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Original Article

Effect of cryogenic treatment on drill tool for enhancing metal cutting operation of aluminium alloy IS737.Gr19000

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ABSTRACT

Drilling is the hole making process on the component face with the aid of a twisted drillbit. Normal drill bits easily wear out through penetration of drill bit into the workpiece material due to force generated in the drilling operation. So this work tries to investigate the machining parameters with cryogenically treated drill bits on various responses. Cryogenic treatment is one of the thermal engineering processes, which is used to cool the material from the temperature of −150 °C to −273 °C. This research work utilizes cryogenically treated drill tools for investigating the drilling performance on aluminium alloy (IS737.Gr19000) workpiece material. The independent variables and dependent variables are studied in this experimental analysis are spindle speed, feed rate and machining time, entry and exit burr dimensions, thrust force, torque, Ovality, surface roughness, respectively. The theoretical investigation is also carried out with statistical analysis. The response surface methodology with Box Behnken design the 17 experimental runs with 9 different treated drill tools are carried out. The cryogenically treated drill bit gave good results on burr dimensions, Ovality, surface roughness on drilled hole quality. The tool wear performance was also studied with drill tool geometry measurements with the tool makers microscope. The cryogenically treated drill bits gave the best results than the normal drill bit.

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1. Introduction

Manufacturing processes can include heat treating, machining or reshaping the material. Machining is a material removal process, which is utilized to remove the unwanted material from the workpiece in the means of chips by cutting tool. The tool material selection with respect to workpiece material property plays a vital on the quality of the reshaped product. So, tool material and its property are important during the machining process. However, normal and coated tool bits deliver lesser tool life and it increases production cost. So many researchers were utilized different methods like input parameter selection and enhanced the process with different combinations of tools on the considered workpiece. Further, this methodology also increases the production cost, Insense; this work presents the cryogenic property to increase the tool life and performance. Cryogenic process is used to treat the materials with the temperature range from −150 °C to −273 °C. This treatment is mainly used for removing the residual stress and improving the wear resistance of steel. On behalf of this High-Speed Steel drill bit used for cryogenic treatment. The main advantage of cryogenic treatment is to increase product life and avoid the breakage of materials during service [1–4].

The various researches are utilized the cryogenic process for their respective works. In that, Brousseau et al. [5] revealed new trends for innovative manufacturing and new design technologies used. A. Krimpenis [6] described the application of modeling techniques and optimization techniques in the Multiple Tool CNC Rough Machining process. Susheel Kalia [7] determined Cryogenic Procedure with the materials at low temperatures and he reviewed about effects of the cryogenic process on different metals, composites, non-metals and alloys. Simranpreet Singh Gill et al. [8] planned cryogenic processing of various cutting tool steel materials. And the work is proposed that cryogenic treatment improves the tool life and cutting mechanisms are ambiguous.

Simranpreet Singh Gill et al. [9] revealed that cryogenic treatment is the responsible factor for enhancing the tool steels mechanical properties with phase transformation between austenitic to martensite and precipitation of carbides in solid solution. Shane Y. Hon et al. [10] determined that cryogenic cooling on tool materials had economic and ecological benefits than commercial tool materials with different machining approaches. Simranpreet Singh Gill et al. [11] performed cryogenic treatment on High-Speed Steel material and the results show that the hardness and wear rate of the material is improved in the Rockwell hardness test and pin-on-disc wear test.

Erol Kilickap et al. [12] utilized the response surface methodology to predict the surface roughness of drilled holes in the drilling of AISI 1045. The RSM model has higher efficiency to predict the drilled hole surface quality value. Also, Erol Kilickap [13] modeled the burr dimensions on drilling operation; this experiment also determined that the RSM gives a better mathematical model for burr dimensions. So response surface methodology is one the best mathematical c = modeling techniques for analyzing the engineering problems, Ahamed et al. [14] determined the drilling parameters for reduced tool wear and maximized surface finish on aluminium metal matrix composite through statistical analysis. Gül Tosun [15] obtained optimal parameters for surface roughness in metal matrix hole drilling through the design of experiment concepts such as Taguchi experimental design. Ali Akhavan Far id et al. [16] determined the effect of spinsl = dle speed and feed rate on chip morphology and revealed that built-up edge formation on the rake face of the tool creates irregular patterns on the surface of the removed chip surface. Susana Ferreiro et al. [17] organized a statistical model for detecting the burr dimensions in drilling operation on aluminium (Al 7075-T6) and the work proposed that the statistical modeling technique predicts the best burr dimensions than other data mining techniques. Rotberg et al. [18] clamping force on the workpiece during the drilling operation and also the work determines the various cutting conditions on dilled hole geometry. Barnes et al. [19] demonstrated heat treatment effects on drilling of Al/SiC metal matrix composite the softer workpiece material produces lower cutting forces with hard tool materials and the height of the burr during drilling were presented to be higher with the soft workpiece materials. Alper Uysal et al. [20] predicted tool wear with statistical analysis based on the statistical analysis investigated that the lesser tool angles with the increased feed rate reduce the tool wear.

The analysis of variance technique is used to identify the parameter influence considered responses. Based on the influencing parameter, the regression models were developed. Eyup Bagci et al. [21] stated that the statistical analysis is suitable for temperature changing study during drilling of Al7075 − T651 workpiece material with a twist drill. Jianbo Yu [22] organized an online mathematical modeling technique for predicting the tool wear in possible applications. Eyup Bagci et al. [23] drill bit temperature and its effects on workpiece quality monitoring through finite element method. Song Zhang et al. [24] determined the tool and workpiece quality with experimental and statistical study; the statistical study with measurement technique gives better results in the drilling process. Chaus [25] determined that the wear resistance property of HSS and austenitic temperature on workpiece material have been analyzed with data collection techniques for predicting the wear resistance behavior of HSS and based on the collected data, maximum wear resistance is observed. Kantheti Venkata Murali [26] proposed second order mathematical model for predicting the best input parameter on surface quality enhancement study in drilling operation under various drilling conditions. Grant Mark Robinson et al. [27] proposed that future development of micro and Nano scale machining is developed through statistical analysis.

Based on this literature survey cryogenic process improved the drilling process productivity with reduced cost of production. Similarly, the statistical tool is one of the best techniques for identifying the parameter influence on drilling performance and framing the mathematical model for process planning engineers of the manufacturing industry. So, this work utilizes the cryogenic process on the HSS drill bit for improving the drilling performance with statistical analysis.

Fig. 1 – Vertical milling machine.

Table 1 – Machine tool specification.

Machine tool Manufacturer	Alto
Spindle speed range	80–4540 rpm
Feed range	0.038,0.076 and 0.203 mm/rev
Dimensions of table	1270mm × 252 mm

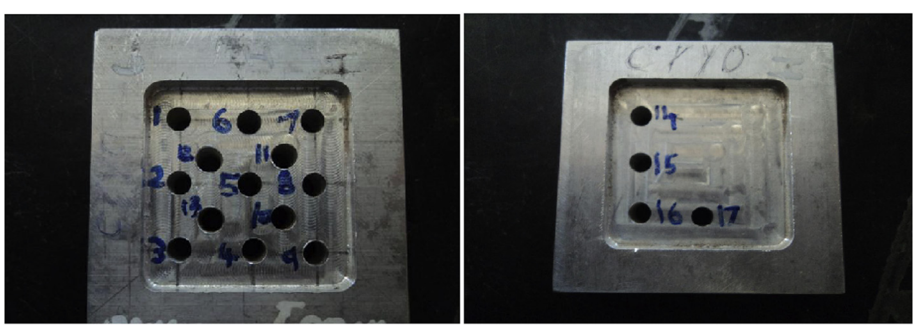
2. Experimental work

The methodology considered for this work is to conduct the experiments with cryogenic treated tool with statistical analysis. The purpose of this experiment is to determine the drilling time, thrust force, torque, burr dimensions, ovality and surface roughness. The drilling experiments are conducted on a vertical milling machine, as presented in Fig. 1.

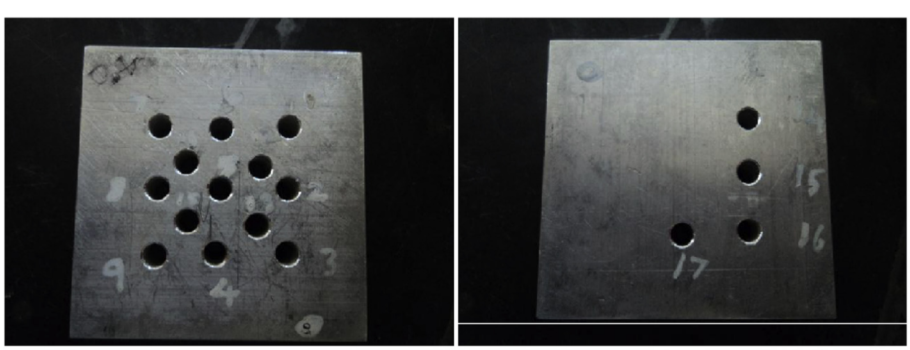
The workpiece material for the experiment is Aluminium alloy with the grade of IS737.Gr19000. The size of the workpiece material is 750 × 750 × 180 mm. The same is clamped on the machine tool table with a drill tool dynamometer vice for determining the thrust force and torque. Various spindle speeds and feed rates are used to drill the workpiece on the component face within the range of machine tool specifications, as presented in Table 1.

The design of the experiment concept is utilized for conducting the experiments with the cryogenic treated tool and aluminium alloy workpiece material. In the design of the experiment concept, the responses surface methodology for identifying the effects of input parameter on considered responses and Box Behnken design is used with 17 combinations of spindle speed and feed rate for conducting the experiments on the workpiece material. The hole entry and exit side of the drilled workpiece materials are as shown in Fig. 2.

Figure 2 (a) shows the workpiece entry side in which the drill is started. The drill started from the entry side and finished at the exit side. Figure 2 (b) displays the exit side of the drilled hole in which the drill ends. The 6 mm diameter High



(a)



(b)

Fig. 2 – Drilled workpiece (a) Entry side, (b) Exit side.

Fig. 3 – Cryogenically treated 6 mm drill bit.

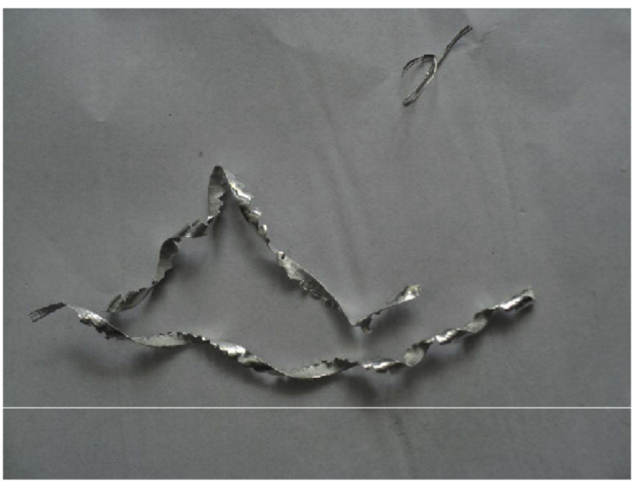


Fig. 4 – Chip produced during drilling.

Speed Steel (HSS) drill bit (Flute length = 57 mm and Overall length = 93 mm) is used for the experiment and every experiment utilizes individual drill bit for analyzing purposes, as shown in Fig. 3. Cryogenic process is used to treat the drill bit with a temperature of −196 °C. For treating the drill bit with cryogenic process Liquid nitrogen (LN2) is the most common element and treatment cycle time takes around 48 h to complete. The 3 levels of spindle speed 1860, 2270 and 4540 rpm and 3 levels of feed rare 0.038, 0.076 and 0.203mm/rev are selected based on machine tool specification. The continuous ribbon type chip produced by cryogenic treated drill bit as shown in Fig. 4.

2.1. *Measurement of responses*

The identification of thrust force and torque employed by using the drill tool and the results are noted from the digital display of the monitoring device. In that X display shows thrust force and Y display shows torque, as shown in Fig. 1. The height of the burr is measured by using a mechanical comparator. The drilled hole is placed on the surface of the mechanical comparator (L.C = −0.01 mm) and 120° angler in three different positions is marked on the hole top surface then the dial gauge moves transciently on the hole surface then the mean value of burr dimension is calculated and noted. The mean value is taken for position 1, position 2, and position 3. With this procedure, the mean entry burr height and exit burr height are measured. The same positions are used to determine the burr thickness with the aid of tool makers microscope. The Ovality is measured with the aid of a profile projector. In this instrument, the drilled workpiece is placed on the profile projector table. I profile projector vertical scale reading and horizontal scale readings are noted. Then, the ovality is obtained by the formula

$$Ovality = \frac{(D_{max} - D_{min})}{(D_{max} + D_{min})} \times 100$$

The tool makers microscope (3X magnification, the field of view = 8 mm, Least count = 0.01 mm) is used to measure the point angle, chisel length, lip length of the tool and the same is tabulated in Table 2. The measurement was carried out before machining and after machining on the drill bit. Finally, subtracting both from this tool wear dimensions are measured for 9 different tools.

3. Results and discussion

The drilling experiments are carried out using a cryogenically treated drill bit with three different levels of spindle speed and feed rate. According to the results obtained from the planned work are machining time, burr height, burr thickness, thrust force, torque and Ovality are tabulated in Table 3.

ANOVA is the statistical procedure, which is utilized to determine the significant parameters with respect to the size of the variance amongst experimental data. Table 4 illustrates

Table 2 – Tool wear measurement.

Drill Bit No	Speed (rpm)	Feed (mm/rev)	Point Angle (deg)	Chisel Length (mm)	Lip Length1 (mm)	Lip Length 2 (mm)
1	4540	0.038	3.3	0.7	0.32	1
2	4540	0.076	19.7	0.67	0.82	0.26
3	4540	0.203	6.5	0.46	0.61	0.77
4	2270	0.203	4.5	1.47	0.11	0.86
5	2270	0.038	5.6	1.09	1.24	0.32
6	2270	0.076	0.7	0.56	0.12	1.39
7	1860	0.076	4.1	0.94	0.12	0.25
8	1860	0.038	2.7	0.72	0.75	0.28
9	1860	0.203	0.9	0.9	0.67	0.18

Table 3 – Experimental data.

Spindle Speed (rpm)	Feed (mm/rev)	Machining time (sec)	Entry burr height (mm)	Exit burr height (mm)	Entry Burr thickness (mm)	Exit burr thickness (mm)	Ovality (mm)	Thrust force Kg F	Torque Kg m	Surface roughness (μm)
4540	0.038	0.08	0.5	1.45	0.048	0.04	0.9523	55	0	1.21
4540	0.076	0.04	0.53	1.1	0.028	0.438	1.7309	43	0.1	0.98
4540	0.076	0.04	0.68	1.58	0.448	0.432	0.624	58	0.1	0.78
4540	0.203	0.02	0.6	1.93	0.044	0.438	1.4162	87	0.1	1.65
2270	0.203	0.04	0.88	1.56	0.44	0.438	0.9419	56	0.1	1.2
2270	0.203	0.04	1.36	1.43	0.456	0.448	0.9463	53	0.1	0.75
2270	0.038	0.15	0.31	1.83	0.036	0.03	0.3134	37	0	0.82
2270	0.038	0.16	0.81	1.71	0.438	0.028	0.624	46	0	1
2270	0.076	0.08	1.26	0.8	0.438	0.47	1.6077	121	0	0.78
2270	0.076	0.08	0.53	0.9	0.458	0.458	1.7727	158	0.1	1.21
2270	0.076	0.08	0.98	4.13	0.048	0.47	0.6568	132	0.1	1.05
2270	0.076	0.09	1.73	2.65	0.04	0.464	1.2903	143	0.1	0.93
2270	0.076	0.08	1.13	4.26	0.016	0.48	0	158	0.1	0.88
1860	0.076	0.09	0.38	2.11	0.026	0.418	0.6493	53	0	0.6
1860	0.076	0.09	0.33	3.68	0.418	0.416	0.4866	55	0	0.92
1860	0.038	0.18	0.28	3.1	0.422	0.414	0.4897	32	0	0.79
1860	0.203	0.06	0.21	4.26	0.026	0.446	0.788	69	0	0.27

the ANOVA table for Machining time, burr dimensions (Entry and Exit of hole), Ovality, Thrust force, Torque and Surface Roughness as dependent variables. The table contains the main components are the sum of squares, source of variance, F value, degrees of freedom, mean square and probability with F value.

3.1. *Machining time data Analysis*

Based on table F-Value of model 92.21 suggests the developed model is important for prediction. The chance cause of the experiment is 0.01%, so the F-Value of the machining time ANOVA table has a larger value because of noise developed from the experimental setup. The other model terms in the ANOVA table has significant when it has less than 0.05 of the probability of F- value. So in the calculated table, spindle speed (A), feed rate (B), AB, B^2 are the important model terms. But the model terms have more than 0.1 means the model terms are not playing an important in deciding the response value. In the model outline, the adequate precision ratio has the value of 30.239; it is more 4 means model can be used for further prediction within the range of independent variable levels that considered for the experiment.

3.2. *Burr Height Data Analysis*

Here, the F-value of Entry burr height and Exit Burr height models are 92.21 and 3.27, indicating the models are significant. Based on this analysis, spindle speed and feed rate are both important for entry burr height. However, in Exit burr height, the spindle speed plays vital than the feed rate. Adequate precision of burr height analysis is 30.239 for the exit side and 5.218 at the entry side, which have values more than 4, so these models are suitable for further prediction within the design space of experiments levels.

3.3. Burr thickness Data Analysis

Thickness ANOVA table analysis on F-value of Entry burr thickness and Exit Burr thickness models are 14.11 and 3.27 indicates the models are significant. Based on this analysis, spindle speed and feed rate both are not playing a vital on burr dimensions. So for burr thickness analysis, the tool geometry with cutting conditions are to be added in future works of cryogentic treatment of drill tool than burr height analysis.

3.4. *Ovality Data Analysis*

The probability of model F − value is 10.82, which denotes that the model considered for analysis has significant. The ovality analysis also needed the tool geometry incorporation with cryogenic treatment for further investigations.

3.5. *Thrust force and torque Data Analysis*

The thrust force and torque ANOVA analysis proposes that the F-value 3.43 and 5.11 implies that models have significant differences. In the thrust force model, the feed rate and spindle speed play a vital on considering responses of thrust

Table 4 – Analysis of Variance table for considered responses.

Source	Sum of squares	Degrees of freedom	Mean square	F – Value	p-value p > F	
Machining time ANOVA table						
Model	0.031	5	6.232E-003	92.21	<0.0001	Significant
A-spindle speed	4.913E-004	1	4.913E-004	7.27	0.0208	
B-feed rate	7.151E-003	1	7.151E-003	105.79	< 0.0001	
AB	8.203E-004	1	8.203E-004	12.14	0.0051	
A^2	1.241E-004	1	1.241E-004	1.84	0.2027	
B^2	7.542E-003	1	7.542E-003	111.58	< 0.0001	
Residual	7.435E-004	11	6.759E-005			
Total	0.032	16				
Entry Burr Height ANOVA table						
Model	0.031	5	6.232E-003	92.21	<0.0001	Significant
A-spindle speed	4.913E-004	1	4.913E-004	7.27	0.0208	
B-feed rate	7.151E-003	1	7.151E-003	105.79	< 0.0001	
AB	8.203E-004	1	8.203E-004	12.14	0.0051	
A^2	1.241E-004	1	1.241E-004	1.84	0.2027	
B^2	7.542E-003	1	7.542E-003	111.58	< 0.0001	
Residual	7.435E-004	11	6.759E-005			
Total	0.032	16				
Exit Burr Height ANOVA table						
Model	1.80	5	0.36	3.27	0.0471	Significant
A-spindle speed	1.332E-004	1	1.332E-004	1.210E-003	0.9729	
B-feed rate	0.26	1	0.26	2.33	0.1550	
AB	1.700E-003	1	1.700E-003	0.015	0.9033	
A^2	1.41	1	1.41	12.76	0.0044	
B^2	0.26	1	0.26	2.38	0.1515	
Residual	1.21	11	0.11			
Total	3.01	16				
Thrust force ANOVA table						
Model	18959.72	5	3791.94	3.43	0.0413	Significant
A-spindle speed	751.26	1	751.26	0.68	0.4276	
B-feed rate	9835.95	1	9835.95	8.88	0.0125	
AB	706.43	1	706.43	0.64	0.4413	
A^2	6590.61	1	6590.61	5.95	0.0328	
B^2	9878.81	1	9878.81	8.92	0.0124	
Residual	12177.34	11	1107.03			
Total	31137.06	16				
Torque ANOVA table						
Model	0.030	5	5.922E-003	5.11	0.0115	Significant
A-spindle speed	6.168E-004	1	6.168E-004	0.53	0.4808	
B-feed rate	8.033E-003	1	8.033E-003	6.94	0.0233	
AB	2.853E-004	1	2.853E-004	0.25	0.6295	
A^2	9.667E-003	1	9.667E-003	8.35	0.0147	
B^2	8.359E-003	1	8.359E-003	7.22	0.0212	
Residual	0.013	11	1.158E-003			
Total	0.042	16				
Surface Roughness ANOVA table						
Model	0.69	3	0.23	4.06	0.0307	Significant
A-spindle speed	0.38	1	0.38	6.79	0.0218	
B-feed rate	0.082	1	0.082	1.45	0.2503	
AB	0.34	1	0.34	5.97	0.0296	
Residual	0.74	13	0.057			
Total	1.43	16				
Entry Burr Thickness ANOVA table						
Model	93.77	5	18.75	14.11	0.0001	Significant
A-spindle speed	2.468E-005	1	2.468E-005	1.857E-005	0.9966	
B-feed rate	0.33	1	0.33	0.25	0.6261	
AB	0.038	1	0.038	0.028	0.8690	
A^2	2.57	1	2.57	1.93	0.1899	
B^2	0.20	1	0.20	0.15	0.7035	
Residual	15.95	12	1.33			

(continued on next page)

Table 4 – (continued)

Source	Sum of squares	Degrees of freedom	Mean square	F – Value	p-value p > F	
Total	109.71	17				
Exit Burr Thickness ANOVA table						
Model	0.91	5	0.18	3.32	0.0411	Significant
A-spindle speed	2.349E-003	1	2.349E-003	0.043	0.8391	
B-feed rate	0.018	1	0.018	0.33	0.5782	
AB	1.593E-003	1	1.593E-003	0.029	0.8672	
Aˆ2	9.404E-003	1	9.404E-003	0.17	0.6854	
Bˆ2	6.007E-003	1	6.007E-003	0.11	0.7458	
Residual	0.65	12	0.055			
Total	1.56	17				
Ovality ANOVA table						
Model	14.66	5	2.93	10.82	0.0004	Significant
A-spindle speed	0.028	1	0.028	0.10	0.7519	
B-feed rate	1.01	1	1.01	3.73	0.0773	
AB	0.011	1	0.011	0.042	0.8407	
Aˆ2	0.16	1	0.16	0.60	0.4526	
Bˆ2	0.59	1	0.59	2.19	0.1647	
Residual	3.25	12	0.27			
Total	17.91	17				

force and torque. And the adequate precision of the developed model 5.386 and 7.851 are greater than 4. According to the statistical analysis procedure, the adequate precision value is more than 4 means the process planning engineer can utilize the model for further parameter selection in the machine within the range of parameter design of experiments. So the thrust force and torque models can be utilized for drilling operation.

3.5. *Surface Roughness Data Analysis*

The Surface roughness model F – value 4.06 propose the developed model is useful for prediction. In surface roughness analysis, the spindle speed indic = vidualy plays on surface roughness and the interaction effect of spindle speed with feed rate has a significant effect than the individual role of feed rate on surface roughness; the adequate precision of the

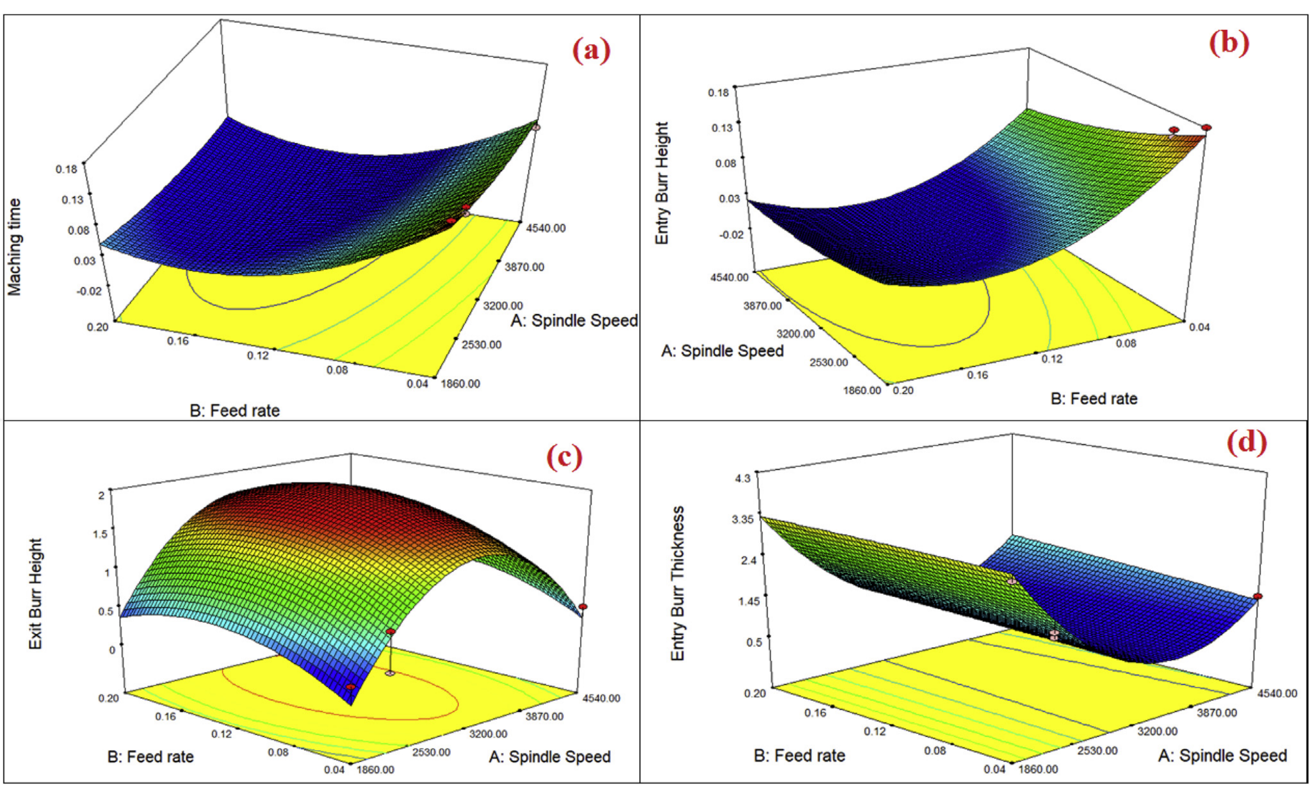


Fig. 5 – Response Surface Plots (a) Machining time (b) Entry burr height (c) Exit burr height (d) Entry burr thickness.

developed model is 8.598. So, this model can be utilized for surface roughness prediction on considered machine tool specification and design space of the experiment.

3.6. *Effect of independent variables on dependent variables*

Based on cryogenic treated drill bit, the following effects are made with the machining process on drilling operation. The results of the spindle speed and feed rate effects are evaluated with the response surface plot. According to Fig. 5 (a), the low feed rate with all the combinations of spindle speed maximize the machining time. So, the higher feed rate with all the combinations of spindle speed produces higher productivity. However, feed rate plays a vital role in machining time than feed rate. Figure 5 (b) and (c) represent the entry burr height and exit burr height. The lower spindle speed with a higher feed rate develops the higher entry burr height. According to Fig. 5 (c), the midlevel spindle speed and feed rate produced the higher exit burr height. Figure 5 (d) depicts the Entry burr thickness. The feed rate does not play on entry burr thickness, but the spindle speed has an impact on entry burr thickness. Also, the midlevel of spindle speed with all feed rate combinations directs the minimum entry burr thickness.

In response to Fig. 6 (a), the maximum spindle speed with all the combinations of feed rate produces the lesser exit burr thickness. The ovality of the produced hole is represented in Fig. 6 (b). According to the response plot, the minimum ovality occurs at minimum spindle speed at all the levels of feed rate that considered for an experiment. The tool life is mainly affected by force applied on the workpiece material and resistive force given to the tool material by workpiece material. So the effect of feed rate and spindle speed on thrust force is evaluated and the same is presented in Fig. 6 (c); the mid level of spindle speed and feed rate produces higher thrust force. The twist moment is the responsible factor for removing the workpiece material with the aid of the drill bit. So the torque analysis is also important in tool life evaluation, the effect of spindle speed and feed rate on torque is monitored and the same is represented in Fig. 6 (d). Here also, the mid level of spindle speed and feed rate produces the maximum torque.

Finally, the machined surface quality is the responsible factor for the reliability of the component in service. So, the surface roughness of the drilled hole with cryogenically treated drill bit is depicted in Fig. 7. The higher level of spindle speed with a higher level of feed rate generated a poor surface finish. However, the feed rate has less significance on

Table 5 – Model outline.

Model	R^2	Adj. R^2	Pre. R^2	Ade. Pr.
Maching time	0.9767	0.9661	0.7901	30.239
Entry Burr Height	0.9767	0.9661	0.7901	30.239
Exit Burr Height	0.598	0.4153	0.237	5.218
Entry Burr Thickness	0.8546	0.7941	0.6984	3.095
Exit Burr Thickness	0.5804	0.4056	−0.7199	1.244
Ovality	0.8184	0.7427	0.7278	3.351
Thrust force	0.6089	0.4311	−4.4804	5.386
Torque	0.6992	0.5624	−0.7865	7.851
Surface Roughness	0.4836	0.3644	−0.1491	8.598

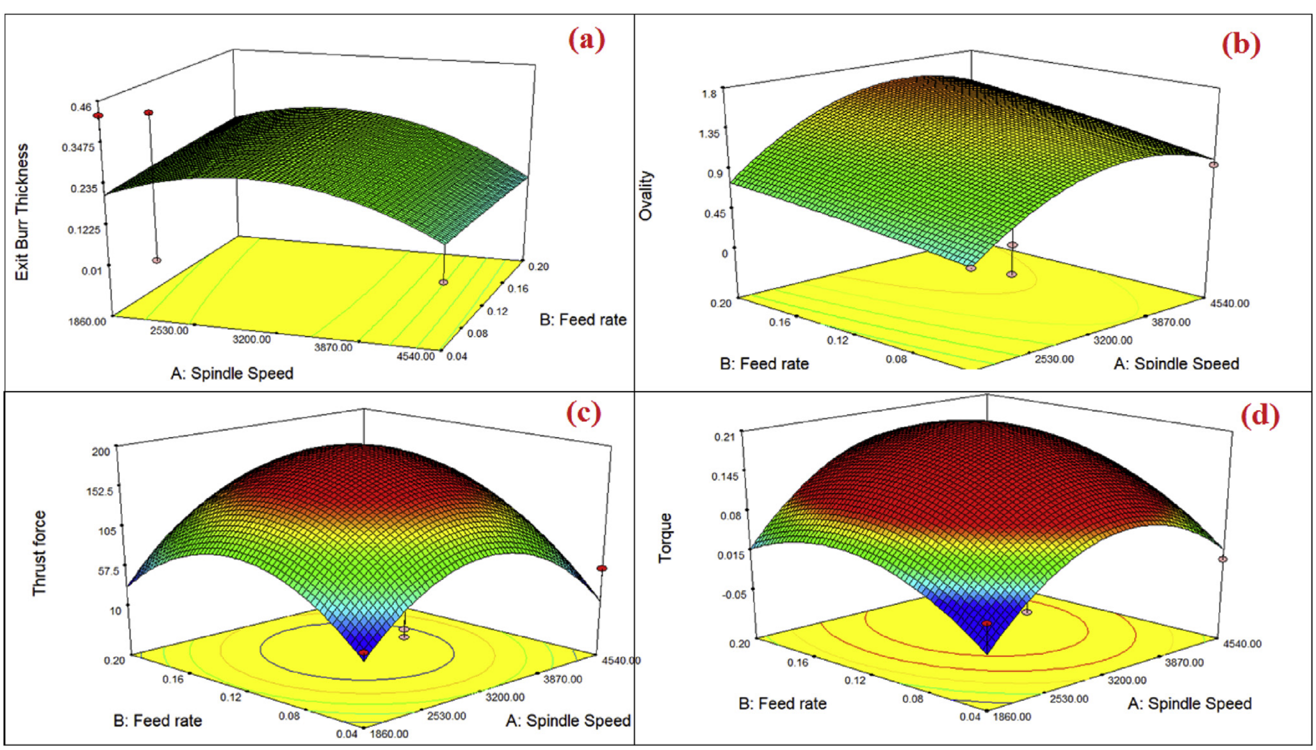


Fig. 6 – Response Surface Plots (a) Exit Burr thickness (b) Ovality (c) Thrust force (d) Torque.

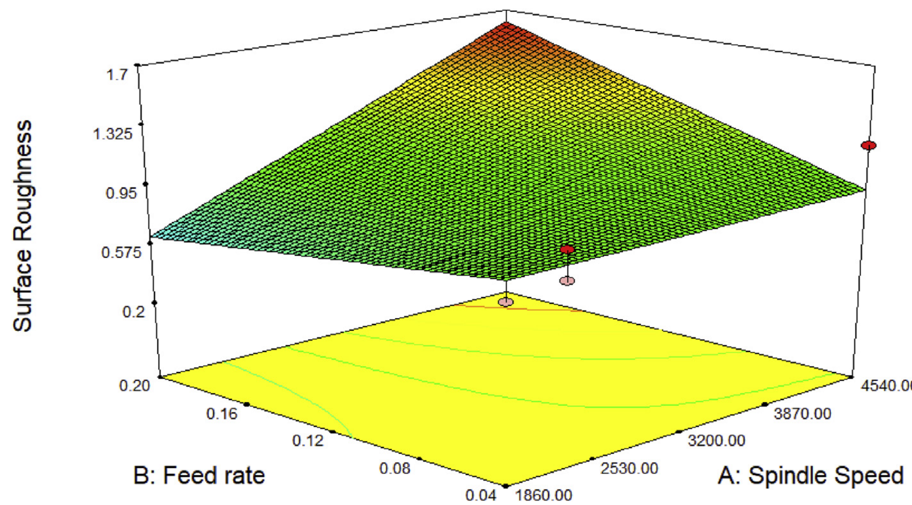


Fig. 7 – Response surface plots for surface roughness.

Table 6 – Validation of machining time regression model.

Experimental Run	Spindle Speed (rpm)	Feed (mm/rev)	Experimental Machining time (sec)	Regression Machining time (sec)	% of deviation
1	4540	0.038	0.08	0.09	−16.64
2	4540	0.076	0.04	0.03	20.59
3	4540	0.076	0.04	0.03	20.59
4	4540	0.203	0.02	0.02	−15.78
5	2270	0.203	0.04	0.04	−5.21
6	2270	0.203	0.04	0.04	−5.21
7	2270	0.038	0.15	0.15	−1.94
8	2270	0.038	0.16	0.15	4.43
9	2270	0.076	0.08	0.08	−2.50
10	2270	0.076	0.08	0.08	−2.50
11	2270	0.076	0.08	0.08	−2.50
12	2270	0.076	0.09	0.08	8.89
13	2270	0.076	0.08	0.08	−2.50
14	1860	0.076	0.09	0.10	−9.15
15	1860	0.076	0.09	0.10	−9.15
16	1860	0.038	0.18	0.17	5.08
17	1860	0.203	0.06	0.05	12.21

Table 7 – Validation of entry and exit burr height regression model.

Experimental Run	Experimental Entry burr height (mm)	Regression Entry burr height (mm)	% of deviation	Experimental Exit burr height (mm)	Regression Exit burr height (mm)	% of deviation
1	0.5	0.40	20.46	1.45	0.40	72.57
2	0.53	0.64	−21.48	1.1	0.64	41.47
3	0.68	0.64	5.32	1.58	0.64	59.25
4	0.6	0.76	−26.53	1.93	0.76	60.66
5	0.88	0.80	9.62	1.56	0.80	49.02
6	1.36	0.80	41.52	1.43	0.80	44.38
7	0.31	0.67	−115.65	1.83	0.67	63.47
8	0.81	0.67	17.47	1.71	0.67	60.91
9	1.26	0.86	31.70	0.8	0.86	−7.57
10	0.53	0.86	−62.38	0.9	0.86	4.38
11	0.98	0.86	12.18	4.13	0.86	79.16
12	1.73	0.86	50.25	2.65	0.86	67.52
13	1.13	0.86	23.84	4.26	0.86	79.80
14	0.38	0.82	−117.03	2.11	0.82	60.91
15	0.33	0.82	−149.91	3.68	0.82	77.59
16	0.28	0.64	−129.42	3.1	0.64	79.28
17	0.21	0.73	−246.11	4.26	0.73	82.94

changing surface quality than spindle speed. If spindle speed increases, the surface roughness also increases.

3.7. Regression analysis

The regression analysis is used to make a relationship between independent variable spindle speed and feed rate on considered responses. The model predictability is evaluated based on R^2 value. If R^2 value is closer to 1 that means the model predictability is the best one. So here, the second order polynomial equations are developed for predicting the response values like machining time, entry and exit burr height, entry and exit burr thickness, ovality, thrust force, torque and surface roughness are presented from equation 1 to 9. The model outline with R^2, predicted R^2, adjacent R^2, Adequate precision are tabulated in Table 5. All the developed models' predictability can be validated with experimental data. So the validation of developed models is also carried out in this work.

$$\textit{Machining time} = 0.38719 - 7.48022E - 005{*}N - 3.18506{*}f + 1.08585e - 004{*}N{*}f + 6.52276e - 009{*}N^2 + 9.40609{*}f^2 \quad (1)$$

$$\textit{Entry burr height} = -6.52866 + 4.56165E - 003{*}N + 15.51906{*}f - 1.56338E - 004{*}N{*}f - 6.94179E - 007{*}N^2 - 55.39026{*}f^2 \quad (2)$$

$$\textit{Exit burr height} = -6.52866 + 4.56165E - 003{*}N + 15.51906{*}f - 1.56338E - 004{*}N{*}f - 6.94179E - 007{*}N^2 - 55.39026{*}f^2 \quad (3)$$

$$\textit{Entry burr thickness} = 9.55633E - 004{*}N - 28.82406{*}f - 7.55386E - 007{*}N{*}f - 1.95966E - 007{*}N^2 - 55.39026{*}f^2 \quad (4)$$

Table 8 – Validation of torque and surface roughness regression model.

Experimental Run	Experimental Torque (Kg m)	Regression Torque (Kg m)	% of deviation	Experimental Surface roughness (μm)	Regression Surface roughness (μm)	% of deviation
1	0	0.02	–	1.21	0.93	23.00196
2	0.1	0.09	13.79	0.98	1.09	−11.3755
3	0.1	0.09	13.79	0.78	1.09	−39.9334
4	0.1	0.11	−10.83	1.65	1.63	1.481123
5	0.1	0.09	14.34	1.2	0.78	34.60635
6	0.1	0.09	14.34	0.75	0.78	−4.62984
7	0	0.02	–	0.82	0.92	−11.7948
8	0	0.02	–	1	0.92	8.328236
9	0	0.08	–	0.78	0.89	−13.6306
10	0.1	0.08	20.49	1.21	0.89	26.75049
11	0.1	0.08	20.49	1.05	0.89	15.58866
12	0.1	0.08	20.49	0.93	0.89	4.696875
13	0.1	0.08	20.49	0.88	0.89	−0.71808
14	0	0.02	–	0.6	0.85	−41.5439
15	0	0.02	–	0.92	0.85	7.688746
16	0	−0.05	–	0.79	0.91	−15.6982
17	0	0.02	–	0.27	0.63	−134.391

Table 9 – Validation of entry and exit burr thickness regression model.

Experimental Run	Experimental Entry Burr thickness (mm)	Regression Entry Burr thickness (mm)	% of deviation	Experimental Exit burr thickness (mm)	Regression Exit burr thickness (mm)	% of deviation
1	1.45	1.12	22.66	0.048	1.23	−58.88
2	1.1	1.66	−50.70	0.028	1.41	−68.91
3	1.58	1.66	−4.92	0.448	1.41	−47.91
4	1.93	1.38	28.71	0.044	2.01	−98.29
5	1.56	2.58	−65.64	0.44	1.54	−55.17
6	1.43	2.58	−80.70	0.456	1.54	−54.37
7	1.83	2.05	−11.84	0.036	0.71	−33.88
8	1.71	2.05	−19.69	0.438	0.71	−13.78
9	0.8	2.65	−231.02	0.438	0.90	−23.34
10	0.9	2.65	−194.24	0.458	0.90	−22.34
11	4.13	2.65	35.88	0.048	0.90	−42.84
12	2.65	2.65	0.07	0.04	0.90	−43.24
13	4.26	2.65	37.84	0.016	0.90	−44.44
14	2.11	2.61	−23.78	0.026	0.81	−39.41
15	3.68	2.61	29.03	0.418	0.81	−19.81
16	3.1	2.00	35.53	0.422	0.62	−9.96
17	4.26	2.59	39.27	0.026	1.46	−71.65

Table 10 – Validation of ovality and thrust force regression model.

Experimental Run	Experimental Ovality (mm)	Regression Ovality (mm)	% of deviation	Experimental Thrust force Kg F	Regression Thrust force Kg F	% of deviation
1	0.9523	0.86	9.84	55	15.13	72.49
2	1.7309	1.24	28.42	43	79.46	−84.80
3	0.624	1.24	−98.54	58	79.46	−37.01
4	1.4162	1.44	−1.44	87	68.89	20.81
5	0.9419	0.92	2.79	56	81.99	−46.40
6	0.9463	0.92	3.24	53	81.99	−54.69
7	0.3134	0.58	−84.52	37	65.97	−78.28
8	0.624	0.58	7.33	46	65.97	−43.40
9	1.6077	0.90	43.82	121	121.61	−0.50
10	1.7727	0.90	49.05	158	121.61	23.03
11	0.6568	0.90	−37.50	132	121.61	7.87
12	1.2903	0.90	30.01	143	121.61	14.96
13	0	0.90	–	158	121.61	23.03
14	0.6493	0.86	−31.71	53	76.98	−45.25
15	0.4866	0.86	−75.75	55	76.98	−39.96
16	0.4897	0.54	−10.35	32	22.91	28.41
17	0.788	0.83	−5.88	69	32.11	53.46

$$\textit{Exit burr thickness} = 2.30235E-004*N - 1.22976*f - 1.21548E-004*N*f - 3.95772E-008*N + 6.53432*f \quad (5)$$

$$\textit{Ovality} = 2.01848E-005*N + 12.92851*f + 6.42419E-004*N*f + 1.15875E-008*N - 51.21179*f \quad (6)$$

$$\textit{Thrust force} = -451.20213 + 0.29574*N - 2462.78701*f + 0.100077*N*f - 4.75425E-005*N^2 - 10765.32437*f^2 \quad (7)$$

$$\textit{Torque} = -0.66600 + 3.90194E-004*N + 2.66590*f + 6.40344E-005*N*f - 5.75781E-008*N^2 - 9.90243*f^2 \quad (8)$$

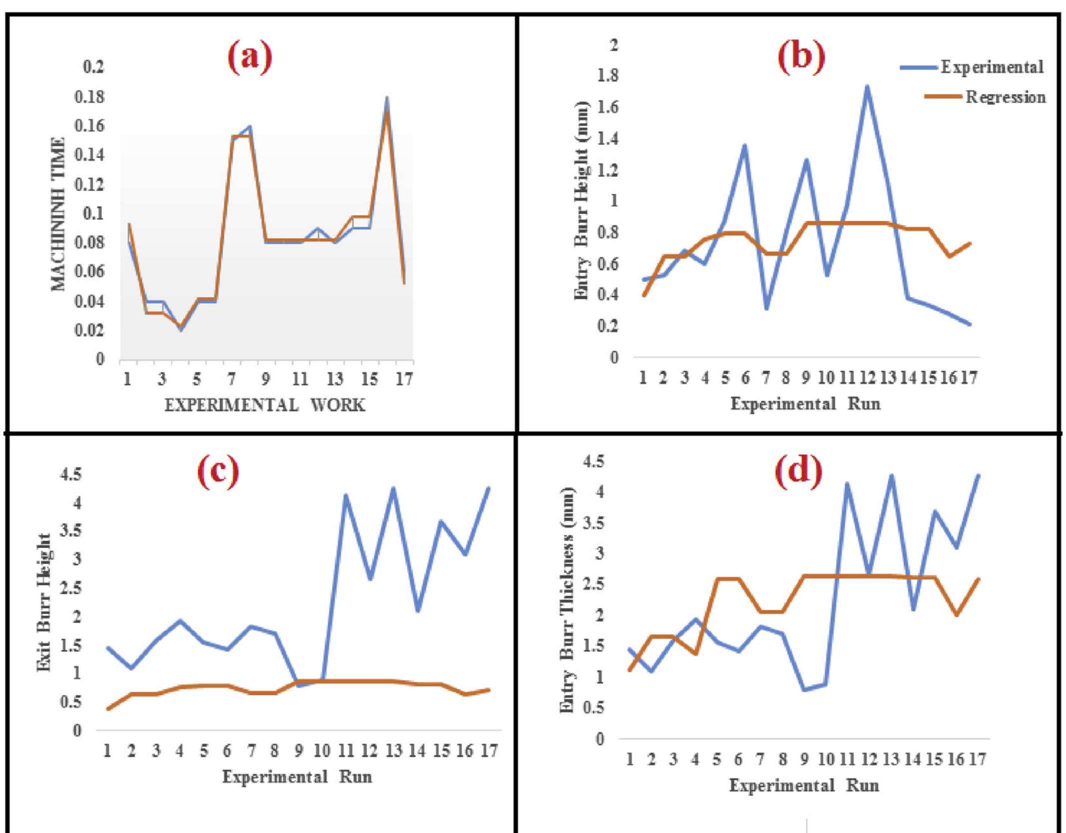


Fig. 8 – Validation plot of a) Machining time b) Entry burr height c) Exit burr height d) Entry burr thickness regression models.

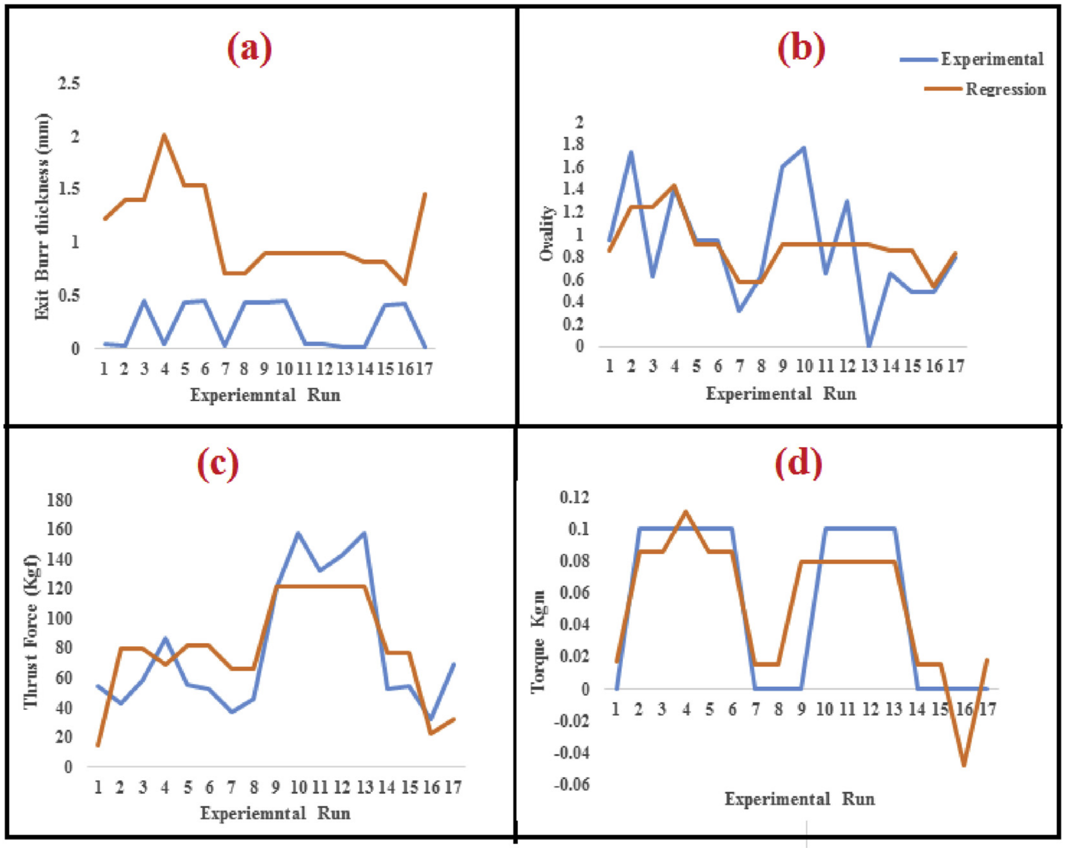


Fig. 9 – Validation plot of a) Exit burr thickness b) Ovality c) Thrust force d) Torque regression models.

$$Surface\ roughness = 1.12236 - 7.71999e - 005*N - 5.80529*f + 2.20499E - 003*N*f \quad (9)$$

The developed regression models are validated with experimental data and the percentage of deviation is also represented from Tables 6–10 for considered responses. The average percentage of deviation for machining time was −0.08, entry burr height as −38.6, exit burr height as −57.40, entry burr thickness as −26.68, exit burr thickness as −44.09, ovality as −10.70, thrust force as −10.95, torque as 14.16, surface roughness −8.92. The machining time, ovality, thrust force and surface roughness have a very less percentage of deviation, as presented in Fig. 8–10 So, these models can be utilized for further investigations. However, the burr dimensions model has very poor predictability according to the considered experimental procedure. So, this work suggests the burr dimensions analysis needs further experimental analysis for enhancing the Cryogenic drilling process.

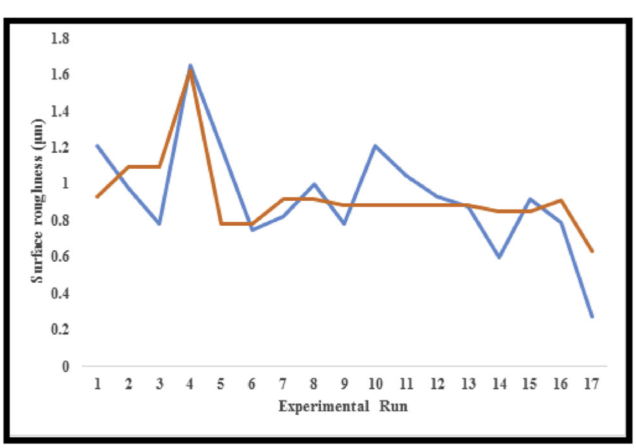


Fig. 10 – Validation plot of surface roughness regression model.

4. Conclusion

The drill bit is dipped in cryogenic treatment for 38 h, making it normal to keep at room temperature. The cryogenically treated drill bits were used to make the hole in the workpiece. The drilling is done with aluminium alloy. The experiments with the various speed and feed the hole is conducted and the results are achieved from this experimental and theoretical work are as follows.

- The spindle speed and feed have increased, the machining time was reduced. When the speed is increased, the entry burr height has reached the maximum at the middle level of the spindle speed. There is no feed rate contribution. The exit burr height is increased with the incremental of feed and the exit burr height is minimum with the middle level of spindle speed. The entry burr thickness is minimum with the incremental feed rate at mid-level of spindle speed. Bu the incremental feed rate reduced the exit burr thickness with midlevel of spindle speed.

- The ovality of the drilled hole also increased with incremental spindle speed and feed rate. The minimum ovality 0 occurred at a spindle speed of 2270 rpm with a feed rate 0.076 mm/rev.
- The thrust force reached the maximum 158 Kgf at a middle level of spindle speed 2270 rpm and feed rate of 0.076 mm/rev on considered levels of input parameters.
- The torque from 0 to 0.1 Kgm linearly increased with spindle speed and feed rate increments of considered levels of spindle speed and feed rate.
- In cryogenically treated drill bits tool wear with point angle, the point angle gets maximum19.7 deg with the incremental of spindle speed,
- When the speed has increased, the chisel length has a maximum value of 1.47 mm at its middle point. An increase in feed has increased in the chisel length.
- When the speed had increased, the lip length1 and lip length2 had maximum values 1.24 and 1.39 mm at the middle of the speed 2270 rpm. An increase in the feed from 0.038 to 0.203 mm/rev results in a minimum value at the middle of the feed.
- When the speed and feed had increased, the lip length of the drill bit also increased.

The developed regression models of machining time, ovality, thrust force, and surface roughness have the best agreement with experimental data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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