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"A STUDY OF THRUST FORCE IN DRILLING OF EN-8 STEEL USING FACTORIAL DESIGN''

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Abstract

Drilling is one of the most common and fundamental machining processes. Metal machining has been an interesting topic of research for decades.. The EN-8 steel is widely used as a main material in die making industries. A study of thrust force during drilling of EN-8 steel will be quite useful. In the present work the response surface methodology based two level full factorial design design has been selected for development of prediction models and optimization of drilling parameters for minimum thrust force. An effort has also been made to investigate the effect of drilling parameters on thrust force during drilling of EN-8 steel.

Keywords: RSM, Analysis of Variance (ANOVA), Design of Experiments (DOE), EN-8 steel and Face Centered Design.

1. INTRODUCTION

In the manufacturing industries, various machining processes (turning, milling, drilling etc.) are adopted for removing the material from the workpiece to obtain finished product. Among the various metal removing processes, drilling is the one of most important metal removing process as compared to other traditional machining processes. Drilling is use for making the hole in the workpieces. Hole making is a most important machining process in manufacturing. During the drilling, the drill rotates and fed into the work piece to remove the material in the form of chips that move along the fluted shank of the drill. Different drilling tools and hole making methods are used for drilling. The selection of different tools and methods depends on the type of workpiece, size of the hole, the quantity of holes, and the quantity of the holes in given time periods. Also, drilling is used as an initial process for many machining operations, such as reaming, tapping and boring. Drilling process is widely used in the aerospace, aircraft and automotive industries.

During the drilling of the workpiece, it has long been recognized that the drilling conditions (drill point geometry, drill and workpiece materials, drilling parameters like feed rate and spindle speed) affect the performance of the operation to a greater extent. These drilling conditions should be selected to optimize the economics of drilling operations. So it can be achieved by empirical modeling of performance as a function of machining conditions using design of experiments (DOE). The proposed work will be employed for optimization of drilling conditions for minimum thrust force using response surface methodology based on two level full factorial design.

Thus objectives of the present study are:

A. Optimizations of drilling conditions for minimum thrust force during drilling of EN-8 die steel using tungsten carbide drills.

B. Development of thrust force prediction model in terms of drilling conditions using RSM based on two level full factorial design.

C. To investigate the effect of drilling conditions (spindle speed, feed, and diameter of hole) on thrust force during drilling of EN-8 die steel.

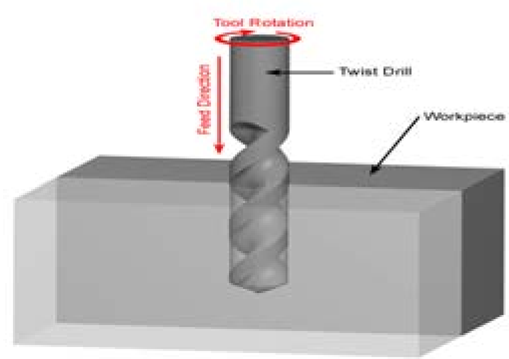

Figure1: Drilling process

II. LITERATURE REVIEW

Metal machining has been an interesting topic of research for decades. Early research efforts include topics, such as, chip formation, heat generation at tool-chip and tool-work interfaces, tool wear, tool life, cutting force analysis, machinability, power requirements, manufacturing cost and productivity etc. With more

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emphasis on productivity, in past few decades, research efforts seem to have been diverted towards the study of tool wear, cutting forces and surface finish/roughness in metal machining.

Studies have been reported on mathematical modeling and selection of machining parameters for optimization of thrust forces, surface finish, MRR tool wear during the drilling in recent past. A brief review of research on the topic is presented below.

Madival (1998) employed artificial neural network to investigate the effect of drilling parameters on surface roughness during the drilling of composite. An attempt has also been made to developed surface roughness prediction model using ANN. The cutting speed and feed have been considered as drilling parameters. The result clearly shows that surface finish decreases with increase in feed rate for all the values of cutting speed.

Lin and Chen (1999) experimentally investigate the effect of cutting speed, feed and type of drill on drill wear, torque, hole quality and thrust force during the drilling of carbon fiber-reinforced composite materials. It has been revealed that as the cutting speed increases the wear of drill also increase and the thrust force increases with increase in drill wear. It has also been found that tool wear is the major problem encountered when drilling carbon fiber reinforced composite materials at high speed.

Tosun and Muratoglu (2003) experimentally investigated the effect of feed rate and cutting speed on surface roughness during the drilling of Al/17% Sic of metal-matrix composites. For drilling purpose HSS, TiN coated HSS and solid carbide drills have been used. The result shows that the surface roughness decrease with increase in feed rate at all the spindle-speed for all the drills. Also, with increase in speed, the surface roughness increases with HSS drills but the surface roughness is not clear in the TiN coated HSS and solid carbide drills.

Choudhury et al. (2004) made use of Taguchi optimization approach to optimize the cutting parameters for end milling of AISI H13 hardened steel using Tin coated carbide inserts. The milling parameters evaluated are cutting speed, feed rate and depth of cut. An orthogonal array, signal-to-noise (S/N) ratio and Pareto analysis of variance (ANOVA) are employed to analyze the effect of these milling parameters. The analysis of the results shows that the optimal combination for low resultant cutting force and good surface finish are high cutting speed, low feed rate and small depth of cut. It has also been found that Taguchi method is suitable to solve the stated problem with minimum number of trials as compared with a full factorial design.

Nouari et al. (2005) experimentally investigated the effect of machining parameters on tool wear, hole diameter deviations and surface roughness during the dry drilling of aluminum alloy 2024 using coated tungsten carbide drill, uncoated tungsten carbide drill and HSS drill. The drilling experiments were performed on rigid instrumented drilling bench. The result shows that minimum hole deviation and minimum surface roughness has been achieved with in terms of maximum and minimum hole diameter deviations and surface roughness are obtained for the uncoated and coated tungsten carbide drills. The HSS tool is found not suitable for dry machining of aluminum alloy 2024. The cutting speed has been found most significant parameter that affects the surface roughness, tool wear and hole deviation during the dry drilling of aluminum alloy A2024.

Reddy and Rao, 2005 experimentally investigated the effect of solid lubricant on surface quality, cutting forces and specific energy during end milling of AISI 1045 steel. The end milling operation has been carried out using solid coated carbide end mill of different tool geometry (radial rake angle and nose radius). The graphite and molybdenum disulphide have been employed as solid lubricant. A attempt has also been made to compare the results obtained in wet machining with solid lubricant assist machining. The results revealed that the use of solid lubricant successfully reduces the cutting forces, specific energy, surface roughness, chip size during end milling. Also, the friction between tool and workpiece has been significantly reduced in molybdenum disulphide assisted machining as compared with graphite and wet assisted machining.

C.C. Tsao (2006) used Taguchi methodology to investigate the effect of drilling parameters on thrust force and surface roughness during the drilling of quality associated with core drill in drilling of carbon fibre reinforced plastic (CFRP) laminate. The grit size of diamond, thickness, feed rate and spindle speed have been considered as drill parameters. The ANOVA has also been used to investigate most significant parameter that affect the thrust force and surface roughness during the drilling process. The result indicates that the thickness and feed rate have been found most significant parameters that affect the surface roughness and thrust force. It has also been found through conformation runs that Taguchi methodology is a effective tool for the evaluation thrust force and surface roughness (errors within 10%) during drilling of composite material.

Gaitonde et al. (2006) used Taguchi methodology with a new concept of fitness function for each trial of orthogonal array to optimize multi-objective response during the drilling of AISI 316L stainless steel. The Taguchi design for the multi-objective optimization problem is based on a new concept of fitness function to minimize burr size. The burr height and burr thickness have been considered as response while cutting speed, feed, point angle and lip clearance angle have been considered as drilling parameters. The results show that this new approach can be efficiently employed for the multi optimization during the drilling process.

Mohan et al, (2006) used Taguchi methodology to investigate the effect of drilling parameters and workpiece parameters on peel up and push down delamination factor during the drilling of glass fibre reinforced plastic (GFRP) composite laminates. The speed, feed rate, drill size have been considered as drilling parameters and thickness of glass fibre reinforced plastic has been considered as workpiece parameter. The signal-to-noise ratio is used to investigate the effect of parameters on peel up and push down delamination factor during drilling.An attempt has also been made to optimize the parameters for minimum delamination. The specimen thickness and cutting speed have been found significant effect on peel up delamination, on the other hand the specimen thickness and feed have been found significant effect on push down delamination.

Haq et al. (2007) used grey relational analysis with Taguchi methodology for multi response optimization of machining parameters during the drilling Al/SiC metal matrix composite. The cutting speed, feed and point angle have been considered as drilling parameters while surface roughness, cutting force and torque have been considered as responses. ANOVA has also been used to identify most significant parameter that affects the responses. The results show that this new approach i.e grey relation analysis with Taguchi is a effective tool for multi response optimization.

Karnik et al. (2007) made an attempt to investigate best technique for the prediction of burr size during the drilling of AISI 316 L stainless steel. For this a comparison has been made between the prediction values of burr size, those obtained using RSM based on three level full factorial design and artificial neural network. The cutting speed, feed, and point angle have been considered as cutting parameters for both models. The comparison between the predicted values from both models clearly indicates that the ANN models provide more accurate prediction results as compared to those obtained through RSM models.

Kaneriya and Sharma, (2014) optimized the drilling parameters for minimum temperature generated during the drilling, maximum material removal rate and maximum drill tool life during the dry drilling of AISI 304 austenitic stainless steel using RSM. Three type of drills HSS, cobalt coated HSS and K20 Solid Carbide drill tool have been used to investigate the effect of drill type on temperature. The feed rate and spindle speed have been used as drilling parameters. All the experiments have been conducted on vertical machining center (VMC 1050) machine. The temperature of drill bit has been measured using infrared thermometer. The experimental results have been simulated with DEFORM 3D software.

III. EXPERIMENTAL DETAILS

A.Selection of Drilling Parameters and the Range of Drilling Parameters:

The process parameters that were chosen for experimentation are given as under:

1. Spindle speed (RPM)
2. Feed (mm/rev.)
3. Diameter of hole (mm)

These are the main drilling parameters that affect the thrust force. Also, machine operator can change these parameters at the time of machining. The levels of each input parameter were decided by studying the literature in detailed and according to machine limitations. Table 3.1 shows the levels of drilling parameters according to RSM based on two level full factorial design.

Table 3.1 Drilling parameters and their levels

Table 3.1 Drilling parameters and their levels

Factor	*Name*	*Units*	*Type*	*Minimum (-1)*	*Maximum (+1)*
A	*Spindle Speed*	*(RPM)*	*Numeric*	*1000*	*2000*
B	*Feed*	*(mm/rev.)*	*Numeric*	*0.04*	*0.06*
C	*Dia. of hole*	*(mm)*	*Categoric*	*10*	*14*

B.Machining Trial:

In the present work RSM based on two level full factorial design has been used to plan the experiments. Total 16 numbers of experiments has been finalized according to RSM. Out of 16 experiments, 8 are the factorial points, 4 are the centre point with one diameter of hole and remaining 4 with other diameter of hole. The table 3.2 shows the design layout for experimentation.

Table 3.2 Design layout for experimentation

Std	*Run*	*A:Spindle speed (RPM)*	*B: Feed (mm/rev.)*	*C:Drill diameter (mm)*	*Thrust force (N)*
6	*1*	*2000*	*0.04*	*14*	*1636*
9	*2*	*1500*	*0.05*	*10*	*1891*
16	*3*	*1500*	*0.05*	*14*	*1998*
4	*4*	*2000*	*0.06*	*10*	*1955*
7	*5*	*1000*	*0.06*	*14*	*2366*
13	*6*	*1500*	*0.05*	*10*	*1857*
12	*7*	*1500*	*0.05*	*14*	*2003*
3	*8*	*1000*	*0.06*	*10*	*2228*
11	*9*	*1500*	*0.05*	*10*	*1887*
14	*10*	*1500*	*0.05*	*14*	*1963*
5	*11*	*1000*	*0.04*	*14*	*1920*
15	*12*	*1500*	*0.05*	*10*	*1862*
1	*13*	*1000*	*0.04*	*10*	*1672*
2	*14*	*2000*	*0.04*	*10*	*1494*
10	*15*	*1500*	*0.05*	*14*	*1998*
8	*16*	*2000*	*0.06*	*14*	*2018*

C. Experimental Set Up:

1) CNC Vertical Machining Centre:

The drilling operations have been carried out on a CNC MILL MT250 Machining Center, Make-Hytech educational equipment ltd., India. The CNC vertical machining centre equipped with continuously variable spindle speed up to 4000 rpm, and 2HP motor drive was used for experimentation. The major machining operations that can be carried out are milling, drilling, boring etc.

2) Cutting Inserts:

Coated carbide tool performs better than uncoated carbide tools. On this basis, commercially accessible K-series, tungsten carbide high speed core drills with Tialn coating having 10 mm diameter and 14 mm diameter with two flute have been used for experimentation. The inserts were manufactured by Changzhou Hongjian Tools Co., Ltd. China.

3) Coolant:

Coolant has been used in all the experiments. SUPERCUT cutting oil by SHELL COMPANY has been used in the ratio of 20:1 i.e 20 litres of water and 1 litre of cutting oil in it.

D. Thrust force Measurement:

In the present work, cutting force in Z direction (thrust force) during the drilling of EN-8 steel is measured using dynamometer made by Unitech scales and measurements pvt. Ltd. This dynamometer can measure all three direction forces simultaneously and displayed.

Table 3.3 Measurement results

Run	A:Spindle speed (RPM)	B: Feed (mm/rev.)	C:Drill diameter (mm)	Thrust force (N)
1	2000	0.04	14	1636
2	1500	0.05	10	1891
3	1500	0.05	14	1998
4	2000	0.06	10	1955
5	1000	0.06	14	2366
6	1500	0.05	10	1857
7	1500	0.05	14	2003
8	1000	0.06	10	2228
9	1500	0.05	10	1887
10	1500	0.05	14	1963
11	1000	0.04	14	1920
12	1500	0.05	10	1862
13	1000	0.04	10	1672
14	2000	0.04	10	1494
15	1500	0.05	14	1998
16	2000	0.06	14	2018

IV. DEVELOPMENT OF THRUST FORCE PREDICTION MODEL

To develop the thrust force prediction model in terms of spindle speed, feed and diameter of hole, the measure value of thrust force along with the values of drilling parameters have been fed into the design expert. For the development of prediction model first step is ANOVA analysis.

A.ANOVA for Metal Removal Rate (MRR) Prediction Model:

The analysis of variance (ANOVA) is based on two assumptions.

(1) The variables are normally distributed

(2) Homogeneity of variance. Significant violation of either assumption can increase the chances of error.

To check the assumption of normal distribution, the normal probability plot of the residuals for thrust force is shown in figure.4.1.The normal probability plot indicates whether the residuals follow a normal distribution or not, if the residuals follow a normal distribution majority of points will follow a straight line except some moderate scatter even with normal data. The figure displays that the residuals generally fall on a straight line implying that the errors are distributed normally.

The figure.4.2 represents residuals versus the predicted thrust force plot. It tests the assumption of constant variance. The plot should be a random scatter. The figure shows that there is no obvious pattern and it shows unusual structure. This implies that there is no reason to suspect any violation of the independence or constant variance assumption.

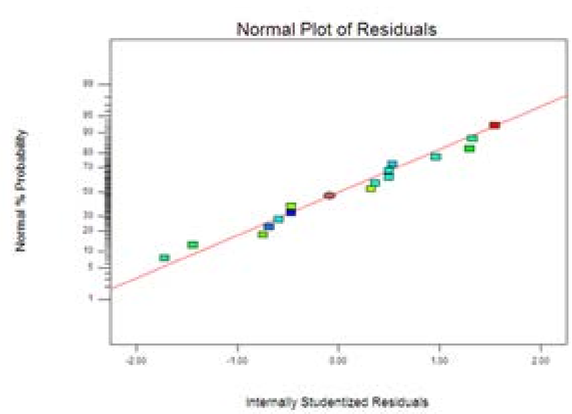

Figure 4.1 Normal probability plot of residuals for thrust force

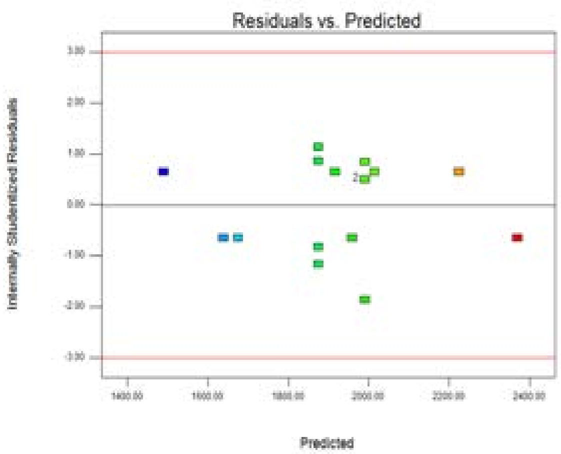

Fig. 4.2 Plot of residuals v/s predicted thrust force

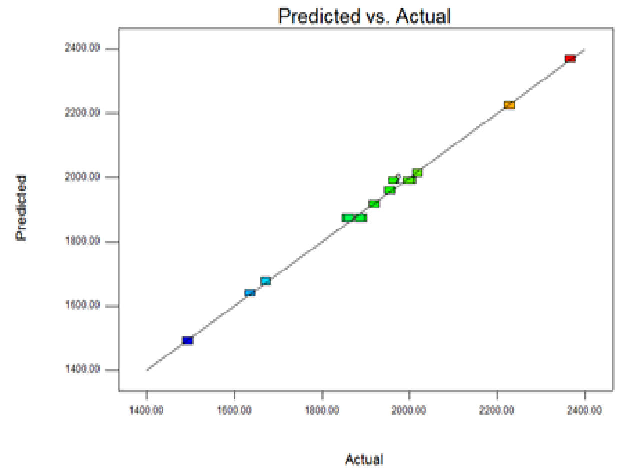

Figure 4.3 Plot of predicted v/s actual thrust force

B.ANOVA Analysis for Thrust:

The ANOVA was carried out for a significance level of α = 0.05, i.e. for a confidence level of 95%. The ANOVA for thrust force is summarized in Table 4.1.

The table 4.1, shows that the value of "Prob. > *F*" for model is less than 0.0001 which is less than 0.05, that indicates the model is significant, which is desirable as it indicates that the terms in the model have a significant effect on the thrust force.

Source	*Sum of Squares*	*degree of freedom*	*Mean Square*	*F-Value*	*p-value Prob > F*
Model	*653650.8*	*7*	*93378.7*	*158.46*	*< 0.0001S*
A-Spindle speed	*146611.1*	*1*	*146611.1*	*248.80*	*< 0.0001*
B-Feed	*425503.1*	*1*	*425503.1*	*722.07*	*< 0.0001*
C-drill dia	*69696.0*	*1*	*69696.0*	*118.27*	*< 0.0001*
AB	*3160.1*	*1*	*3160.1*	*5.36*	*0.0492*
AC	*4095.1*	*1*	*4095.1*	*6.95*	*0.0299*
BC	*4465.1*	*1*	*4465.1*	*7.58*	*0.0250*
ABC	*120.1*	*1*	*120.1*	*0.20*	*0.6636*
Residual	*4714.3*	*8*	*589.3*		
Lack of Fit	*2798.5*	*2*	*1399.3*	*4.38*	*0.0671 NS*
Pure Error	*1915.8*	*6*	*319.3*		
Cor Total	*658365.0*	*15*			
Std. Dev.	*24.3*		*R-Squared*		*0.993*
Mean	*1921.8*		*Adj R-Squared*		*0.987*
C.V. %	*1.3*		*Pred R-Squared*		*0.857*
PRESS	*93881.8*		*Adeq Precision*		*49.883*

Table 4.2 Reduce ANOVA table for thrust force

Source	Sum of Squares	degree of freedom	Mean Square	F-Value	p-value Prob > F
Model	653530.6	6	108921.8	202.78	< 0.0001 S
A-Spindle speed	146611.1	1	146611.1	272.94	< 0.0001
B-Feed	425503.1	1	425503.1	792.15	< 0.0001
C-drill dia	69696.0	1	69696.0	129.75	< 0.0001
AB	3160.1	1	3160.1	5.88	0.0383
AC	4095.1	1	4095.1	7.62	0.0221
BC	4465.1	1	4465.1	8.31	0.0181
Residual	4834.4	9	537.2		
Lack of Fit	2918.6	3	972.9	3.05	0.1140 NS
Pure Error	1915.8	6	319.3		
Cor Total	658365.0	15			
Std. Dev.	23.2		R-Squared		0.993
Mean	1921.8		Adj R-Squared		0.988
C.V. %	1.2		Pred R-Squared		0.956
PRESS	28639.8		Adeq Precision		56.361

Table 4.2 shows the reduce ANOVA table for thrust force after the elimination of insignificant model terms using backward elimination method. The value of "Prob. > *F*" for model is less than 0.0001 which is less than 0.05, that indicates the model is still significant. In the same manner, the value of "Prob. > *F*" for main effect of spindle speed, feed, hole diameter and two-level interaction of spindle speed and feed; spindle speed and hole diameter; feed and hole diameter are less than 0.05 so these terms are still significant model terms. The value of "Prob. > *F*" for lack-of-fit is 0.1140 which is greater than 0.05, it indicates lack of fit still insignificant.

The R^2 value is equal to 0.993 or close to 1, which is desirable. The adjusted R^2 value is equal to 0.988; it is particularly useful when comparing models with different number of terms. The result shows that the adjusted R^2 value is very close to the ordinary R^2 value. Adequate precision value is equal to 56.361; a ratio greater than 4 is desirable which indicates adequate model discrimination. Adequate precision value compares the range of the predicted values at the design points to the average prediction error.

C. Thrust force prediction model

The regression model for thrust force in terms of coded factors is shown as follows:

$$Thrust\ force = 1921.75 - 135.38 * A + 230.63 * B + 66 * C - 19.88 * A * B - 22.63 * A * C - 23.6 * B * C \quad (4.1)$$

While, the following regression models in terms of actual factors are given in equations 4.2 and 4.3 for hole diameter 10 mm and 14 mm respectively.

$$Thrust\ force = 624.62 - 0.0267 * Spindle\ speed + 31387.5 * Feed - 3.975 * Spindle\ speed * Feed \quad (4.2)$$

$$Thrust\ force = 1128.62 - 0.117 * Spindle\ speed + 26662.5 * Feed - 3.975 * Spindle\ speed * Feed$$

D. Contribution of drilling parameters on thrust force

The fig.4.4, shows the half normal plot, the extreme right side factor has the highest effect on the response, however as the dots corresponding to the particular factor comes nearer and nearer to the line, it shows these value affects the least. The value at the right extreme has the strongest effect on the thrust force and keeps on decreasing as it comes nearer and nearer to the line. It can also be understood in the fig 4.5, which shows the of effectiveness rank wise. The graph is between t-value and rank of factors.

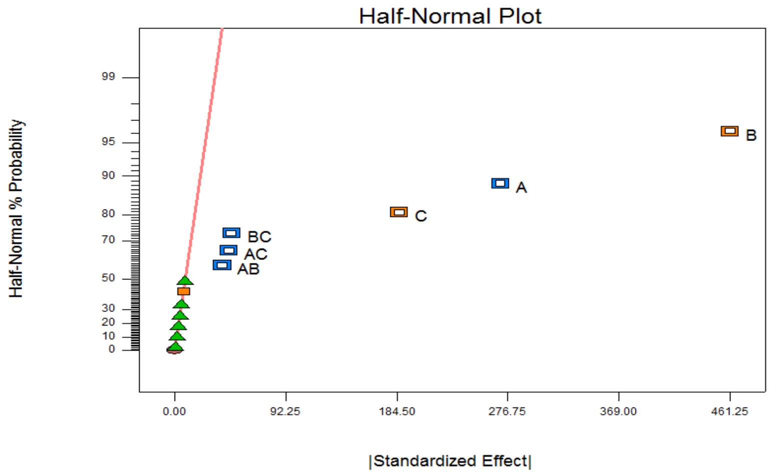

Fig.4.4: A half normal plot shows the effectiveness of the factors

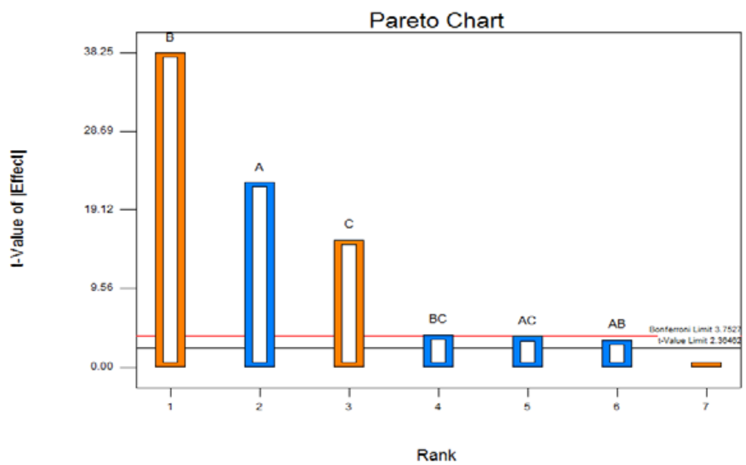

Fig.4.5: Graph between t-value and rank

The t-value here denotes the effectiveness of the factor. As it can be seen from the fig above, that the most effective factor is B, followed by A,C, combination of B& C, A& C, than combination of A&B.

V. RESULTS AND ANALYSIS

A. Effect of drilling parameters on thrust force

The effect of spindle speed on thrust force at constant feed (0.05 mm/rev.) and constant hole diameter (10mm) is shown in figure 5.1.

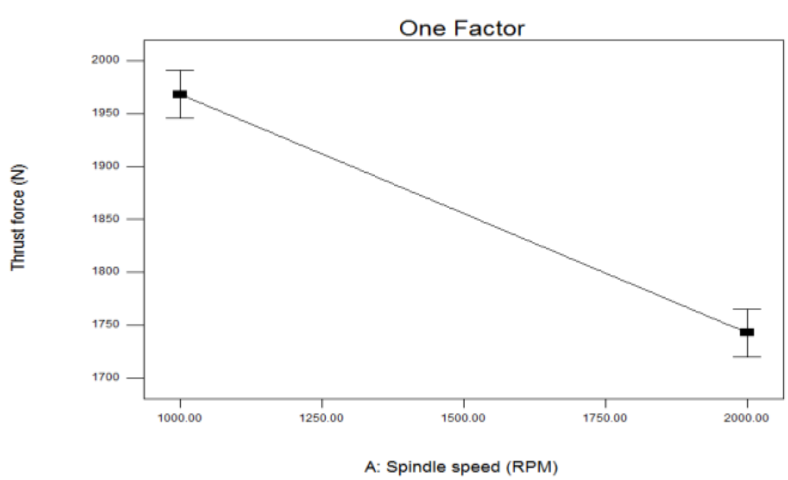

Figure 5.1.: Plot between spindle speed on thrust force at constant feed (0.05 mm/rev.) and constant hole diameter (10mm)

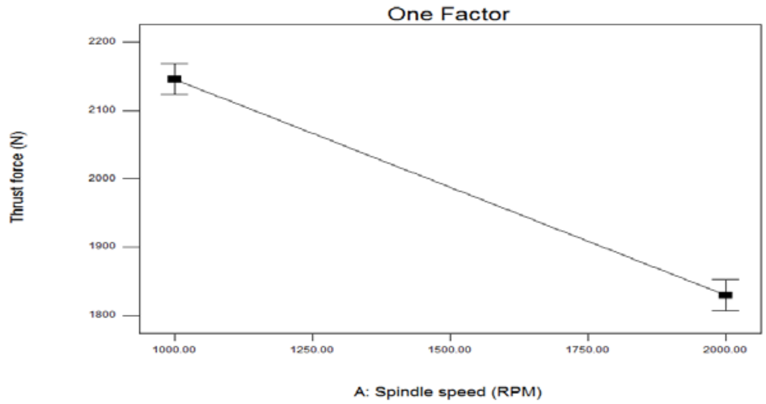

Figure 5.2.: Plot between spindle speed on thrust force at constant feed (0.05 mm/rev.) and constant hole diameter (14 mm)

Figure 5.3 and 5.4 shows the effect of feed on thrust force at constant spindle speed (1500 RPM), constant depth of hole 10mm and 14 mm respectively. From the plot it is clear that as feed increases the thrust force also increases. This is due to the fact that, as feed increases, the maximum chip thickness also increased, as a result, the chip volume which is cut per unit time increases and the metal shows resistance against rupturing causing a higher thrust force. Also as the feed increases the friction force between tool and workpiece also increases that produce more thrust.

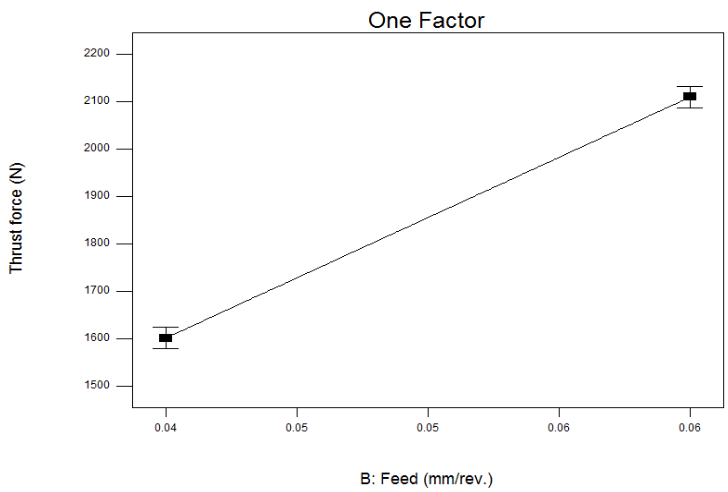

Figure 5.3.: Plot between feed on thrust force at constant spindle speed (1500 RPM) and constant hole diameter (10mm)

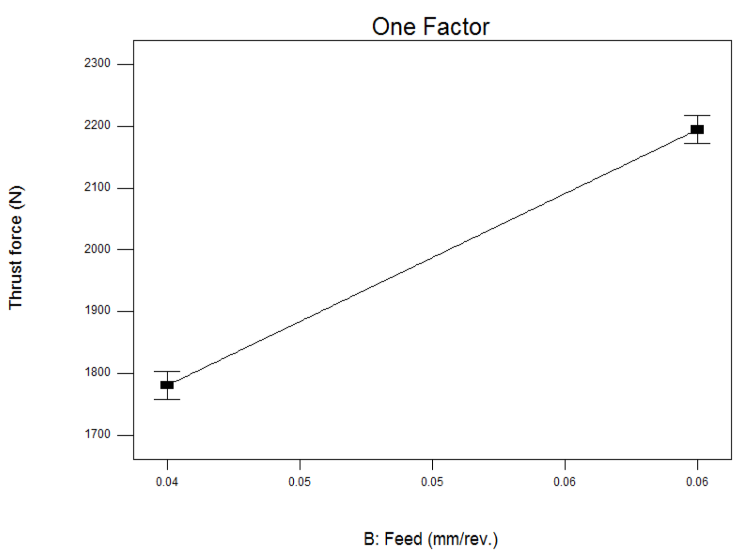

Figure 5.4.: Plot between feed on thrust force at constant spindle speed (1500 RPM) and constant hole diameter (14 mm)

Figure 5.5 shows the effect of hole diameter on thrust force at feed (0.05 mm/rev.), and spindle speed (1500 RPM). From the plot it is clear that as diameter of hole increases from 10 mm to 14 mm the thrust force also increases.

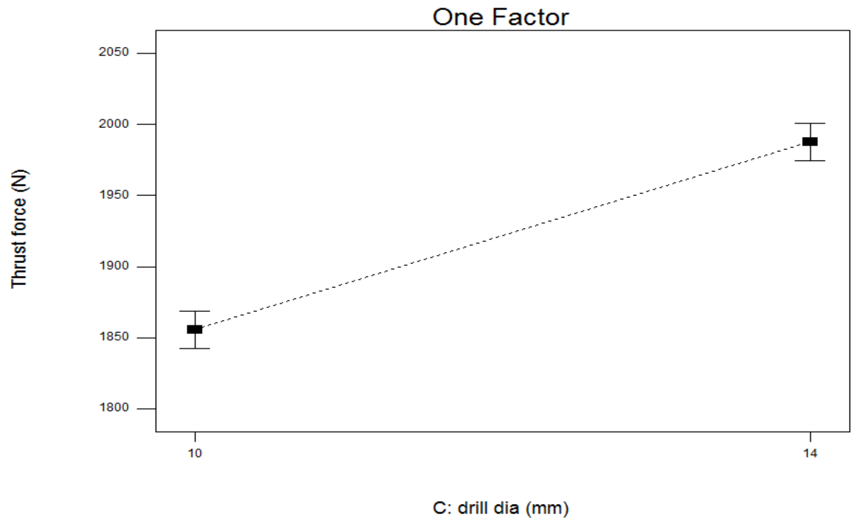

Figure 5.5: Plot between hole diameter and thrust force at feed (0.05 mm/rev.), and spindle speed (1500 RPM)

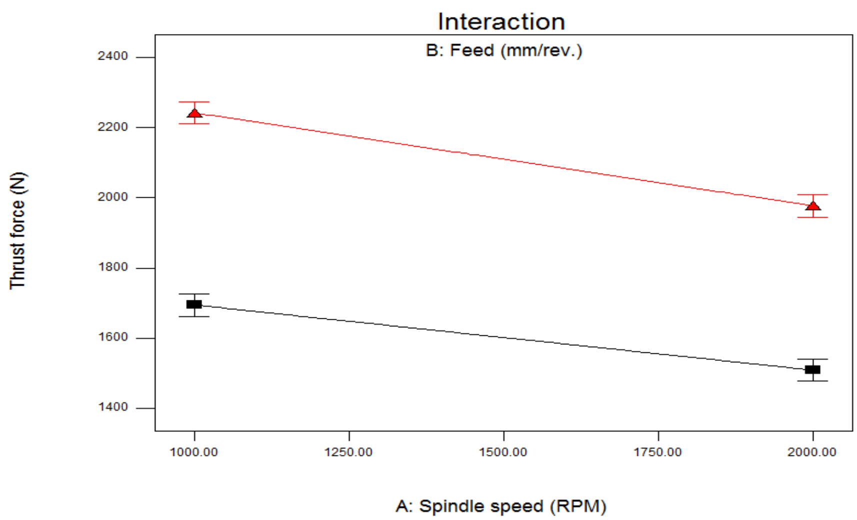

Figure 5.6: interaction plot for thrust force between the spindle speed and feed at constant diameter of hole (10 mm).

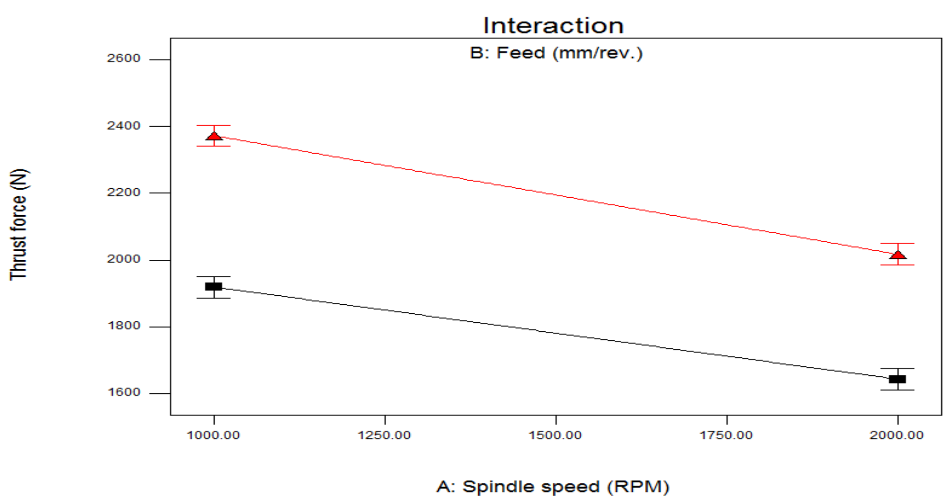

Figure 5.7: interaction plot for thrust force between the spindle speed and feed at constant diameter of hole (14 mm).

The figure 5.6 and 5.7 shows the interaction plots for thrust force between the spindle speed and feed at constant depth of hole 10 mm and 14mm respectively. In the plots, the black line shows the graph between spindle speed and thrust force at constant feed (0.04 mm/rev.) while red line shows the graph between spindle speed and thrust force at constant feed (0.06 mm/rev.). From the interaction plot it is clear that as the spindle speed increase the thrust force decreases for both the values of feed.

The figure 5.8 shows the interaction plot for thrust force between the spindle speed and diameter of hole at constant feed (0.05 mm/rev.). In the plot, the red line shows the graph between spindle speed and thrust force at constant diameter of hole (10 mm) while green line shows the graph between spindle speed and thrust force at constant diameter of hole (14 mm).

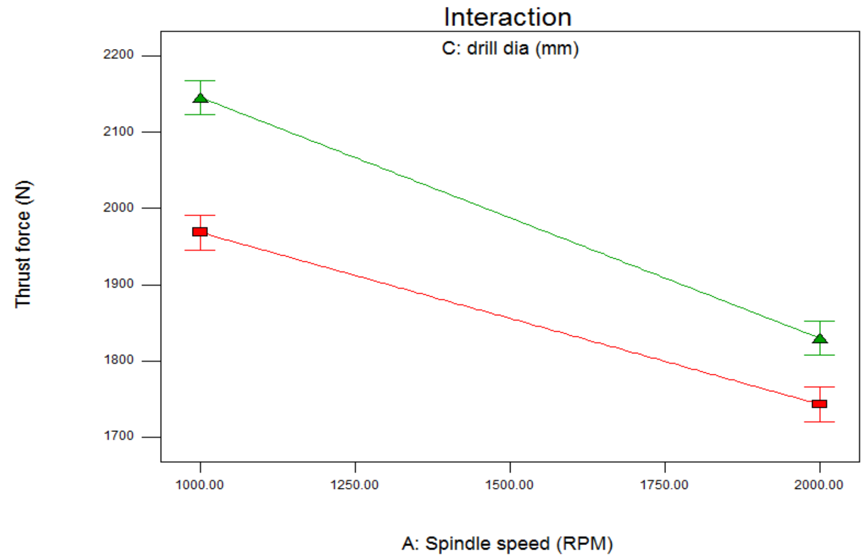

Figure 5.8: interaction plot for thrust force between the spindle speed and diameter of hole at constant feed (0.05 mm/rev.)

The figure 5.9 shows the interaction plot for thrust force between the feed and diameter of hole at constant spindle speed (1500 RPM). In the plot, the red line shows the graph between feed and thrust force at constant diameter of hole (10 mm) while green line shows the graph between feed and thrust force at constant diameter of hole (14 mm). From the interaction plot it is clear that as the feed increase the thrust force also increases for both the values of diameter of hole. It is also visible that for every value of feed, the thrust force is higher at high value of diameter of hole (14mm) as compare to low value of diameter of hole (10 mm).

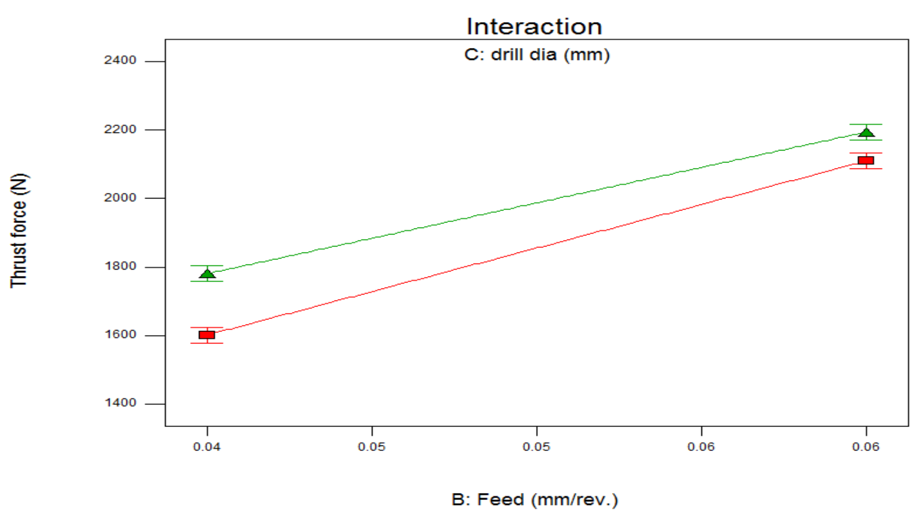

Figure 5.9: interaction plot for thrust force between the feed and diameter of hole at constant spindle speed (1500 RPM)

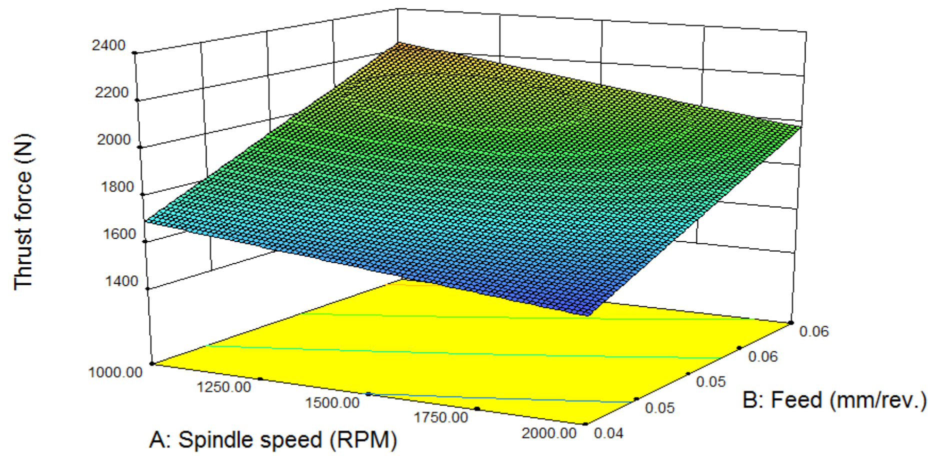

Figure 5.10 3D plot for thrust force between spindle speed and feed at constant diameter of hole (10 mm)

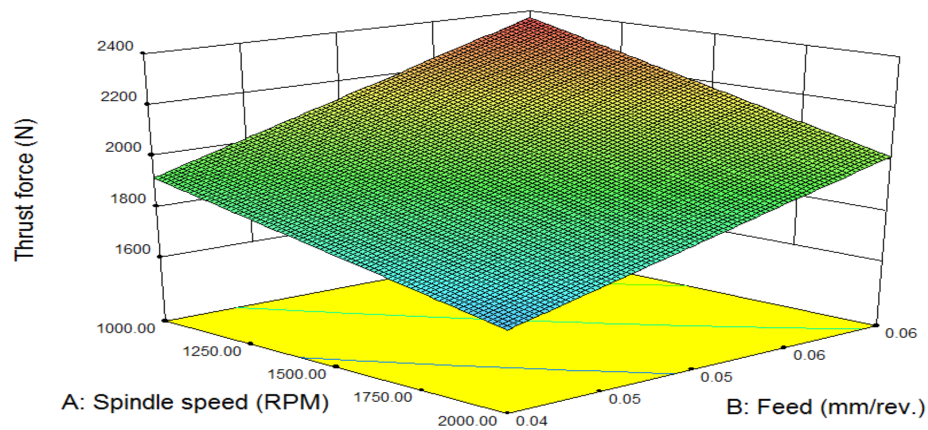

Figure 5.11 3D plot for thrust force between spindle speed and feed at constant diameter of hole (14 mm)

The figures 5.10 and 5.11 show the 3 D plots for surface roughness at 10 mm and 14 mm of diameter of drill respectively. From the all 3D plots it is clear that as the thrust force increase with increase in feed and diameter of hole while it decreases with increase in spindle speed.The minimum thrust force is achieved at 10 mm of hole diameter , minimum feed and at maximum value of spindle speed.

B. Optimization of drilling parameters for minimum thrust force:

In the present study, the aim is to obtain the optimal values of drilling parameters for minimum thrust force. The constraints used during the optimization process are summarized in Table 5.1.The optimal solutions are reported in table 5.2 .

Table 5.1 Constraints for optimization of drilling parameters

Name	*Goal*	*Lower limit*	*Upper limit*
A:Spindle Speed (RPM)	*is in range*	*1000*	*2000*
B:Feed (mm/rev.)	*is in range*	*0.04*	*0.06*
C:Diameter of hole (mm)	*is in range*	*10*	*14*
Thrust force (N)	*minimize*	*1494*	*2366*

Table 5.2 Optimization results for thrust force

S.NO	*Spindle Speed (RPM)*	*Feed (mm/rev.)*	*Diameter of hole (mm)*	*Thrust force (N)*	*Desirability*	*Remarks*
1	*2000*	*0.04*	*10*	*1508*	*0.983*	*Selected*

VI. CONCLUSION

The important conclusions drawn from the present work are summarized as follows:

1) Thrust force increases with increase in feed, increase in depth of hole while thrust force decreases with increase in spindle speed.

2) All the three independent parameters (spindle speed, feed and diameter of hole) seem to be the influential drilling parameters that affect the thrust force.

3) The mathematical prediction models for thrust force have been developed. The predicted results are in good agreement with the measured ones. These relationships are applicable within the ranges of tested parameters.

4) The ANOVA table clearly shows that the feed seems to be the most significant factor that affects the thrust force.

5) The minimum thrust force 1508 N has been obtained at spindle speed 200 RPM, diameter of hole 10 mm, and feed 0.04 mm/rev.

6) The interaction effect of spindle speed and feed; feed and diameter of hole and diameter of hole and spindle speed have also been found significant for thrust force.

7) The R-square values are found close to one that indicated the good prediction ability of develop model.

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