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Determination of Optimum Parameters for Drilling Stainless Steel using Response Surface Methodology (RSM)

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A B S T R A C T

Key words:
Stainless Steel,
Response Surface
Methodology
(RSM),
Surface roughness,
Process parameters

The study investigated the application of Response Surface Methodology (RSM) in determination of optimum parameters required for drilling stainless steel based on L9-A 34-2 fractional factorial design. The SS304 stainless steel workpiece is of length 200mm, breadth of 80mm and thickness of 0.75mm. The study employed the following process parameters namely, cutting speed which ranges from 1400-1700rpm, feed rate which ranges from 0.11-0.75mm/rev, depth of cut which ranges from 0.25-0.75mm and tool which ranges from 6-8mm, for minimizing surface roughness of drilled hole in SS304 stainless steel. Analysis of Variance (ANOVA) was carried out to test for the significant level of the process parameters for optimizing surface roughness. The findings revealed that for an optimal value of drilling parameters for minimizing surface roughness, cutting speed, feed rate, depth of cut and tool should be set at 1500rpm, 0.35mm/rev, 0.50mm and 6mm, for a surface roughness value of 6.56μm. The findings also revealed that there exist with a good agreement between the estimated and experimental results based on the mathematical model formulated.

1. Introduction

Stainless steel is an alloy of iron with a minimum of 10.5% chromium which raises its resistance to corrosion. Stainless steels of various kinds are used in thousands of application which include domestic (cutlery, sinks, washing machine drums, microwave oven liners, razor blades), architectural/civil engineering (door and window fitting, street furniture, reinforcement bar, masonry supports), transport (exhaust systems, road tankers, ship containers, refuse vehicles), springs, fasteners (bolts, nuts and washers), wire, etc.

Drilling as a machining operation which is selected in the study became necessary because most of the product been manufactured usually requires fasteners which allow the passage of bolt and nut. Some research scholars posited that fasteners on the manufacturers design are so coarse due to poor surface finish during machining which in turns leads to wear due to inaccurate process parameters been employed by manufacturers.

Sudha et al., (2013) investigated the optimization of surface roughness when drilling stainless steel SS304 with HSS drill. The experiments were conducted on a universal milling

machine. Response surface methodology [RSM] and analysis of variance (ANOVA) was employed for executing the planning of experiments and to find the significant control factors and percentage contributions of each control factor. The drilling parameters used for the optimization were spindle speed, feed rate, slurry concentration and mesh size using multiple performance characteristics for the surface roughness. The result showed that the feed rate and spindle speed are the most significant factors which affect the surface roughness and that the performance in the drilling can be effectively improved by using this approach.

Arshad et al., (2014) focused on optimizing deep drilling parameters based on Taguchi method for minimizing surface roughness using solid carbide cutting tool on material AISI 321 austentic stainless steel. The study considered four cutting parameters namely, which are cutting fluid, speed, feed and hole depth, each at three levels except the cutting fluid at two levels. The study employed L18 orthogonal array in their design of experiment. The result of the findings revealed that the combination of factors and their levels A2B3C2D1 i.e. the machining done in the presence of cutting fluid, at a speed of 500rpm with a feed of 0.04mm/s and hole-depth of 25mm yielded the optimum i.e. minimum surface roughness. The ANOVA results also indicated that all the four cutting parameters significantly affect the surface roughness with maximum contribution from the

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speed, followed by the cutting fluid, feed and hole-depth.

Sundeep et al., (2014) experimentally investigated drilling behaviour of austenitic stainless steel (AISI 316) in order to optimize the process parameters using L9 orthogonal array design of experiment of Taguchi methodology. The process parameters namely are spindle speed, feed rate and drill diameters as influenced by the response variables which are surface roughness and metal removal rate during drilling operations. The experimental results indicated that the cutting speed plays a dominating role in surface roughness and metal removal rate in drilling based on the process parameters considered.

Kunal and Abhishek (2015) discussed the experimental study on performance characteristics of AISI 304 stainless steel during CNC drilling process based on Taguchi L16 orthogonal array by taking point angle, drill diameter, feed rate and spindle speed at two levels. The findings revealed that factors like spindle speed, feed rate and point angle affect the performance parameters of surface roughness and ovality in drilling process.

Ferit et al., (2012) searched on the optimum cutting parameters when drilling an AISI 304 stainless steel using modified HSS drill tools. The study employed the application of Taguchi technique and analysis of variance (ANOVA) for minimization of surface roughness. The findings revealed that the best results of the surface roughness were obtained at higher cutting speeds and lower feed rates by using 0.5µm drill. The findings also revealed that the analysis of the confirmation experiments for the surface roughness has shown that Taguchi parameter design can successfully verify the optimum test.

Gaitonde and Karnik (2012) employed Taguchi's quality loss function approach and a multi-response optimization method to determine the best combination values of cutting speed, feed, point angle, and lip clearance angle for specified drill diameters to simultaneously minimize burr height and burr thickness during drilling of AISI 316L stainless steel workpiece. The findings revealed that at higher cutting speed, temperature increases with the increase in feed, which helps the material to deform more easily and thus increase in burr size. The findings also revealed that the low values of lip clearance angle provide enough support for drilling edges, causing the drill to easily break the chips, resulting into smaller burrs.

Nayan and Gaurav (2014) evaluated on dry drilling of AISI 304 austentic stainless steel to reduce temperature caused in drill tool by optimizing drilling parameters and selecting suitable drill tool material. The performance parameter experimentally investigated on are feed rate and spindle speed to minimize the temperature at drill tool bit. The findings revealed that feed rate has a greater influence on a twist drill bit temperature in dry drilling of AISI 304 austenitic stainless steel material and that the spindle

speed has a smaller influence on a twist drill bit temperature in dry drilling of AISI 304 austenitic stainless steel material.

The various researchers under review had adopted various process parameters techniques for machining optimization of workpiece. Sudha et al., (2013) adopted a planned experiment for spindle speed (345rpm to 740rpm), feed rate (32.5mm/min to 78mm/min) and slurry concentration (20% to 30%) conducted on universal milling machine according to Box Behnken Design (BBD) of RSM. Arshad et al., (2014) employed Taguchi techniques for cutting fluid, speed (300rpm to 500rpm), feed rate (0.03mm/s to 0.05mm/s) and hole depth (25mm to 35mm) conducted on CNC lathe machine. Sundeep et al., (2014) also employed Taguchi techniques for drill diameter (6mm to 10mm), cutting speed (500rpm to 1100rpm) and feed rate (0.1mm/rev to 0.2mm/rev) conducted on radial drilling machine. Kunal and Abhishek (2015) adopted Taguchi design as well for spindle speed (300rpm to 500rpm), feed rate (20mm/min to 50mm/min), point angle (900 to 1180) and depth of hole (15mm to 18mm) conducted on vertical milling/drilling machine.

Ferit et al., (2012) also adopted Taguchi design for drill modification condition (0 to 0.5), cutting speed (15m/min to 25m/min) and feed rate (0.08mm/rev to 0.16mm/rev) conducted on CNC milling machine. Gaitonde and Karnik (2012) employed Taguchi techniques for cutting speed (8m/min to 24m/min), feed rate (0.04mm/rev to 0.12mm/rev), point angle (1180 to 1340) and lip clearance (80 to 120). Nayan and Gaurav (2014) employed planned experiment for speed (1200rpm to 1500rpm), feed rate (0.06mm/rev to 0.08mm/rev) and depth of hole which was kept constant at 20mm throughout the experiment. However, it is observed that a lot of attention had been shifted away from planned experimental design to Taguchi design for the experimental run trials of the process parameters without considering the type of machine (either automated or manually operated) used and the workpiece for the experiment as we can see from the related study. It is in view of this that the study seeks to investigate on optimum process parameters for drilling SS304 stainless steel based on planned experimental design so as to minimize surface roughness.

2.0   Experimental Details

The present experimental investigation; includes selection of drilling parameters, range of drilling parameters, formation of the design matrix using Response Surface Methodology (RSM) based on L9-A 34-2 fractional factorial design, selection of workpiece material, experimental set-up and measurement of surface roughness.

2.1   Section of Drilling Parameters and the Range of Drilling Parameters

The process parameters that were chosen for experimentation are :

i.   Cutting speed (rpm);
ii.   Feed rate (mm/rev);
iii. Depth of cut (mm); and
iv. Tool diameter (mm).

These are the main drilling parameters that affect the surface roughness. The levels of each input parameter were decided by studying literature in detailed and according to machine limitations. Table 1 shows the ranges of drilling parameters according to RSM based on L9-A 34-2 fractional factorial design.

2.2   Trial Machining Experiment

Experiments were conducted using the design of experiments (DOE) technique of RSM based on L9-A 34-2 fractional factorial design and optimization of the results using Analysis of Variance (ANOVA) to find minimum surface roughness. The range of machining conditions was based on the industry practice for the considered SS304 stainless steel experimented on vertical drilling machine. The composition properties of the workpiece are shown in Table 2.

A total of 9 numbers of experiments with three repetitions each was finalized according to RSM based on L9-A 34-2 fractional factorial design. Table 3 shows the design layout for the experimentation.

2.3   Experimental Set Up:

Drilling operation was carried out on a vertical pillar drilling machine, METALIK PK203 model, with a speed range of 75rpm to 3200rpm driven by a motor of 1.5KW that is been operated manually having feed ranges from 0.1mm/rev to 0.8mm/rev as shown in Figure 1 . A cutting High speed steel (HSS) diameter tools of 6mm, 8mm and 10mm was used for experimentation with introduction of coolant.

Figure 1: Vertical pillar drilling machine

Table 1: Drilling Parameters and their Levels

Factor	Process Parameter	Units	Type	Minimum (+1)	Maximum (-1)
X1	Cutting speed	(rpm)	Numeric	1400	1700
X2	Feed rate	(mm/rev)	Numeric	0.11	0.75
X3	Depth of cut	(mm)	Numeric	0.25	0.75
X4	Tool	(mm)	Numeric	6	10

Table 2: Composition Ranges of 304 Grade Stainless Steel

Grade	C	Mn	Si	P	S	Cr	Mo	Ni	N
304 Min.	-	-	-	-	-	18.0	-	8.0	-
Max.	0.08	2.0	0.75	0.045	0.030	20	-	10.5	0.10

Source: Ficici *et al.,* (2012)

Table 3: Design Layout for the Machining Experiment

Test No.	XI: Speed(rpm)	X2: Feed(mm/rev)	X3: Depth of cut(mm)	X4:Tool(mm)
1	1400	0.11	0.25	6
2	1400	0.18	0.5	8
3	1400	0.75	0.75	10
4	1500	0.11	0.5	6
5	1500	0.18	0.75	8
6	1500	0.75	0.25	10
7	1700	0.11	0.75	6
8	1700	0.18	0.25	8
9	1700	0.75	0.5	10

2.4 Surface Roughness Measurement

A coupling ultrasonic thickness meter, TM-8810 model as shown in Figure 2; was used to measure the surface roughness of the drilled holes in the SS304 stainless steel workpiece. It has a sensor which is attached to the digital meter reading equipment. The sensor is inserted into the drilled base hole of the workpiece and the meter reads. If the sensor is placed on a workpiece without a drilled hole, the digital meter will not read. Table 4 shows the values of the surface roughness measured in triplicate along with the average surface roughness and the experimental run order.

3.0 Results and Discussion

3.1 Development of Surface Roughness Prediction Model

The surface roughness prediction model was developed in terms of cutting speed, feed rate, depth of cut and tool, the measured value of surface roughness which along with the experimental run order must have been fed into the design data. For the development of prediction model, the first step is ANOVA analysis.

The analysis of variance (ANOVA) is based on two assumptions:
i. The variables are internally distributed; and
ii. Homogeneity of variance. Significant violation of either assumption can increase the chances of error.

In order to establish the assumption of normal distribution, the normal probability plot of the residuals for surface roughness plotted in Figure 3 was used. Figure 3 shows that the residuals fall on a straight line, which implies that the errors are distributed normally. Figure 4 represents residuals versus the fitted surface roughness plot. It shows that there is no obvious pattern and unusual structure in the points. This implies that there is no reason to suspect any violation of the independence or constant variance assumption.

The ANOVA was carried out using the measured data at a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. The ANOVA analysis for surface roughness is as summarized in Table 5.

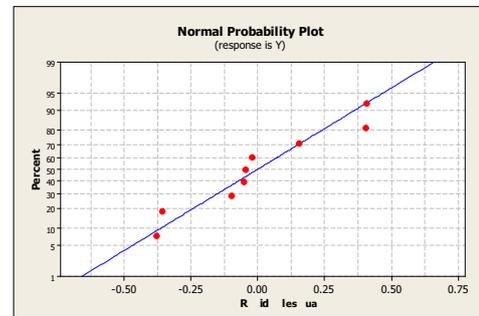**Figure 2**: Coupling ultrasonic thickness meter

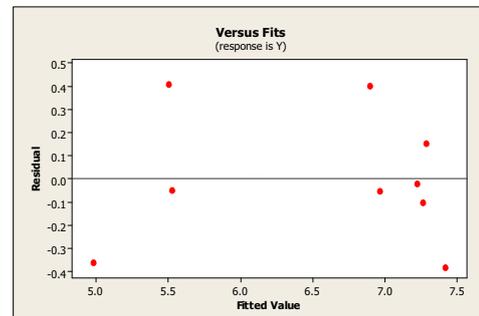**Figure 3**: Normal Probability Plot of Residuals for Surface Roughness

Figure 4: Plot of Residuals vs. Fitted Value of Surface Roughness

Table 4: Results Measurements

Test No.	Process Parameters				Surface roughness of stainless steel(μm)				
	XI: Speed(rpm)	X2: Feed(mm/rev)	X3: Depth of cut(mm)	X4: Tool (mm)	1st	2nd	3rd	Mean surface roughness(μm)	Standard Error surface roughness
1	1400	0.11	0.25	6	4.33	9.18	7.98	7.16	1.46
2	1400	0.18	0.5	8	5.04	9.49	7.79	7.44	1.30
3	1400	0.75	0.75	10	6.06	8.34	6.32	6.91	0.72
4	1500	0.11	0.5	6	6.32	5.06	6.33	5.91	0.42
5	1500	0.18	0.75	8	6.07	3.73	6.64	5.48	0.89
6	1500	0.75	0.25	10	4.02	6.03	3.80	4.62	0.71
7	1700	0.11	0.75	6	6.37	5.40	9.34	7.04	1.19
8	1700	0.18	0.25	8	3.94	9.01	8.65	7.20	1.63
9	1700	0.75	0.5	10	5.51	8.63	7.77	7.30	0.93

Table 5: ANOVA for Surface Roughness of Stainless Steel

Factor					Linear Regression Effect	
	DOF	Sum of Square (SS)	Mean of Sum of Square (MSS)	F-Statistic	Predicted Value (P-value)	Remarks
X1	1	0.2534	6.7589	42.16	0.003	Significant
X2	1	0.3628	0.3628	2.26	0.207	Not Significant
X3	1	0.0338	0.0338	0.21	0.670	Not Significant
X4	1	6.5057	6.5057	40.58	0.003	Significant
Error	4	0.6413	0.6413			
Total	8	7.7970				

$R^2 = 91.77\%$; Adj. $R^2 = 83.55\%$ *P-value < 0.05 or 5% is Significant

Factor					Linear Square Regression Effect	
	DOF	Sum of Square (SS)	Mean of Sum of Square (MSS)	F-Statistic	Predicted Value (P-value)	Remarks
X1	1	0.2534	6.7589	78.07	0.013	Significant
X2	1	0.3628	0.0006	0.01	0.943	Not Significant
X3	1	0.0338	0.4906	5.67	0.140	Not Significant
X4	1	6.5057	6.5057	75.14	0.013	Significant
X2*X2	1	0.0042	0.0042	0.05	0.847	Not Significant
X3*X3	1	0.4640	0.4640	5.36	0.147	Not Significant
Error	2	0.1732	0.0866			
Total	8	7.7970				

$R^2 = 97.78\%$; Adj. $R^2 = 91.12\%$ *P-value < 0.05 or 5% is Significant

Factor					Linear Interaction Regression Effect	
	DOF	Sum of Square (SS)	Mean of Sum of Square (MSS)	F-Statistic	Predicted Value (P-value)	Remarks
X1	1	0.2534	0.0381	**	**	Not Significant
X2	1	0.3628	0.1610	**	**	Not Significant
X3	1	0.0338	0.0122	**	**	Not Significant
X4	1	6.5057	0.0379	**	**	Not Significant
X1*X2	1	0.2730	0.1515	**	**	Not Significant
X1*X3	1	0.1900	0.0042	**	**	Not Significant
X2*X3	1	0.0418	0.0879	**	**	Not Significant
X2*X4	1	0.1365	0.1365	**	**	Not Significant
Error	0	**	**			
Total	8	7.7970				

$R^2 = **$; Adj. $R^2 = **$ *P-value < 0.05 or 5% is Significant

Factor					Quadratic Regression Effect	
	DOF	Sum of Square (SS)	Mean of Sum of Square (MSS)	F-Statistic	Predicted Value (P-value)	Remarks
X1	1	0.2534	5.4977	**	**	Not Significant
X2	1	0.3628	0.1193	**	**	Not Significant
X3	1	0.0338	0.3441	**	**	Not Significant
X4	1	6.5057	6.5057	**	**	Not Significant
X2*X2	1	0.0042	0.0646	**	**	Not Significant
X3*X3	1	0.4640	0.0623	**	**	Not Significant
X1*X2	1	0.0076	0.0854	**	**	Not Significant
X1*X3	1	0.1655	0.1655	**	**	Not Significant
Error	0	**	**			
Total	8	7.7970				

$R^2 = **$; Adj. $R^2 = **$ *P-value < 0.05 or 5% is Significant

The characterization of machined surface quality was limited only to surface roughness. Table 5 shows the computed ANOVA for surface roughness for stainless steel based on the linear effect, linear square effect, linear interaction effect and quadratic effect respectively. It is observed that the linear effect and linear square effect showed a very high significant with the process parameters except for feed and depth of cut. However, the linear effect displayed a best fit in terms of the model performance for the experimental study.

Based on the linear effect, the coefficient of determination (R2) is reasonably high with a value of 91.77% which explains the effect of the surface roughness on the considered factors (speed, feed, depth of cut and tool). The Adjusted R2 of 83.55% explained the true behaviour of the R2. The remaining 8.23% is been explained by the disturbance error which is unobservable during the experiment. Also, the P-values of the F-statistic calculated at 5% significance level, revealed that only feed and depth of cut as a factor does not contributes significantly in explaining the surface roughness of stainless steel after drilling operation. The statistical analysis shows a similar technique with the work done by Osarenmwinda (2012) that employed linear regression model to estimate the surface roughness of machined components under various cutting speed.

The regression model for surface roughness in terms of linear effect is given in equation (1):

$$\text{Surface Roughness} = -38.7005 + 0.0368 * X1 - 0.7005 * X2 + 0.3000 * X3 - 5.5100 * X4 \quad (1)$$

The model equation (1) is as well validated graphically to reveal the good agreement between the experimented and estimated value of the surface roughness as shown in Figure 5:
The result of the machining experiment for surface roughness as in Table 4 were inputted into a MINITAB 16 software based on the experimental plan for further analysis. The surface roughness was plotted against the process parameters based on the experiment measurements through surface plot graph

3.2   *Effect of Drilling Parameters on Surface Roughness*

The essence of the surface plot in Figure 6 (A-F) is to check for minimum value of surface roughness on the stainless steel by varying the drilling parameters using MINITAB software. In Figure 6A, it was observed that at a speed of 1500rpm with a feed rate of 0.55mm/rev, surface roughness value is 6.70μm. Also, in Figure 6B, it was observed that at a speed of 1500rpm with tool diameter of 8mm, surface roughness value is 6.71μm. In Figure 6C, 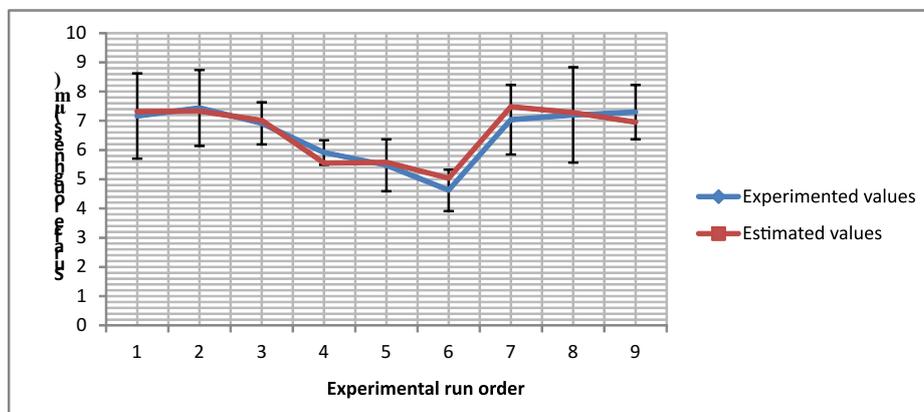it was observed that at a speed of 1500rpm with depth cut of 0.25mm, surface roughness value is 6.28μm. In Figure 6D, it is observed that at a feed rate of 0.75mm and depth cut of 0.75mm, value of surface roughness is 7.17μm. In Figure 6E, it is observed that at a feed of 0.30mm/rev with tool diameter of 8mm, value of surface roughness is 5.34μm. In Figure 6F, it is observed that at a depth cut of 0.75μm with tool diameter of 10mm, value of surface roughness is 7.18μm. However, due to the various value of surface roughness recorded from the surface plot, constraints of the drilling parameters was thereby employed so as to have an optimal value of drilling parameters for minimizing surface roughness as shown in section 3.3.

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Figure 5 : Comparison bet ween measured and predicted value for surface roughness of SS304 stainless steel

0.25mm, surface roughness value is 6.28μm. In Figure 6D, it is observed that at a feed rate of 0.75mm and depth cut of 0.75mm, value of surface roughness is 7.17μm. In Figure 6E, it is observed that at a feed of 0.30mm/rev with tool diameter of 8mm, value of surface roughness is 5.34μm. In Figure 6F, it is observed that at a depth cut of 0.75μm with tool diameter of 10mm, value of surface roughness is 7.18μm. However, due to the various value of surface roughness recorded from the surface plot, constraints of the drilling parameters was thereby employed so as to have an optimal value of drilling parameters for minimizing surface roughness as shown in section 3.3. Figure 6 (A-F): Estimated responses surface roughness parameters of stainless steel versus the considered factors of investigation.

3.2   Optimization of Drilling Parameters for Minimum Surface Roughness

Since the aim of the study is to obtain an optimal value of drilling parameters for minimizing surface roughness, the constraints for the drilling parameters for optimization process were set for cutting speed (1400rpm to 1700rpm), feed rate (0.11mm/rev to 0.75mm/rev), depth of cut (0.25mm to 0.75mm) and tool diameter (6mm to 10mm) on a MINITAB software as shown in Table 6 .Table 7 which shows the optimal solution of the set constraints revealed that for a minimum . surface roughness on the SS304 stainless steel, cutting speed, feed rate, depth of cut and tool should be set at 1500rpm, 0.35mm/rev, 0.50mm and 6mm respectively.
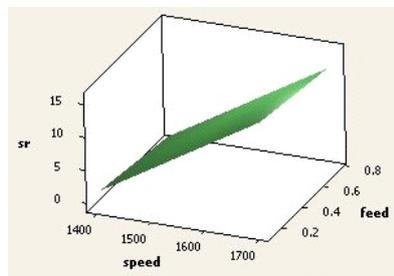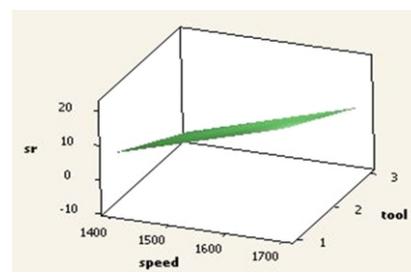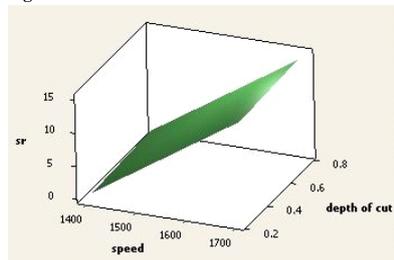

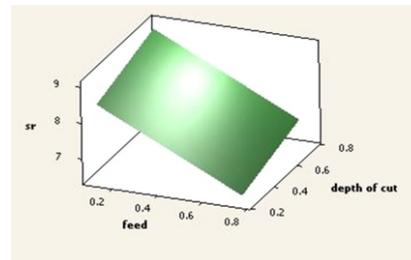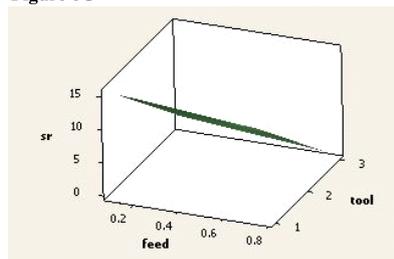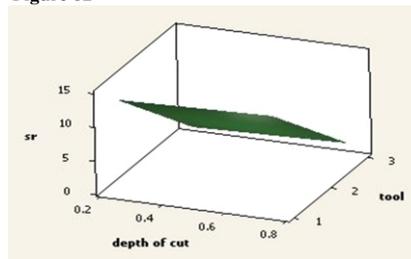Figure 6A

Figure 6B

Figure 6C

Figure 6D

Figure 6E

Figure 6F

Table 6: Constraints for Optimization of Drilling Parameters for Stainless Steel

Name	Goal	Lower limit	Upper limit
X1: Cutting Speed (rpm)	is in range	1400	1500
X2: Feed Rate (mm/rev)	is in range	0.11	0.75
X3: Depth of Cut (mm)	is in range	0.25	0.75
X4: Tool (mm)	is in range	6	8
	minimize	4.62	7.44

Table 7: Optimization Results for Surface Roughness

S/No.	Cutting Speed (rpm)	Feed Rate (mm/rev)	Depth of Cut (mm)	Tool (mm)	Surface Roughness (μm)	Desirability	Remarks
1	1500	0.35	0.50	6	6.56	0.6312	Selected

The reason for this particular selection was because the desirability value of 0.6312 (63.12%) is greater than 50%, which however is reliable.

4.0   Conclusion

The experimental investigation revealed that the same optimal solution of the response variable from the surface plot cannot be actualized easily because the surface plot displays various values of optimal solution with a particular combination of process parameters settings because the optimum condition of the drilling process is concerned with minimizing surface roughness which requires varying process parameters during experimentation. It is observed that after constraints had been set for the process parameters, optimum surface roughness of value of 6.56μm is obtained at a cutting speed of 1500rpm, feed rate of 0.35mm/rev, depth of cut at 0.50mm and tool diameter of 6mm respectively. Hence, to acquire a minimal surface finish of workpiece based on the thickness of the SS304 stainless steel, the set values should be considered.

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