Table 4 shows the model statistics for burr height and burr thickness. It reveals that the modified quadratic model is the best suggested model, because it has the better statistical values than the other models. The cubic and modified quadratic model has similar statistical values; still modified quadratic model is suggested because of lesser terms when compared with cubic model. So, for further analysis this modified quadratic model was used.

Table 4 : Model summary statistics of Burr height and Burr thickness

Burr height					
Statistical values	**Linear**	**2FI**	**Quadratic**	**Modified Quadratic**	**Cubic**
Coded Factors	***A & B***	***A, B & AB***	***A, B, AB, A^2 & B^2***	***A, B, AB, A^2, B^2, A^2B & / AB^2***	***A, B, AB, A^2, B^2, A^2B, AB^2, A^3 & B^3***
R-Squared	0.1662	0.2005	0.7176	0.8726	0.8734
Adj R-Squared	0.0470	0.0160	0.5893	0.7961	0.7750
Pred R-Squared	-0.2381	-0.8034	-1.0774	0.0034	-8.3459
Adeq Precision	3.7026	3.4931	6.8397	9.8942	8.7089
Burr thickness					
R-Squared	0.0517	0.0930	0.3735	0.8530	0.8530
Adj R-Squared	-0.0838	-0.1163	0.0887	0.7386	0.7386
Pred R-Squared	-0.3372	-1.3724	-6.2676	-6.8870	-6.8870
Adeq Precision	1.5556	2.8705	3.5952	9.3432	9.3432

Table 5 and 6 shows the ANOVA results of the modified quadratic model for the burr height and burr thickness respectively. ANOVA is commonly used to summarize the test for significance on individual model coefficient. The Model F-value of 11.41 implies the model is significant. There is only a 0.06% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A^2, B^2, A^2B are significant model terms. A & B are the coded factors of spindle speed and feed rate respectively. Values greater than 0.1000 indicate the model terms are not significant. The "Lack of Fit F-value" of 1.14 implies the Lack of Fit is not significant relative to the pure error. There is a 36.56% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good for the model to fit.

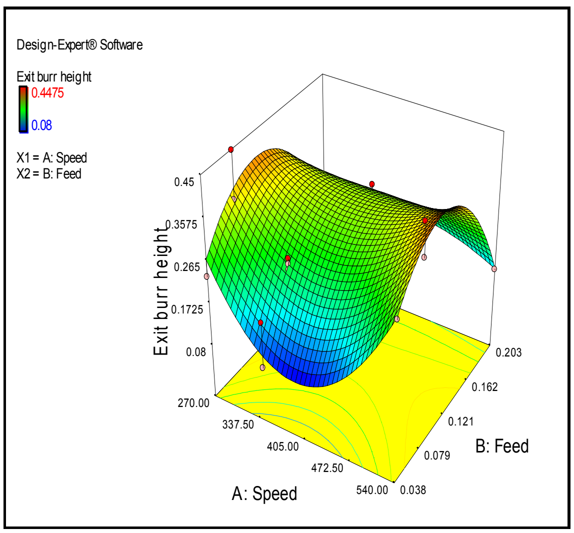
The table 6 shows the burr thickness ANOVA table. The Model F-value of 7.46 implies the model is significant. There is only a 0.38% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, AB, A^2B, AB^2 are significant model terms. The "Lack of Fit F-value" of 1.51 implies the Lack of Fit is not significant relative to the pure error. There is a 25.39% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good for the model to fit.

Table 5 : ANOVA Table for Burr height

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	0.15	6	0.025	11.41	0.0006
A-Speed	8.89E-04	1	8.89E-04	0.4	0.5402
B-Feed	9.05E-03	1	9.05E-03	4.1	0.0705
AB	8.27E-04	1	8.27E-04	0.37	0.5542
A^2	0.015	1	0.015	6.89	0.0253
B^2	0.057	1	0.057	25.99	0.0005
A^2B	0.027	1	0.027	12.16	0.0059
Residual	0.022	10	2.21E-03	—	—
Lack of Fit	4.91E-03	2	2.46E-03	1.14	0.3656
Pure Error	0.017	8	2.15E-03	—	—
Cor Total	0.17	16	—	—	—

Table 6 : ANOVA Table for Burr thickness

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F
Model	0.14	7	0.019	7.46	0.0038
A-Speed	0.024	1	0.024	9.07	0.0147
B-Feed	0.049	1	0.049	18.82	0.0019
AB	0.036	1	0.036	13.8	0.0048
A^2	7.05E-03	1	7.05E-03	2.71	0.1344
B^2	2.83E-03	1	2.83E-03	1.09	0.3247
A^2B	0.048	1	0.048	18.33	0.002
AB^2	0.028	1	0.028	10.89	0.0092
Residual	0.023	9	2.61E-03	—	—
Lack of Fit	3.72E-03	1	3.72E-03	1.51	0.2539
Pure Error	0.02	8	2.47E-03	—	—
Cor Total	0.16	16	—	—	—



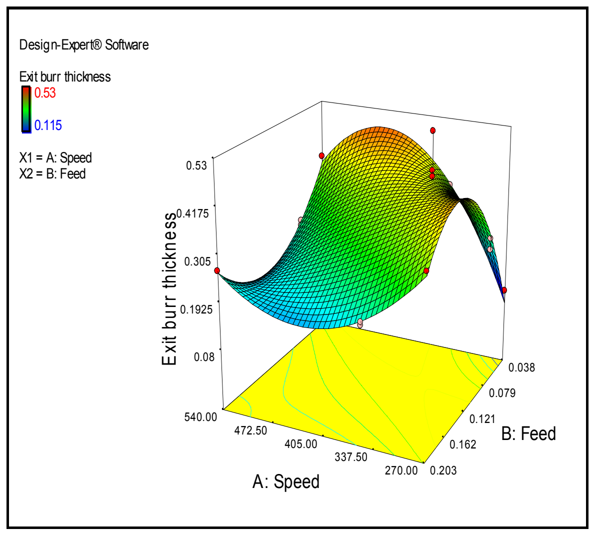


Figure 2 : Burr height Vs Speed and Feed

Figure 3 : Burr height Vs Speed and Feed

The interaction between the inputs (speed and feed) and output (burr height) is shown in figure 2. Interaction of individual input shows, increase in speed decreases burr height till 405 rpm later increases and increase in feed increases burr height up to 0.121 mm/rev. later decreases. A reverse parabolic relation observed in the case of feed and burr height. The interaction between the inputs (speed and feed) and output (burr thickness) is shown in figure 3. Interaction of individual input shows, increase in speed and feed decreases burr thickness. From figure 4, it is evident that residuals are distributed as per normal distribution; the normal distribution provides an excellent model for the data.

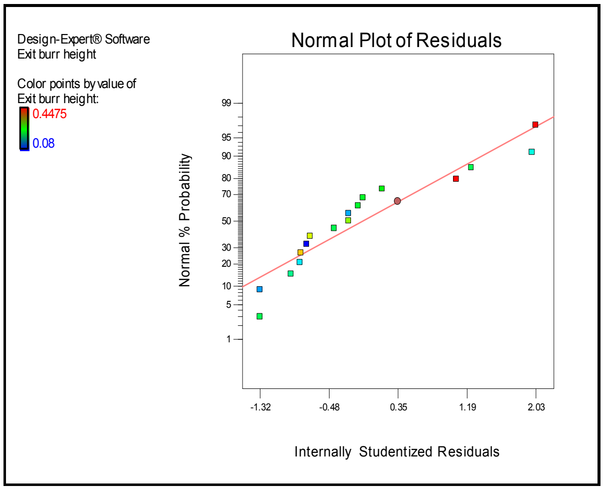


Figure 4 : Normal plot

Empirical Model

The regression models of burr height and burr thickness are given in equation (1) and (2) respectively. In that equation "N" denotes spindle speed and "F" denotes feed rate. Table 7 shows the regression statistics. The coefficient of determination R^2 is used to decide whether a regression model is appropriate. The coefficient of determination R^2 provides an exact match if it is 1 and if the residual increases, R^2 decreases in the range from 0 to 1. For this study, R^2 for burr height is 0.8726 and for burr thickness is 0.8530 which is very closer to unity. Hence the model is reliable. Adj R^2 is used for comparing the residual per unit degree of freedom. Adequate precision compares the range of the predicted values at the design points to the average prediction error. It is a measure of the signal to nose ratio. Ratio greater than 4 indicates adequate model discrimination. In this particular case, it is 9.8942 for burr height and 9.3432 for burr thickness which is above 4. So the model can be used to navigate the response space.

Table 7 : Regression Statistics

Statistical values	Burr height	Burr thickness
R-Squared	0.8726	0.8530
Adj R-Squared	0.7961	0.7386
Pred R-Squared	0.0034	-6.8870
Adeq Precision	9.8942	9.3432

$$\text{Burr Height} = +\,2.25638 - 0.012087 \times N - 7.22866 \times F + 0.071345 \times N \times F + 1.52042 \times 10^{-5} \times N^2 - 25.95518 \times F^2 - 8.95703 \times 10^{-5} \times N^2 \times F \quad (1)$$

$$\text{Burr Thickness} = -\,3.52054 + 0.016922 \times N + 41.10823 \times F - 0.15043 \times N \times F - 1.73916 \times 10^{-5} \times N^2 - 82.01370 \times F^2 + 1.19427 \times 10^{-4} \times N^2 \times F + 0.18767 \times N \times F^2 \quad (2)$$

Statistical package Design Expert 7.0.0 was used to find the optimum input parameters. The optimized parameters for minimum burr height and burr thickness are shown in table 9. The 3D response surface plot for burr height and burr thickness models are shown in figure 2 and 3.

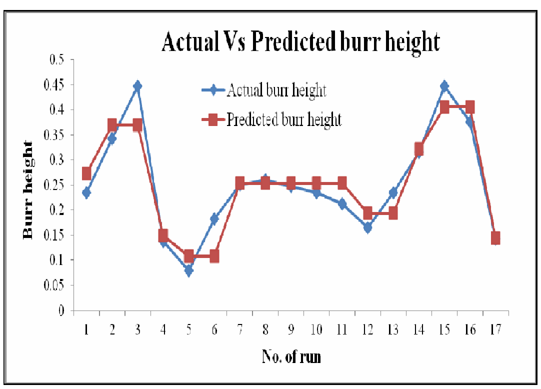
Performance Evaluation

Validation is essential for the response surface equations which were derived from quadratic regression, to know the reliability of the derived mathematical model. Therefore, validation made on the empirical model and the results of the validation proved that the machining parameters of Design Expert could yield the same burr height and burr thickness value for a given component. The table 8 shows the comparison between actual (experimental) Vs predicted (derived from mathematical model) responses and percentage of deviation between actual Vs predicted values. The deviations between actual and predicted values are very smaller so this work extended for optimization. The average percentage of deviation for burr height was noted −2.345% and for burr thickness it was −0.194%, which also well within the range.

Table 8: Actual Vs Predicted Burr height and Burr thickness and its Percentage of deviation

S. No.	Speed rpm	Feed mm/rev	Actual Burr height mm	Predicated Burr height mm	Percentage of deviation	Actual Burr thickness mm	Predicted Burr thickness mm	Percentage of deviation
1	270	0.038	0.234	0.273	-16.645	0.115	0.0847	26.342
2	270	0.076	0.3425	0.370	-7.941	0.265	0.2984	-12.615
3	270	0.076	0.4475	0.370	17.386	0.2925	0.2984	-2.027
4	270	0.203	0.1375	0.149	-8.476	0.365	0.3559	2.483
5	350	0.038	0.08	0.108	-35.218	0.3625	0.3653	-0.765
6	350	0.038	0.1825	0.108	40.726	0.325	0.3653	-12.392
7	350	0.076	0.25	0.253	-1.197	0.375	0.4118	-9.817
8	350	0.076	0.26	0.253	2.695	0.355	0.4118	-16.004
9	350	0.076	0.2475	0.253	-2.219	0.53	0.4118	22.299
10	350	0.076	0.235	0.253	-7.656	0.435	0.4118	5.330
11	350	0.076	0.2125	0.253	-19.055	0.42	0.4118	1.949
12	350	0.203	0.165	0.193	-17.028	0.2225	0.2252	-1.209
13	350	0.203	0.235	0.193	17.832	0.215	0.2252	-4.740
14	540	0.038	0.315	0.322	-2.286	0.385	0.3722	3.313
15	540	0.076	0.4475	0.407	9.146	0.24	0.2545	-6.057
16	540	0.076	0.375	0.407	-8.419	0.2525	0.2545	-0.806
17	540	0.203	0.1425	0.145	-1.512	0.27	0.2662	1.414
Average % of deviation					-2.345			-0.194

The figure 5 and 6 shows the actual and predicted comparison plot for burr height and burr thickness respectively. The actual values are very closer to the predicted values. It is observed that the results are in close agreement with those obtained from the response surface analysis, confirming that the RSM could be effectively used to investigate the influence of process parameters on the responses in drilling of duplex 2205 using solid carbide.



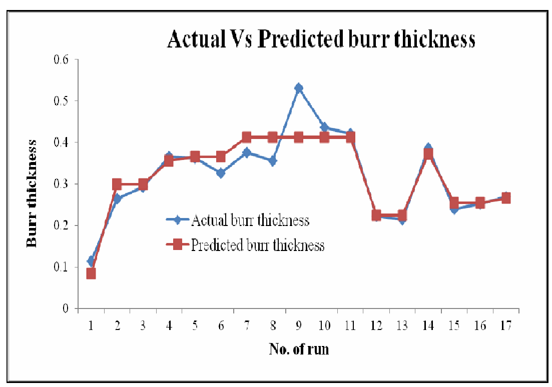


Figure 5 : Actual Vs Predicted burr height

Figure 6 : Actual Vs Predicted burr thickness

Optimization of Parameters

The objective of using RSM is not only to examine the response over the entire factor space but also to locate the region of interest where the response reaches its optimum or near optimal value. Based on the developed mathematical model for associating the selected input parameters on the response, optimality search can be obtained. The objective of the optimization was to minimize the burr height and burr thickness. The lower and upper values of responses considered for its minimization. The parameter setting for which burr height and burr thickness are predicted as 0.1893 and 0.1911 respectively. The desirability for the whole process optimization obtained is 0.7574, it can be concluded that the parameters are within their working range which is shown in table 9.

Table 9 : Optimum Parameters

Spindle speed	Feed rate	Burr height	Burr thickness	Desirability
rpm	mm/rev.	mm	mm	
465.41	0.203	0.1893	0.1911	0.7574

Conclusion

The experimental analysis highlights that the burr height and burr thickness in drilling of Duplex 2205 using solid carbide, was affected by spindle speed and feed rate. Response surface methodology was used in the present investigation, which has proved its adequacy to be an effective tool for analyzing the drilling process in newer materials. Mathematical model for correlating the burr height and burr thickness with the predominant parameters have been obtained. Response plots were obtained to exhibit the influence of the selected two parameters on the response. From the response surface methodology, the following conclusions were made:

1. Burr height influenced by both inputs i.e., spindle speed and feed rate, increase in speed decreases burr height up to 405 rpm eventually increases and increase in feed increases burr height till 0.121 mm/rev. subsequently decreases.
2. Burr thickness besides influenced by both inputs, increase in speed and feed decreases burr thickness in a faster rate.
3. Mathematical model for burr height and burr thickness were proposed (Eqs. (1) and (2)) to correlate the input and responses. Average percentage of deviation was observed −2.345 and −0.194 for burr height and burr thickness respectively, which shows an impact on the model.
4. The performance test of developed model has less percentage of deviation with experimental results. The overall accuracy rate of the present approach for burr height and burr thickness is 87.26% and 85.3% respectively.
5. With the aid of the experimental design and RSM, the optimal values of spindle speed and feed rate for minimizing the burr height and burr thickness were found to be 465.41 rpm and 0.203 mm/rev respectively, with a desirability index of 0.7574.

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