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PREDICTION AND OPTIMIZATION OF SURFACE ROUGHNESS BY COUPLED STATISTICAL AND DESIRABILITY ANALYSIS IN DRILLING OF MILD STEEL

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ABSTRACT: Surface roughness is a very important parameter for determining the quality of any material which has undergone some machining processes. Now a day in different process and assembly industries the quality measure of the products or required equipments has to satisfy certain level in order to ensure good quality. Also in modern competitive market the cost per unit product is one crucial point which in many cases determines the survivability of the industry. Again quality of the product is something which must be integrated in the product in line with the reduction of cost. Now that's why it is very much important to identify the dominating process parameters which, if can be optimized; the best product with minimum manufacturing cost can be achieved. With this goal, the authors of this paper investigated the effect of different process parameters for a vertical CNC drilling machine in order to identify the most dominating factor for surface roughness. A mathematical model is developed for a certain range of operational condition for predicting the surface roughness of the drilled hole. Response surface methodology (RSM) was employed for the whole experimental design. Statistical tools are used for best fitting the developed model and desirability analysis is coupled with it in order to find out the optimum cutting condition for which minimum surface roughness is achieved.
KEYWORDS: machining processes, surface roughness, surface methodology (RSM)

INTRODUCTION

Drilling is one of the machining processes which are widely used for various purposes. Now a day it is frequently used in automotive, aircraft and aerospace and dies or mold industries, home appliances, medical and electrical equipment industries [1]. As a very important process in different process and manufacturing industry drilling process needs to be cost effective along with the assurance of the quality specifications within the experimental limit. Among various performance parameters for drilling process surface roughness, drill hole quality, tool wear etc are very much important in terms of the quality characteristics of the finished product. Among them surface roughness is of crucial importance due to its effect on some important mechanical properties of the material like fatigue behavior, corrosion resistance, creep life etc. Some other functional attributes of the material such as friction, wear, heat transmission, light reflectivity, lubrication property, electrical conductivity etc are also affected by the surface roughness of the finished part [2]. That's why the study and optimization of surface roughness in drilling has got research interest by the researchers.

WUSM [3] first pioneered the use of Response Surface Methodology for testing of tool life. Yogendra Tyagi et al [4] has experimented the drilling of mild steel with the help of CNC drilling machining operation with tool as high speed steel by applying Taguchi method. They applied L9 orthogonal array and analysis of variance (ANOVA) to study the performance characteristics of machining parameter (spindle speed, feed, depth) keeping in consideration of good surface finish and high material removal rate (MRR). The results they obtained by taguchi method and signal-to-noise ratio match closely with ANOVA. They also found out that the feed is most effective factor for MRR and spindle speed is the most effective factor for surface roughness. Upinder Kumar Yadav et al. [5] investigated the effect and optimization of machining parameters (cutting speed, feed rate and depth of cut) on surface roughness. An L'27 orthogonal array, analysis of variance (ANOVA) and the signal-to-noise (S/N) ratio are used in this study. Three levels of machining parameters are used and experiments are done on CNC lathe. In this study they found that feed rate is the most effective factor affecting surface roughness followed by depth of cut. Cutting speed is the least significant factor affecting surface roughness. Ferit Ficici et al.[6] investigated the optimum cutting parameters *when drilling an AISI 304 stainless steel using modified HSS drill tools. In their paper, the Taguchi technique and analysis of variance (ANOVA) are applied for minimization of surface roughness (Ra) influenced by drilling cutting parameters. The optimum drilling cutting parameter combination was obtained by using the analysis of signal-to-noise ratio. They concluded that modification of drill and feed rate were the most influential factors on the surface roughness (Ra).*

Anayet U Patwari, M.D. Arif et al.[7] introduced a new innovative technique to determine the surface roughness of any machined surface by digital image processing which was further verified by using profilometer and was proved to be very fruitful in determining the Ra value with minimum error. This technique has been used for this study. Anayet.U Patwari et al. [8] determined the surface roughness of shaped and horizontally milled surface by image processing. B. Sidda Reddy et al. [8] investigated on the study of minimization of surface roughness by integrating design of experiment method, Response surface methodology (RSM) and genetic algorithm. They did the experiment using Taguchi's L50 orthogonal array in the design of experiments (DOE) by considering the machining parameters such as Nose radius (R), Cutting speed (V), feed (f), axial depth of cut (d) and radial depth of cut(rd). Funda Kahraman [9] in his paper utilized regression modeling in turning process of AISI 4140 steel using Response Surface Methodology (RSM) with rotatable Central Composite Design (CCD). A quadratic model was developed for the prediction and analysis of the relationship between the cutting conditions and surface roughness. In this particular study, a coupled technique with combination of statistical approach and desirability analysis has been used for the optimization and prediction of surface roughness of a drilled hole.

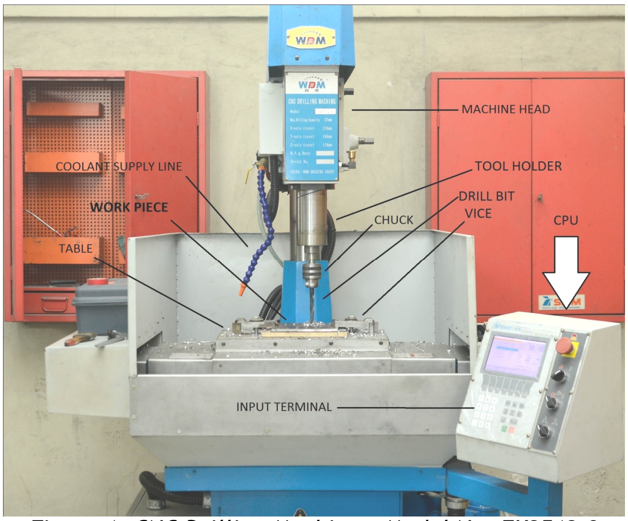


Figure 1: CNC Drilling Machine - Model No: ZK2512-3
Maximum Drill Capacity: 25 mm
X-Axis Travel: 250 mm; Y-Axis Travel: 180 mm;
Z-Axis Travel: 150 mm

EXPERIMENTAL SETUP

For conducting this study a vertical CNC drilling machine is used as shown in Figure 1. The CNC specification is given below.

For this experiment the upper limit and lower limit of the process parameters as shown in Table 1 are considered as follows. According to the design the cutting conditions are expressed in terms of coded factors as shown in Table 2. The sequence of the method followed in this study is shown in Figure 2.

Table 1: Range of process parameter for experiment

Process Variable	Upper Limit	Lower Limit
Spindle Speed (N) R.P.M	225	1000
Feed (f) mm/min	5	15

Table 2: Level of coding

Level of coding	Lowest $-\sqrt{2}$	Low -1	Centre 0	High +1	Highest $+\sqrt{2}$
A/ RPM	225	280.0	475	805	1000
B/Feed, mm/min	5	6	8.75	12.75	15

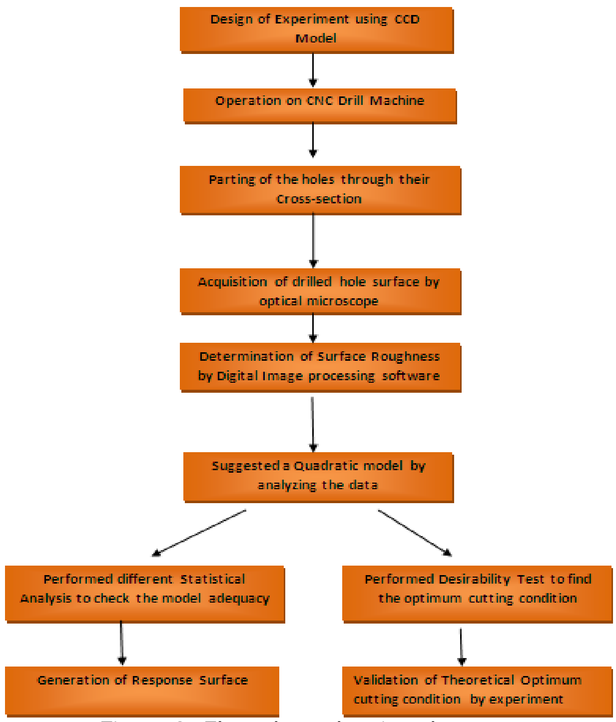


Figure 2: Flow chart showing the steps of the method followed

For determining the predictive mathematical model Central Composite Design (CCD) was used. After the experimental design the operations were performed in the drilling machine and then the drill holes were investigated to analysis the surface pattern using developed digital image processing technique.

The surface roughness is measured by using the image processing software developed by Anayet U Patwari et al. [8]. Then all the experimental data were used to fit an appropriate model for the process and desirability analysis was employed to optimize the process cutting condition for minimum surface roughness. Then another cut was undertaken for the verification of the optimum cutting condition.

DESIRABILITY FUNCTION APPROACH

Desirability function approach is powerful tools for solving the multiple performance characteristics optimization problems, where all the objectives are attained a definite goal simultaneously. The general approach is to first convert each response yi, into an individual desirability function di , that may vary over the range 0≤ di ≤1, where if the response yi meets the goal or target value, then di = 1, and if the response falls beyond the acceptable limit, then di = 0.

The next step is to select the parameter combination that will maximize overall desirability D. For each response Yi(x), a desirability function di(Yi) assigns numbers between 0 and 1 to the possible values of Yi, with di(Yi) = 0 representing a completely undesirable value of Yi and di(Yi) = 1 representing a completely desirable or ideal response value. The individual desirability is then combined using the geometric mean, which gives the overall desirability D:

$$D= (d1(y1)*d2(y2)*d3(y3)*\ldots\ldots\ldots*dk(yk))^{\wedge}(1/k)$$

where, k is the total number of responses. If any response is totally undesirable then (di(yi)=0) then the overall desirability is zero(D=0)

RESULTS AND DISCUSSION

After taking all the surface pictures by the optical microscope with a 10x10 magnification the pictures were used for further analysis by developed image processing software in order to determine the surface roughness (Ra) value. The Ra value for each drilling condition is determined, which is given in table 3.

Table 3: Average surface roughness (Ra) value determined by the developed method [8]

Experimental Order	Type	Factor A-A; Spindle speed	Factor B-B; Feed	Surface Roughness, micro-m
1	Factorial	-1.00	-1.00	0.96
2	Factorial	1.00	-1.00	0.89
3	Factorial	-1.00	1.00	0.91
4	Factorial	1.00	1.00	0.86
5	Centre	0.00	0.00	0.78
6	Axial	-1.41	0.00	0.99
7	Axial	1.41	0.00	0.90
8	Axial	0.00	-1.41	0.86
9	Axial	0.00	1.41	0.93
10	Centre	0.00	0.00	0.80

Table 4: Sequential Model Sum of Squares

Source	Sum of Squares	DF	Mean Square	F Value	Prob>F	Comment
Mean	0.23	1	0.23			
Block	5.934E-003	1	5.934E-003			
Linear	9.323E-003	2	4.662E-003	0.69	0.5279	
2FI	9.216E-005	1	9.216E-005	0.012	0.9158	
Quadratic	0.048	2	0.024	21.05	0.0037	Suggested
Cubic	4.930E-003	2	2.465E-003	9.54	0.0501	Aliased
Residual	7.751E-004	3	2.584E-004			
Total	0.30	12	0.025			

Table 5: Lack of Fit Tests - Model Summary Statistics

Source	Sum of Squares	DF	Mean Square	F Value	Prob>F	Comment
Linear	0.053	6	8.849E-003	24.01	0.0405	
2FI	0.053	5	0.011	28.76	0.0339	
Quadratic	4.968E-003	3	1.656E-003	4.49	0.1874	Suggested
Cubic	3.792E-005	1	3.792E-005	0.10	0.7788	Aliased
Pure Error	7.372E-004	2	3.686E-004			

Table 6: Model Summary Statistics

Source	Std. Dev.	R-squared	Adjusted R-squared	Predicted R-squared	PRESS	Comment
Linear	0.082	0.1476	-0.0655	-0.7919	0.11	
2FI	0.088	0.1491	-0.2156	-2.0118	0.19	
Quadratic	0.034	0.9097	0.8193	0.0074	0.063	Suggested
Cubic	0.016	0.9877	0.9591	0.8357	0.010	Aliased

Table 7: ANOVA for Response Surface Quadratic Model: Analysis of variance table [Partial sum of squares]

Source	Sum of squares	DF	Mean Square	F-value	Prob > F	Comment
Block	5.934E-003	1	5.934E-003			
Model	0.057	5	0.011	10.07	0.0121	significant
A	9.258E-003	1	9.258E-003	8.11	0.0359	
B	6.548E-005	1	6.548E-005	0.057	0.8202	
A^2	0.040	1	0.040	35.32	0.0019	
B^2	0.017	1	0.017	15.14	0.0115	
AB	9.216E-005	1	9.216E-005	0.081	0.7877	
Residual	5.705E-003	5	1.141E-003			
Lack of Fit	4.968E-003	3	1.656E-003	4.49	0.1874	not significant
Pure Error	7.372E-004	2	3.686E-004			
Core total	0.069	11				

Sequential model sum of squares, lack of fit tests and model summary statistics are tabulated in Table 4, 5 and 6 respectively. From the results, it has been observed that Quadratic model is suggested for the prediction of surface roughness.

ANOVA for Response Surface Quadratic Model are tabulated in Table 7. The Model F-value of 10.07 implies the model is significant. There is only a 1.21% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant.

Final Equation of The model in Terms of Actual Factors:

$$Ln(surface\ roughness) = -0.22587-(0.034018*A)+(2.86094E-003*B)+(0.080784*A^2)+(0.052881*B^2)+(4.79990E-003*A*B)$$

Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 4.49 implies the Lack of Fit is not significant relative to the pure error. There is a 18.74% chance that a "Lack of Fit F-value" this large could occur due to noise. Lack of fit is for this particular model is non-significant.

The above Ffigure 3 shows that predicted (natural logarithmic) values of surface roughness are plotted against the actual natural logarithmic values of surface roughness. The model shows uniform deviation from the actual values. Thus a quadratic second order model is suggested and proves to be more accurate in predicting the surface roughness values.

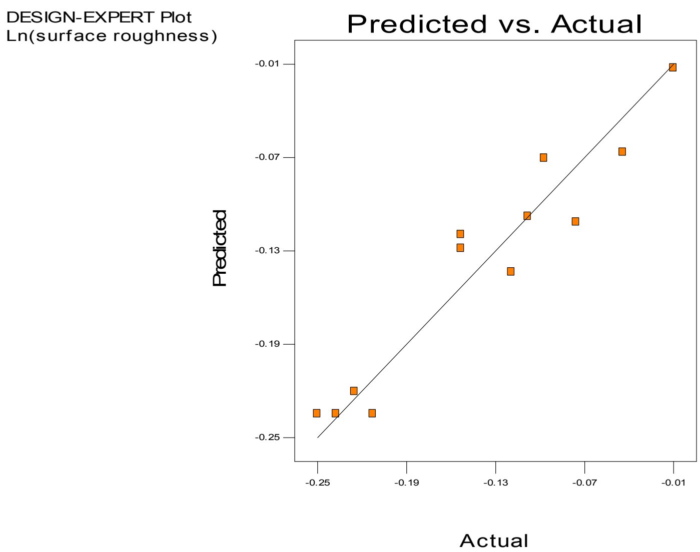


Figure 3: Predicted Vs. Actual Surface Roughness curve against each cutting condition

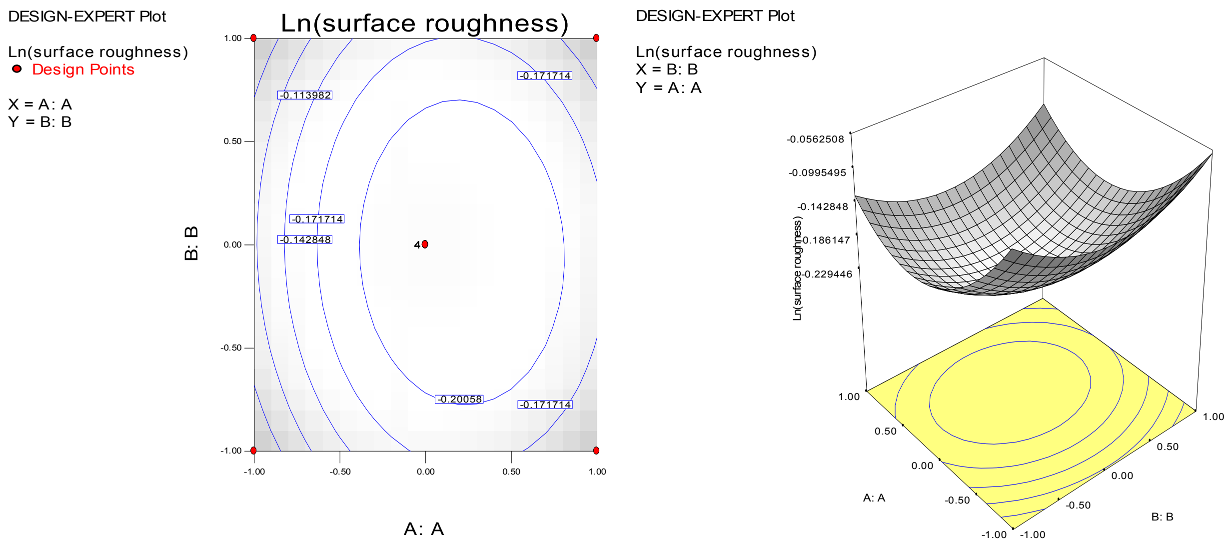
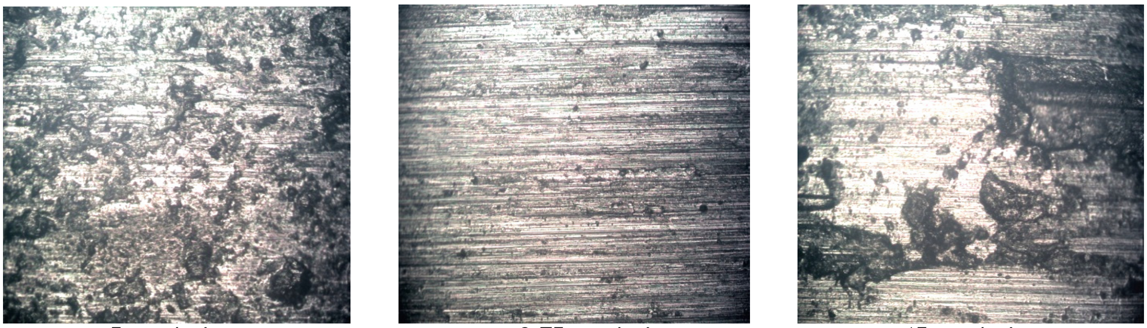


Figure 4: (a) 2-D response surface (b) 3-D response surface

Figure 4(a) shows the two dimensional response surface of surface roughness. It shows the effect of both the cutting speed and feed rate on the surface roughness of the drilled hole surface. The response surface shows that the minimum value of surface roughness is obtained for the increase in cutting speed and decrease in feed rate within our chosen experimental limit of process parameters. Figure 4(b) is the representation of three dimensional contour profiles for the response of surface. It shows the effect of both the cutting speed and feed rate on the surface roughness of mild steel on CNC drilling.

For the observation of feed effect on surface roughness three experiments were conducted keeping the spindle speed constant (475 r.p.m). The microscopic view of the drilled hole is shown in Figure 5 at different feed. From the above pictures the effect of feed rate on surface roughness s clearly shown. It has been observed that there is certain range of feed rate within which the surface roughness will be the minimum.



5 mm/min 8.75 mm/min 15 mm/min

Figure 5 : Effect of feed on drilled hole surface (microscopic)

RESULT OF DESIRABILITY TEST

Desirability function approach was adopted in order to find out the probability of the minimum surface roughness within the range predicted by response surface method (RSM). If the desirability value is greater than 0.9 the values of process parameters was considered to be the optimum for giving minimum surface roughness. Following table 8 shows the parameters and results of desirability function.

Table 8: Desirability test

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A	is in range	-1.414	1.414	1	1	3
B	is in range	-1.414	1.414	1	1	3

Table 9: Solution

Number	A	B	Ln(surface roughness)	Desirability	
1	0.21	-0.04	-0.230	0.922	Selected

Now putting the value of coded 'A' and 'B' predicted by the desirability analysis the following equations for the prediction of optimum value of spindle speed and feed rate was calculated:

$$A = \frac{\ln V - \ln A_0}{\ln A_1 - \ln A_o} \qquad B = \frac{\ln a - \ln B_0}{\ln B_1 - \ln B_o}$$

Converting the predicted coded value in to actual values the following optimum cutting condition has been obtained for minimum surface roughness as shown in Table 9.

Table 10: Optimum Cutting Condition derived from desirability test

Optimum Cutting Speed (V)	Optimum Feed Rate (a)
530.6462341	8.61922

EXPERIMENTAL VALIDATION

For experimental validation of the optimum condition another drill is made and in the same procedure and the surface roughness value is determined. It has been found that the surface roughness value is same as predicted by the analysis. The natural logarithmic value of the minimum surface roughness is -0.23 (coded) which gives the minimum surface roughness value to be 0.79 micro-m. The surface texture of the drilled hole in optimized cutting condition is shown in Figure 6.

Figure 6: Drill hole for validation of optimization model

From the experiment, it has been observed that the calculated and the experimental values show good agreement.

CONCLUSIONS

The following conclusions were drawn from the work:

- *A mathematical model was developed for prediction and optimization of surface roughness of mild steel for drilling in CNC drill machine.*
- *The developed model was coupled with desirability function approach in order to find out the optimum cutting condition within the range.*
- *The model developed shows good agreement with the experimental one.*
- *The cutting parameters like spindle speed and feed has significant effect on surface roughness.*
- *The general tendency shows that with the feed variation the surface roughness increased but with the increase of spindle speed the surface roughness is less and as the speed decreases the surface roughness increases.*

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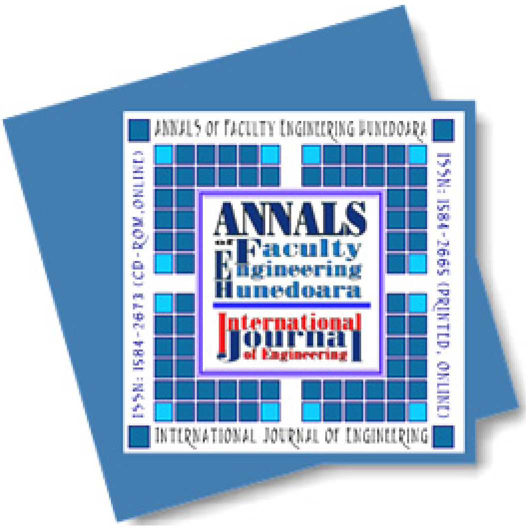

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