

Effect of Material Removal Rate (MRR) on AISI H11 Die Steel in Drilling using Face Centered Design

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Abstract

Drilling is one of the most common and fundamental machining processes. In machining, twist drills with diameters of 1–20 mm are used. Most of automotive components are manufactured using a conventional machining process, such as turning, drilling, milling, shaping and planning, etc.. These focus on producing high quality products in time at minimum cost. The surface roughness and MRR are considered to be a measure of the technological quality of a product. The aim of the present work is to optimize cutting conditions (Cutting speed, feed, wet and dry cutting, depth of hole) parameters for minimum MRR in drilling of AISI H11 using Face Centered Design . Experiments were conducted based on the design of experiments (DOE) and followed by optimization of the results using Analysis of Variance (ANOVA) to find the maximum material removal rate (MRR).

Keywords: MRR, Analysis of Variance (ANOVA), Design of Experiments (DOE), RSM, and Face Centered Design

I. INTRODUCTION

The largest amount of money spent on any one class of cutting tools is spent on drills. Therefore, from the viewpoint of cost and productivity, modeling and optimization of drilling processes are extremely important for the manufacturing industry (S.A. Jalali et.al 1991). Amongst traditional machining processes, drilling is one of the most important metal cutting operations, comprising 33% of all metal cutting operations (Chen W C et.al, 1999). Although modern metal cutting methods have tremendously improved in the manufacturing industry, conventional drilling process still remains one of the most common processes.

The manufacturing industries are focus on producing high quality products in time at minimum cost. The surface roughness is considered to be a measure of the technological quality of a product. Surface roughness is the one of the critical performance parameter that has an appreciable effect on several mechanical properties of machined parts such as fatigue behaviour, corrosion resistance, creep life, etc. It also affects other functional attributes of machined parts like friction, wear, light reflection, heat transmission, lubrication, electrical conductivity, etc. Hence, achieving the desired surface quality is of great importance for the functional behaviour of the mechanical parts.

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 piece to remove the material in the form of chips that move along the fluted shank of the drill.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 maximum MRR using response surface methodology based on face centered design.

II. LITERATURE REVIEW

Drilling operation is evaluated based on the performance characteristics such as surface roughness, material removal rate (MRR), tool wear, tool life, cutting force, hole diameter error, power consumption and are strongly correlated with the cutting parameters such as cutting speed, feed, depth of cut, and tool geometry (Chryssolouris G et.al, 1990, Chua MS et.al, 1993, Yang H et.al,1998, Paulo avim.J et.al,2003) ,which are determined based on experience or by the use of a handbook (Graham T et.al,2008).

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.

Davim and Reis (2002) Used Taguchi methodology to investigate the effect of cutting speed and feed rate on delamination during the drilling of carbon fiber reinforced plastic (CFRP). The ANOVA has also used to investigate the most significant parameter. The cutting speed and feed rate have been considered as drilling parameters. The cutting speed has been found most significant parameter that affects the delamination factor. The delamination factor increases with increase in cutting speed as well as with increase in feed rate.

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.

Cicek (2007) used Taguchi methodology based on L8 orthogonal array to investigate the effects of deep cryogenic treatment and drilling parameters on surface roughness and roundness error during the drilling of AISI 316 austenitic stainless steel with M35 HSS twist drills. An attempt has also been made to optimize the process control factors for hole quality. The two drill, cutting speed and feed rate have been considered as control factors.

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.

Han-Ming Chow et.al, (2008) has explored how different parameters such as drill shape, friction angle, friction contact area ratio, feed rate, and drilling speed would affect the response parameter for austenite stainless steel (AISI 304) using taguchi method.

Hsu and Tsao (2008) used Grey-Taguchi methodology based on Taguchi methodology and grey relation grade for multi response optimization of drilling parameters during the drilling of carbon fiber-reinforced plastic (CFRP) using candlestick drill. The ANOVA analysis has also been carried out to investigate the most significant drilling parameter. The Surface roughness and MRR have been considered as responses while feed rate spindle speed and drill diameters have been considered as drilling parameters. The feed rate and drill diameter have been found most significant parameters that affect the responses. On the other hand spindle speed has been found insignificant parameter during the drilling of CFRP.

Kurt et al. (2008) employed Taguchi methodology to optimized the cutting parameters minimum surface roughness and maximum MRR during the dry drilling operation. The cutting speed, feed rates, depths of drilling and different drills have been considered as cutting parameters. An attempt has also been made to investigate the effect of cutting parameters on responses. In addition to this, linear prediction models have also developed for surface roughness and hole accuracy in terms of drilling parameters. The ANOVA analysis has also been employed to investigate the most significant parameters for hole accuracy and surface roughness.

Ahamed et al. (2009) experimentally investigated the effect of drilling parameters on MRR and tool wear during the drilling of hybrid Al-5%SiCp-5%B4Cp metal matrix composites with HSS drills. An attempt has also been carried out to optimize the drilling parameters for minimum surface roughness and minimum tool wear. The cutting speed and feed have been considered as drilling parameters. Characterization of tool wear and surface integrity are also carried out using SEM. The result reveals that tools wear increases with increase in cutting speeds. The cutting speed has been found most significant parameter that affects the surface roughness. The surface roughness increases with increase in cutting speed. The minimum surface roughness and minimum tool wear have been achieved at lower level of feed and lower level of cutting speed during the drilling of Al-5%SiC-5% B4C composites with HSS tool. .

Khan et al, (2012) used Taguchi methodology to investigate the effect of drilling parameters on hole size deviation during the drilling of acrylic sheet. An attempt has also been made to optimize the drilling parameters for minimum hole deviation. The cutting speed, feed rate, and point angle has been considered as drilling parameters. The cutting speed has been found main influencing factor that affect the hole size deviation followed by feed. Tool angle has been found most complex factor. As the cutting speed increase the hole size deviation also increases. The minimum hole size deviation has been obtained at lower level of cutting speed and higher level of feed rate.

Kivak et al. (2012) experimentally investigated the influence of drilling parameters on the hole quality i.e. circularity and hole diameter and drill wear during the drilling of Inconel 718 using coated carbide drills and uncoated carbide drills. All the drilling experiments have been carried out on CNC milling center under dry cutting conditions using drill having 5 mm dia. The cutting speed and feed have been considered as cutting parameters. The results reveals that as the cutting speed increase, the tool wear and hole quality decreases. The flank wear and chisel edge wear have been observed during the drilling.

Tyagi et al. (2012) used L9 orthogonal based Taguchi methodology to optimized machining parameters for minimum surface roughness and maximum MRR during drilling of mild steel. The drilling operations have been carried out on CNC drilling machine using HSS Tool. The spindle speed, feed, and depth of hole have been considered as drilling parameters. ANOVA analysis has also been employed to identify most significant drilling parameter. An attempt has also been made to develop surface roughness and MRR prediction models.

Neseli, (2014) optimized the drilling parameters for minimum thrust force and torque using L27 orthogonal array based Taguchi methodology during the drilling of AISI 1040 steel. The cutting speed, feed rate, and helix angle have been considered as drilling parameters. An attempt has also been made to investigate the effect of drilling parameters on thrust force and torque. To investigate the effect of drilling parameters on thrust force and torque, signal-to-noise ratio is employed. Analysis of variance (ANOVA) has also been used to investigate the main influencing parameter that affects the thrust force and torque. The results show that feed rate is the most significant parameter that affects the thrust force, while for torque, cutting speed has been found most significant parameters.

Siddiquee et al. (2014) used L18 orthogonal array based Taguchi methodology to optimize drilling parameters for minimum surface roughness during the drilling of AISI321 austenitic stainless steel. All the experiments have been carried out on CNC lathe machine using solid carbide cutting tool. The type of cutting fluid, speed, feed and hole-depth have been considered as process parameters. The signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) have been employed to identify the significance of process parameters and to identify most significant parameter that affect the surface roughness. The confirmation runs has also been conducted to verify the results. The results reveals that the all the process parameters significantly affected the surface roughness. The speed has been found main significant parameter that affect the surface roughness with contribution (27.02%), followed by cutting fluid (25.10%), feed (22.99%), and hole-depth (14.29%).

Sundeep et al. (2014) employed L9 orthogonal array based Taguchi methodology to optimize the drilling parameters for maximum MRR, minimum surface roughness, minimum thrust force and minimum torque during the drilling of AISI 316 austenitic stainless steel. ANOVA analysis has also been employed to investigate the main influencing parameters that affect the responses. The spindle speed, feed rate and drill diameter have been considered as drilling parameters. The results show that the cutting speed has been found main influencing parameter that affects the surface roughness and MRR. As the cutting speed increases the thrust force and torque also increases.

Tamilselvan and Raguraj (2014) used Taguchi methodology to investigate the effect of drilling parameters on thrust force, overcut, taper and circularity of the hole during the drilling of Ti-TiB composite produced by three processes of powder metallurgy namely, spark plasma sintering, hot isostatic pressing and vacuum sintering process. The Analysis of Variance (ANOVA) have also been employed to investigate the effects of parameters on response and estimation of percentage contribution, The spindle speed, feed rate, process, and drill material have been considered as process parameters.

The results show that spindle speed and feed rate have been found most significant parameters that affect the dimensional accuracy of the produce hole, on the other hand, the spindle speed and feed rate affects the thrust force. Also, as the spindle speed increases, the thrust force and over cut decreases.

A. Drilling:

In manufacturing industries, the production of holes in workpiece is a common and most important process. There are many tools and processes for producing the holes. The selection of tools and process mainly depends on type of material, the size of the hole, quantity of holes produce in given time periods. Among the many hole making process, drilling is a major and commonly use hole making process. For some of processes, drilling is the initial process, such as reaming, tapping and boring. As the drill rotates and feed into the work piece, material is removed in the form of chips that move along the fluted shank of the drill. Drilling process involves relative motion between the drill and the work piece. Generally, the drill rotates and feed into the work piece for large workpieces, but sometimes workpiece rotate and feed into the drill. Figure 2.1 show the drilling process in which the drill is fed into the workpiece.

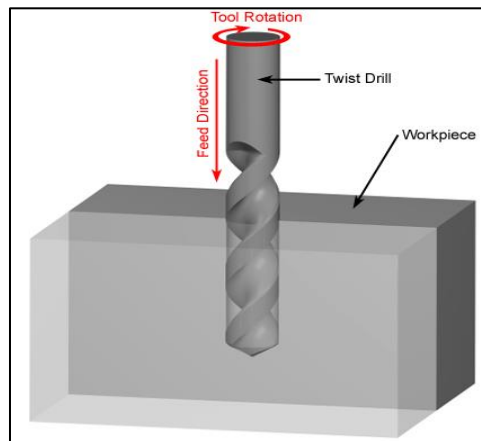


Fig. 1: Drilling Process

Usually, the hole diameters produced using drill are slightly larger than the diameter of drill (oversize). The amount of oversize depends on the selection of drill, on the machine and on the skill of machine operator.

B. MATERIAL REMOVAL RATE (MRR)

Understanding of material removal concept (MRR) in metal cutting is very important in designing process and cutting tool selection to ensure the quality of the product (Shet and Deng, 2000). The material removal rate (MRR) in turning operations is the volume of material/metal that is removed per unit time in mm^3/min . For each revolution of the work piece, a ring shaped layer of material is removed. The following are the derivation of important machining parameters:

C. Spindle Speed:

The spindle speed is measure in revolutions per minute (RPM). It is the rotational frequency of the spindle. Too much spindle speed will cause early tool wear and breakage. The spindle speed significantly affects the tool life and the quality of the surface roughness.

From the equation of spindle speed (n) to achieve a specific cutting speed can be expressed as Eq. (1).

$$N = Kv/\pi d \quad (1)$$

If N is spindle speed in revolutions/minute (rpm), k is a constant to correct the cutting speed (V) and V is the desired cutting speed, and D is diameter of the tool.

D. Feed Rate

The feed rate is a velocity at which the cutter is feed into the workpiece. It is given in units of distance per revolution for turning, milling and other machining process that required cutting of a work piece.

$$f = N * f_r \quad (2)$$

III. EXPERIMENTAL DETAILS

In this experimental work, which includes selection of drilling parameters, selection of range of drilling parameters, formation of design matrix using RSM based on face centred design, selection of work-piece material, experimental set-up, measurement of surface roughness.

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) Depth of hole (mm)

These are the main drilling parameter that affect the surface roughness. 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 face centered design.

Table - 1
Drilling Parameters and Their Levels

Factor	Name	Units	Type	Minimum (+1)	Maximum (-1)
A	Spindle Speed	(RPM)	Numeric	400	1200
B	Feed	(mm/rev)	Numeric	0.01	0.02
C	Depth of hole	(mm)	Numeric	10	20

B. Machining Trial:

Experiments were conducted using the design of experiments (DOE) technique RSM based on face centered design with and then followed by optimization of the results using Analysis of Variance (ANOVA) to find minimum surface roughness. The ranges of machining conditions were based on the real industry practice for AISI die steel. Total 20 numbers of experiments has been finalized according to RSM based on face centered design. Out of 20 experiments, 8 are the factorial points, 6 are the star point and 6 are the centre points. The table 3.2 shows the design layout for experimentation

Table – 2
Design Layout for Experimentation

S.No.	A:Spindle Speed (RPM)	B:Feed (mm/rev.)	C:Depth of hole (mm)
1	400	0.01	10
2	1200	0.01	10
3	400	0.02	10
4	1200	0.02	10
5	400	0.01	20
6	1200	0.01	20
7	400	0.02	20
8	1200	0.02	20
9	400	0.015	15
10	1200	0.015	15
11	800	0.01	15
12	800	0.02	15
13	800	0.015	10
14	800	0.015	20
15	800	0.015	15
16	800	0.015	15
17	800	0.015	15
18	800	0.015	15
19	800	0.015	15
20	800	0.015	15

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

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 with two flute has been used for experimentation.

3) Coolant:

Coolant has been used in all the experiments. SUPERCUT cutting oil has been used in the ratio of 20:1 i.e 20 litres of water and 1 litre of cutting oil in it. Physical properties of cutting oil are summarized in Table 3.4.

Table 3.3 Physical properties of SUPERCUT- cutting oil

D. Evaluation of MRR:

$MRR = (\text{volume of the material removed} / \text{time taken in minute}) \text{ mm}^3/\text{min}$

$MRR = (\text{Area of hole} * \text{depth of hole}) / \text{time taken}$

The volume of material removed is calculated as

$$\text{Volume} = (\pi/4) * d^2 * L \text{ mm}^3$$

d=Dia of hole and L = depth of hole.

The table 3.6 shows the final value of MRR along with run number.

Table – 3
Measurement Results

S.No.	A:Spindle Speed (RPM)	B:Feed (mm/rev.)	C:Depth of hole (mm)	MRR (mm ³ /min)
1	400	0.01	10	417
2	400	0.015	15	741
3	800	0.01	15	679
4	400	0.02	20	1038
5	800	0.02	15	1298
6	800	0.015	10	954
7	800	0.015	15	956
8	1200	0.02	10	1475
9	800	0.015	15	941
10	1200	0.02	20	1487
11	800	0.015	15	958
12	1200	0.015	15	1167
13	800	0.015	15	939
14	400	0.02	10	1081
15	400	0.01	20	439
16	1200	0.01	10	897
17	1200	0.01	20	892
18	800	0.015	20	940
19	800	0.015	15	943
20	800	0.015	15	954

IV. DEVELOPMENT OF METAL REMOVAL RATE (MRR) PREDICTION MODEL

To develop the metal removal rate (MRR) prediction model in terms of spindle speed, feed and depth of hole, the measure value of MRR along with the run order 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 MRR is shown in figure.4.1. 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 MRR plot. 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.

A graph of the actual MRR values versus the predicted MRR values is shown in figure 4.2. The figure reveals that all the data points split evenly by the 45 degree line.

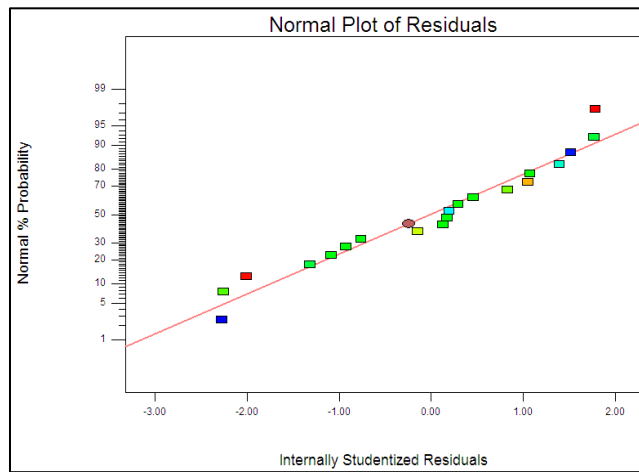


Fig. 2: Normal Probability Plot of Residuals for MRR

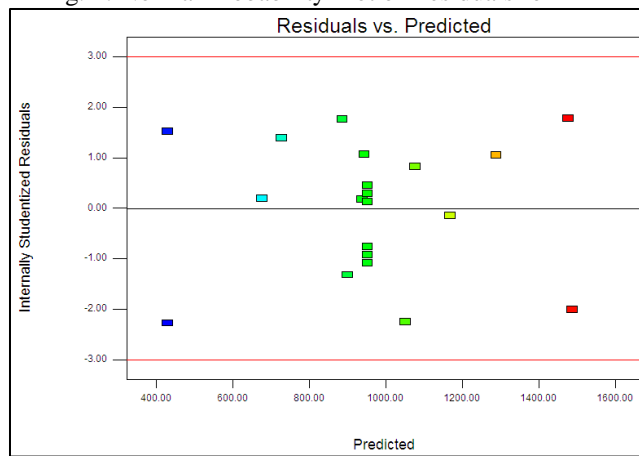


Fig. 3: Plot of Residuals v/s Predicted MRR

B. ANOVA Analysis for MRR:

The ANOVA was carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. The ANOVA for MRR is summarized in Table 4.1.

Table – 4
Resulting ANOVA Table for MRR

Source	Sum of squares	Degree of freedom	Mean square	F-Value	p-value	Prob > F
Model	1422439.25	9	158048.806	918.918	< 0.0001S	
A-Spindle Speed	484880.40	1	484880.400	2819.161	< 0.0001	
B-Feed	933302.50	1	933302.500	5426.349	< 0.0001	
C-Depth of hole	78.40	1	78.400	0.456		0.5149
AB	1012.50	1	1012.500	5.887		0.0357
AC	98.00	1	98.000	0.570		0.4677
BC	288.00	1	288.000	1.674		0.2247
A ²	49.14	1	49.142	0.286		0.6047
B ²	2520.20	1	2520.205	14.653		0.0033
C ²	346.64	1	346.642	2.015		0.1861
Residual	1719.95	10	171.995			
Lack of Fit	1366.45	5	273.289	3.865		0.0821NS
Pure Error	353.50	5	70.700			
Cor Total	1424159.20	19				
Std. Dev.	13.115					R-Squared 0.999
Mean	959.800					Adj R-Squared 0.998

C.V. %	1.366		Pred R-Squared	0.984
PRESS	23066.916		Adeq Precision	113.981

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. In the same manner, the value of “Prob. > F” for main effect of spindle speed, feed and two-level interaction of spindle speed and feed and second order term of feed are less than 0.05 so these terms are significant model terms.

Table – 5
Reduce ANOVA Table for MRR

Source	Sum of squares	Degree of freedom	Mean square	F-Value	p-value	Prob > F
Model	1421400.40	4	355350.1	1932.091		< 0.0001S
A-Spindle Speed	484880.40	1	484880.4	2636.366		< 0.0001
B-Feed	933302.50	1	933302.5	5074.503		< 0.0001
AB	1012.50	1	1012.500	5.505		0.0331
B^2	2205.00	1	2205.000	11.989		0.0035
Residual	2758.80	15	183.920			
Lack of Fit	2405.30	10	240.530	3.402		0.0944NS
Pure Error	353.50	5	70.700			
Cor Total	1424159.20	19				
Std. Dev.	13.562				R-Squared	0.998
Mean	959.800				Adj R-Squared	0.998
C.V. %	1.413				Pred R-Squared	0.996
PRESS	6278.633				Adeq Precision	155.054

Table 4.2 shows the reduce ANOVA table for MRR after the elimination of insignificant model terms using forward 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 and two-level interaction of spindle speed and feed and second order term of feed are less than 0.05 so these terms are still significant model terms.

The R2 value is equal to 0.998 or close to 1, which is desirable. The adjusted R2 value is equal to 0.998. The result shows that the adjusted R2 value is very close to the ordinary R2 value. Adequate precision value is equal to 155.05; 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. MRR Prediction Model:

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

$$MRR = 949.3 + 220.2 * A + 305.5 * B - 11.25 * A * B + 21 * B^2 \tag{4.3}$$

While, the following quadratic equation is the empirical model in terms of actual factors

$$MRR = -286.1 + 0.0635 * Spindle\ speed + 40400 * Feed - 5.625 * Spindle\ speed * Feed + 840000 * Feed^2 \tag{4.4}$$

V. RESULTS AND ANALYSIS

The results of the machining experiment for, MRR were as tabulated in Table 5. The complete results of the 20 experiments performed as per the experimental plan were input into the Design Expert 8.0.7.1 software for further analysis. The MRR was plotted based on the experiment measurements.

A. Effect of Drilling Parameters on MRR:

The effect of spindle speed on MRR at constant feed (0.015 mm/rev.) and constant depth of hole (15mm) is shown in figure 5.1.

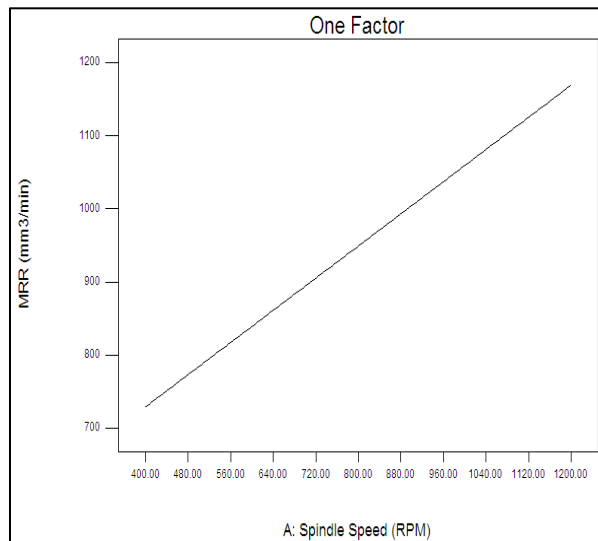


Fig. 4: Plot Between Spindle Speed On MRR At Constant Feed (0.015 Mm/Rev.) And Constant Depth Of Hole (15mm)

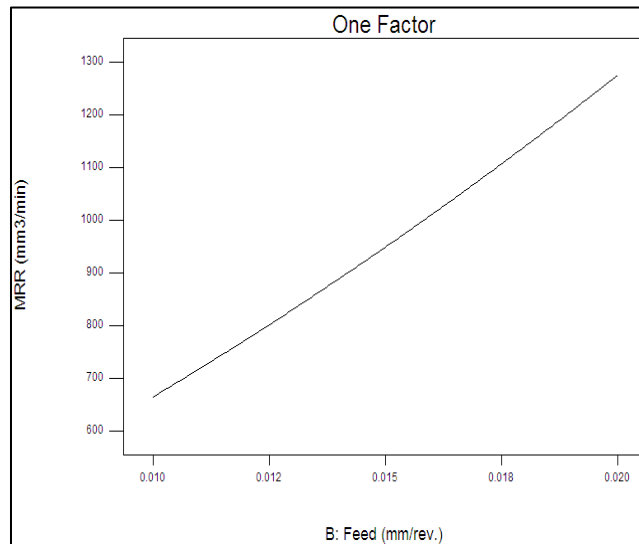


Fig. 5: Plot Between Feed On MRR At Constant Spindle Speed (800 RPM) And Constant Constant Depth Of Hole (15mm).

The plot 5.2 shows that the MRR increases with continuous increase in spindle speed from 400 RPM to 1200 RPM.. As the spindle speed increases the heat generated in the shear zone cannot be conducted away during the very short interval of time, the temperature rise softens the material, that's results increase in MRR. Also as the spindle speed increase, tool traverses the work piece also increases, resulting high MRR.

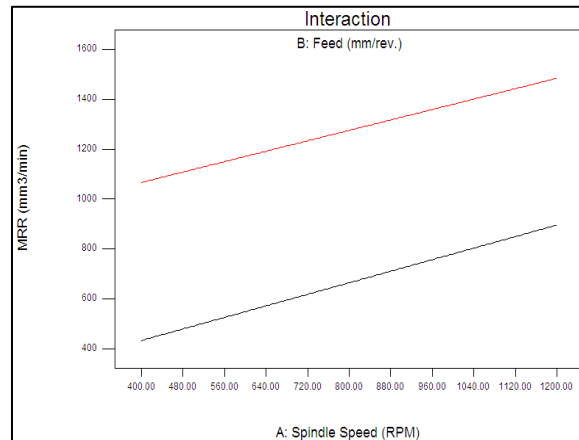


Fig. 6: Interaction Plot For MRR Between The Spindle Speed And Feed At Constant Depth Of Hole (15 Mm).

From the plot 5.3 it is clear that as feed increases the MRR also increases. This is due to the fact that, as feed increases, the maximum chip thickness also increased, hence MRR also increases. Also, at higher feed rate, tool traverses the work piece too fast, resulting high MRR.

The figures 5.4 show the 3 D plots for MRR. From the 3D plots it is clear that MRR increases with increase in spindle speed as well as with increase in feed. The maximum MRR is achieved at high feed and high spindle speed.

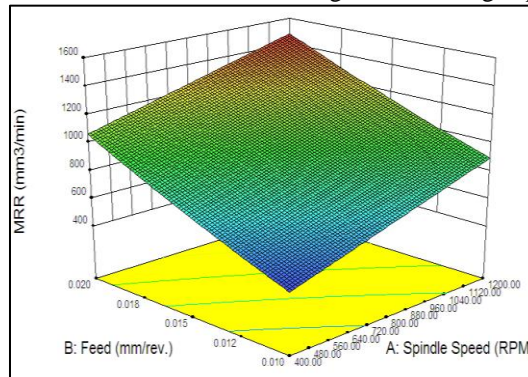


Fig. 7: 3D Plots For MRR Between Spindle Speed And Feed At Constant Depth Of Hole (15 Mm)

B. Optimization of Drilling Parameters for Maximum MRR:

In the present study, the aim is to obtain the optimal values of drilling parameters for minimum maximum metal removal rate. The constraints used during the optimization process are summarized in Table 5.1. The optimal solutions are reported in table 5.2 and 5.3.

Table – 6
Constraints for Optimization of Drilling Parameters

Name	Goal	Lower limit	Upper limit
A: Spindle Speed (RPM)	is in range	400	1200
B: Feed (mm/rev.)	is in range	0.01	0.02
C: Depth of hole (mm)	is in range	10	20
Surface roughness (Microns)	minimize	0.841	2.46

Table – 7
Optimization Results for MRR

S. No.	Spindle Speed (RPM)	Feed (mm/rev.)	MRR (mm ³ /min)	Desirability	Remarks
1	1200.00	0.020	1484.75	0.997	Selected

VI. CONCLUSION

Experimental results demonstrate that the optimal condition of the responses cannot be achieved simultaneously with a particular combination of control parameters settings because the optimum condition of the Drilling process is concerned with minimizing surface roughness. For instance, the optimum Ra is obtained at highest level of cutting speed,. To acquire a minimal surface finish of workpiece, cutting speed should be set as high as possible and the feed rate should be set as low as possible. The important conclusions drawn from the present work are summarized as follows:

- 1) MRR increases with increase in feed, increase in spindle speed while with depth of hole have no effect on MRR.
- 2) The Maximum MRR 1484.75 mm³/min has been obtained at spindle speed 1200 RPM, and feed 0.020 mm/rev.
- 3) Out of three independent parameters (spindle speed, feed and depth of hole), spindle speed and feed have been found significant drilling parameters for MRR while depth of hole has been found insignificant parameter.
- 4) The mathematical prediction model between MRR and drilling parameters, has been developed. The predicted results are in good agreement with the measured ones. These relationships are applicable within the ranges of tested parameters.
- 5) The MRR prediction model clearly shows that the feed seems to be the most significant factor that affects the MRR.
- 6) The quadratic effect of spindle feed has also been appears for MRR.

In this study mathematical modeling and optimization has been attempted only for two response variable. The work can be extended to consider more response variables. Also, more parameters such as point angle, type of drill, diameter of hole, type of materials etc. can be introduced to have a better insight into the process.

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