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Optimal Machining Condition for Turning of Hard Porcelain using Response Surface Methodology

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ABSTRACT

This paper presents the effect of cutting parameters on material Hardness and Pressure during turning of Hard Porcelain Material on CNC turning machine (SINUMERIK802D) at different level. In this work, all the cutting parameters namely, Spindle speed, feed rate, angle of cut and depth of cut are modeled using Response surface methodology (RSM). The impact of Spindle speed, feed rate, angle of cut and depth of cut on the material Hardness and Pressure is examined. Finally, the result of developed mathematical model is examined by ANOVA. From the basis of experimented results, it indicates that the angle of cut and depth of cut is the leading parameters that affect the Hardness and Pressure of material, which can be diminished when the angle of cut and depth of cut were kept at the lower level, while spindle speed and feed rate were kept at the highest level. The effect of spindle speed and feed rate were found to be insignificant as compared to the other factors.

Key words: Hard Turning **(**SINUMERIK802D), Machining parameters, RSM, ANOVA

INTRODUCTION

Turning is one of the most important machining methods used to shaping the metals because turning has a wide range of operating conditions. Conventional turning employs a unique behaviour, which is different from hard turning. In today's market every industry planned their manufacturing process to meet either maximum quality or minimum cost of their product. The Material Hardness and Pressure can be considered as the most important factor form the point of view of manufacturing industries for better product quality and its wide range of functioning in industries [1]. Based on customer demand, it is important to maintain the Material Hardness and Pressure as per requirement for better quality, minimum cost of product. It is a characteristic that improve the performance of mechanical parts as well as production cost of the product [2]. Manufacturing products have two most significant problems these are process modelling and optimization. The manufacturing processes are characterized by multiplicity of dynamically interacting process variables [3]. In recent years various significant advantages have been finding in cutting tool and machine tool. Many surface roughness modelling, simulation and optimization system were designed by using different cutting parameters and optimization methods. Some of literature studies are as follows.

In [4], Gupta et al conducted the effect of process parameters like cutting speed, feed rate and different cooling conditions (i.e. dry, wet and liquid nitrogen used as a coolant) on tool wear (crater and flank wear) in machining of EN24 alloy steel using uncoated tungsten carbide insert tool. Mathematical models for crater and flank wear are found to be statistically significant. Cicek et al [5] conducted the effects of cryogenic treatment and drilling parameters on surface and hole quality were investigated in the drilling of AISI 304 stainless steel under dry drilling conditions. The predictive quadratic models were derived by the RSM to obtain the optimal surface roughness and roundness error as a function of drilling parameters and heat treatments applied to the drills. The Optimization of machining parameters considering multiple responses flank wear, surface roughness and material removal rate (MRR) simultaneously are performed Senthikumar et al [6] by using response surface methodology (RSM). Manimaran et al [7] conducted the grinding experiments on stainless steel AISI 316 in three environments namely dry, wet and cryogenic cooling. The results revealed the reduction in the grinding zone temperature leading to excellent benefits in the machining performance. The surface roughness under cryogenic cooling decreased as compared to dry and wet cooling.

In [8], Campoceco et al presents an experimental study related to the optimization of cutting parameters in roughing turning of AISI 6061 T6 aluminium. Energy consumption and surface roughness were minimized, while the material removal rate of the process was maximized. Latha et al [9] carried out a prediction of surface roughness in drilling of composite materials using fuzzy logic rule–based modelling and ANOVA analyses. The experiments were conducted on a CNC drilling machine. The data for surface roughness were collected under different cutting conditions for various arrangements of spindle speeds, feed rates and drill diameters. They found good agreement between the model results and experimental values. Palanikumar et al [10] modelled the delamination factor and surface roughness in machining of GFRP composites through response surface methodology. Three-factor five-level central composite design was engaged in his study. The results of analysis of variance show that the developed models were adequate at 95% confidence level within the limits of factors being considered. Sun et al [11] concerned with the influence of design variables and different design conditions such as objective functions and constraints on the rotor enactment. RSM based on D-optimal 3-level factorial design and genetic algorithm was used to obtain the optimum solution of a defined objective function including the penalty terms of constraints. Wiper inserts are increasingly being utilized in past years. The impacts of the wiper inserts on the surface roughness were described in turning by Correia et al [12] Using with wiper inserts and high feed rate, was obtained machined surfaces with Ra < 0.8 µm.

The Hardness (HR) and Pressure (P) have been identified as quality aspects and are assumed to be directly related to performance of mechanical sections [13]. Beside from quality, there exist another criterion called Productivity which is directly proportional to the profitability and goodwill of an organization. For these reasons, there has been research and development with an aim of optimizing cutting conditions to obtain desired machining results. To optimize the process, Response surface methodology (RSM) are now widely used to determine a suitable polynomial equation for describing the response surface in place of one factor at one time experimental approach which is time consuming and exorbitant in cost. Response surface methodology (RSM) is a pool of statistical and mathematical methods that are useful for modelling and analysing engineering problems. Using RSM for analysing and optimization provides an operative tool for determining the factors affecting the desired response if there are number of factors and interactions in the experiment [14].

The key objective of present work is to identify the efficient optimal cutting parameter for multiple quality characteristics by using the Hardness and Pressure values (HR and P) as multi objective functions via Response surface methodology for CNC turned Hard porcelain.

EXPERIMENTAL DETAILS

In this experimental study, the material to be machined is hard porcelain which is the combination of Quartz powder, feldspar powder, ball clay and kaolin with various chemical compositions. Examination of machined material was carried out using suitable instruments at different values as per the requirement. The dimensions of specimen were of 3000mm x 400Φ. The chemical composition of clay specimen is presented in table1. The cutting tool used is made up of Al_2O_3 (R7.5, 10^0). The dimension of Cutting tool: 15mm OD and 10^0 Angle. The machining operations are taken as per the conditions given by the design matrix randomly so as to avoid the mathematical errors. The Hardness (HR) and Pressure (P) can be taken as output in this study. The material and turning machine used in this study is shown in fig.1. The Hardness (HR) & Pressure (P) of the machine test specimen is measured using Pentometer Hardness tester and pressure gauge respectively.

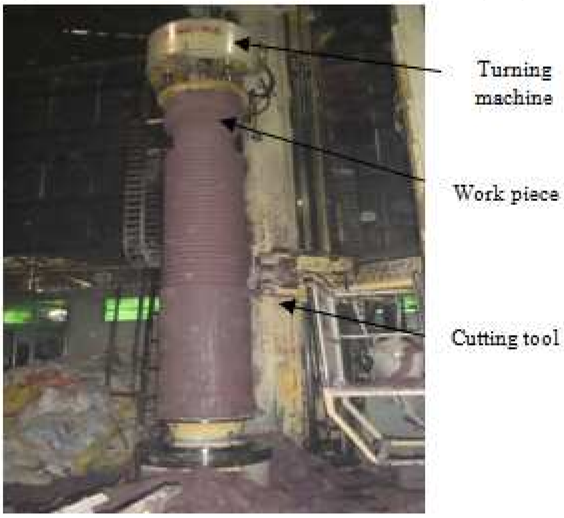

Fig 1. Experimental setup of Hard turning

Table -1 Chemical Composition of the Material

Chemical	Sio_2	Al_2O_3	KN	LiO (loss on ignition)	Fe (Iron)
Quartz Powder	99.5%	0.5%	NIL	NIL	NIL
Feldspar	70%	15%	15%	NIL	NIL
Ball clay	70%	15%	NIL	12%	3%
Kaolin	67%	18%	NIL	10%	5%

EXPERIMENTAL DESIGN

Response Surface Methodology

Response surface methodology is emphases a well- known most widely used approach on the optimization of the input parameters model. Sometimes called as independent variable is based on either physical experiments, simulation experiments or experimental observations. These models need to be evaluated statistically for their suitability and then they can be utilized for an optimization of the initial model. RSM also calculates relationship between the manageable input parameters and the achieved response surface [15]. This whole process includes six steps shown in fig. 2[16].

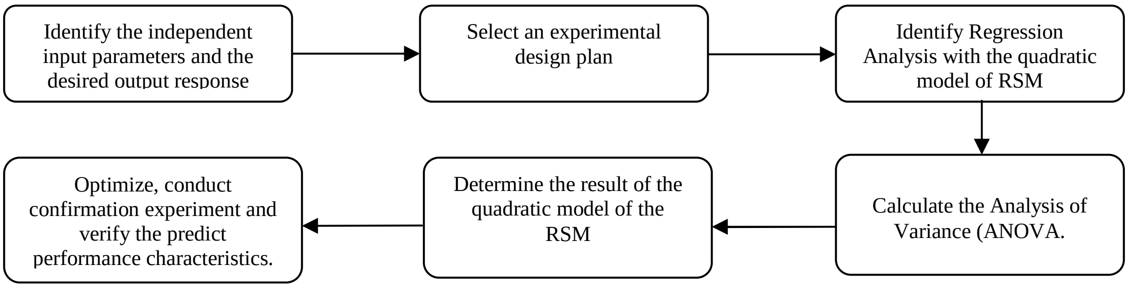

Fig. 2 Processed step of Response surface methodology

In the current study, the relationship between the input parameters, spindle speed (SS), feed rate (FR), angle of cut (AOC), depth of cut (DOC)) and the output X defined as machinability features, Hardness (HR), Pressure (P) is given as:

$$X = \Phi\ (SS, FR, AOC, DOC) \qquad (1)$$

Where Φ is the response function. At most, response surface methodology has a functional relationship between input variables and output variables and this relation can be expressed by second order polynomial equation which is given below [17, 18]:

$$\Psi = b_0 + \sum_{i=1}^{n} b_i X_i + \sum_{ij}^{k} b_{ij} X_i X_j + \sum_{i=1}^{n} b_{ii} X_i^2 \qquad (2)$$

Where Ψ is the estimate response (Hardness and Pressure), b_o is constant, b_1 , b_{11} and b_{111} represents the linear, quadratic and cross-product terms coefficients respectively. X represents the coded variables.

The common method used in RSM is regression method based on least square method. This method is usually used to identify the regression coefficient which is shown in the following equation [19].

$$b = \begin{bmatrix} b_0 \\ b_1 \\ \dots \\ \dots \\ b_r \end{bmatrix} = (X^T X)^{-1} X^T \eta = \left[\frac{1}{P} \sum_{j=1}^{k} \eta_j ,\ \frac{\sum_{j=1}^{P} x_{1j} \eta_j}{\sum_{j=1}^{P} x_{1j}^2}, \dots\dots, \frac{\sum_{j=1}^{P} x_r \eta_j}{\sum_{j=1}^{P} x_{rj}^2} \right]^T \qquad (3)$$

Where r is the number of objective function and p is the number of factor. The b term consists a set of unknown parameter that can be estimated by collecting experimental system data. These data can be collected either by physical experiments or by numerical experiments. The parameters can be selected by regression analysis based on experimental data.

EXPERIMENTAL PROCEDURE OF TURNING

According to the literature survey and on the basis of specification of material, finally the four cutting parameters and their level of experiments are selected in this work. These parameters are spindle speed (SS), feed rate (FR), angle of cut (AOC) and depth of cut (DOC). The experimental conditions have been given in the Table 2.

Table -2 Cutting Parameters and their Levels

Symbol	Factors	Units	Level 1	Level 2	Level 3
SS	Spindle speed	m/min.	200	250	300
FR	Feed rate	mm/rev.	7	9	11
AOC	Angle of cut	Degree	0	5	10
DOC	Depth of cut	Mm	2.5	3.0	3.5

MATHEMATICAL MODELLING AND ANALYSIS

In present work, L27 Box- Behnken design of Response surface methodology is used to develop the experimental design matrix. Based on number of selected parameters, the most suitable array is L27, which needs 27 runs and has 26 degree of freedom (DOF). The developed experimental design matrix of L27 arrays is shown in Table 3. The first column of table denotes spindle speed (SS), second denotes feed rate (FR), third column denotes angle of cut (AOC), and the fourth column denotes depth of cut (DOC). The output results (values of HR and P) are shown in column fifth and sixth respectively in Table3. The impact of each control factor can be more clearly shown in fig. 3 and 4 respectively, with response graphs. These figures help to find out the ideal cutting parameters (the level with the highest point on the graphs) as well as to achieve the effect of each parameter. The line in Fig. 3 and 4, which connect between the levels can clearly show the powerful impact of each control factor. Especially, the angle of cut and depth of cut shows a strong effect on Material Hardness (HR) and Pressure (P). The cutting speed has a smaller effect which is clearly shown by Fig.3.

Table -3 Experimental Design Matrix with their Results

Exp. No.	Control factors level				Hardness (HR)	Pressure (P)
	Spindle speed (SS)	Feed rate (FR)	Angle of cut (AOC)	Depth of cut (DOC)		
1.	200	7	5	3.0	1.25	17.0
2.	300	7	5	3.0	1.40	20.4
3.	200	11	5	3.0	1.35	20.9
4.	300	11	5	3.0	1.75	21.5
5.	250	9	0	2.5	1.30	9.3
6.	250	9	10	2.5	1.45	17.6
7.	250	9	0	3.5	1.43	17.4
8.	250	9	10	3.5	1.80	21.2
9.	200	9	5	2.5	1.28	17.8
10.	300	9	5	2.5	1.60	20.2
11.	200	9	5	3.5	1.55	20.4
12.	300	9	5	3.5	1.72	21.2
13.	250	7	0	3.0	1.37	18.0
14.	250	11	0	3.0	1.44	20.1
15.	250	7	10	3.0	1.65	20.7
16.	250	11	10	3.0	1.85	21.5
17.	200	9	0	3.0	1.48	17.5
18.	300	9	0	3.0	1.41	17.8
19.	200	9	10	3.0	1.28	22.0
20.	300	9	10	3.0	1.85	22.2
21.	250	7	5	2.5	1.32	16.9
22.	250	11	5	2.5	1.46	20.1
23.	250	7	5	3.5	1.49	17.9
24.	250	11	5	3.5	1.90	22.1
25.	200	7	0	2.5	1.00	10.0
26.	200	7	10	3.5	1.47	21.2
27.	250	9	5	3.0	1.50	22.5

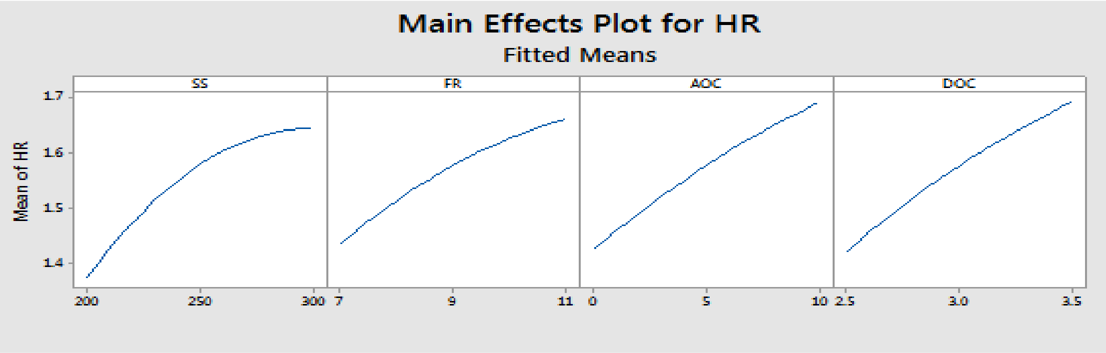

Fig.3 Effect of parameters on Hardness (HR)

Fig.4 Effect of parameters on Pressure (P)

Table -4 ANOVA of Quadratic Response Surface Design for HR

Source	DF	Adj SS	Variance	F-Value	P-Value
SS	1	0.2260	0.2260	23.03	0.000
FR	1	0.1568	0.1568	15.98	0.002
AOC	1	0.2184	0.2184	22.26	0.000
DOC	1	0.2268	0.2268	23.11	0.000
SS*SS	1	0.0200	0.0200	2.04	0.179
FR*FR	1	0.0036	0.0036	0.37	0.153
AOC*AOC	1	0.0015	0.0015	0.16	0.697
DOC*DOC	1	0.0017	0.0017	0.18	0.678
SS*FR	1	0.0083	0.0083	0.85	0.374
SS*A0C	1	0.0771	0.0771	7.86	0.016
SS*DOC	1	0.0227	0.0227	2.32	0.154
FR*AOC	1	0.0000	0.0000	0.00	0.991
FR*DOC	1	0.0059	0.0059	0.60	0.452
AOC*DOC	1	0.0057	0.0057	0.58	0.460
Error	12	0.1177	0.0098		
Total	26	1.1932			

Table -5 ANOVA of Quadratic Response Surface Design for P

Source	DF	Adj SS	Adj MS	F-Value	P-Value
SS	1	3.383	3.3835	0.90	0.360
FR	1	16.594	16.5944	4.44	0.057
AOC	1	59.253	59.2526	15.84	0.002
DOC	1	32.303	32.3032	8.63	0.012
SS*SS	1	0.107	0.1073	0.03	0.868
FR*FR	1	0.021	0.0205	0.01	0.942
AOC*AOC	1	10.429	10.4291	2.79	0.121
DOC*DOC	1	16.535	16.5352	4.42	0.057
SS*FR	1	0.516	0.5157	0.14	0717
SS*A0C	1	0.288	0.2883	0.08	0.786
SS*DOC	1	1.824	1.8236	0.49	0.498
FR*AOC	1	1.411	1.4106	0.38	0.551
FR*DOC	1	0.004	0.0036	0.00	0.976
AOC*DOC	1	2.617	2.6169	0.70	0.419
Error	12	44.896	3.7413		
Total	26	277.54			

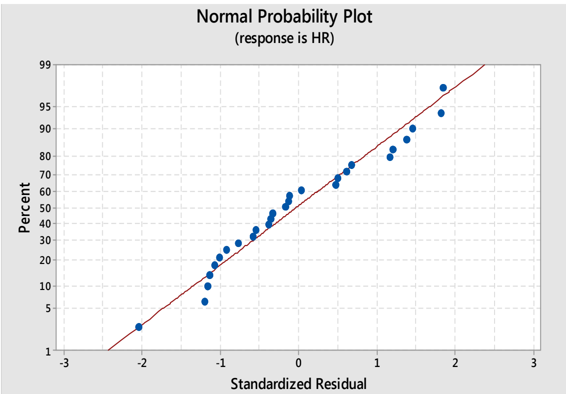

Fig.5 Normal probability plot for HR

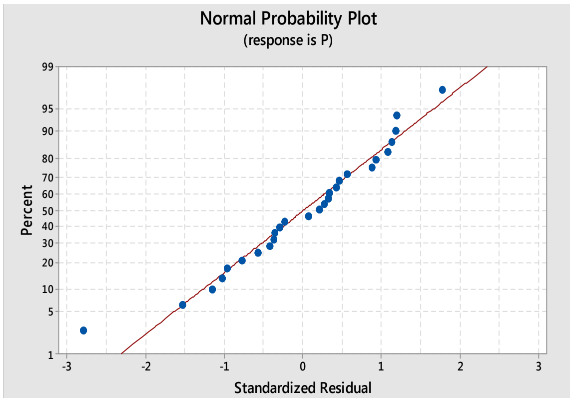

Fig.6 Normal probability plot for P

Figure 5&6 indicate that the quadratic models are proficient to represent the system under the given experimental domain. These interaction effects of variables on response parameters can be better understood by plotting on three-dimensional (3-D) surface, based on the model equation (4) and (5). Since each model had four variables, one variable was taken as constant at the centre line for each plot, therefore total of 12 response surface plots were made for the responses (Fig. 7 and 8).

Analysis of variance essentially consists of separating the total variation in an experiment into components which helps to find out the controlled factors and error. The statistical implication of parameters is evaluated by the P-value of ANOVA table. In present study Table 4 and 5 shows ANOVA result for Material Hardness and Pressure respectively. The term sum of square in ANOVA table is used to determine square of deviation from the grand mean. F-ratio is used to check the adequacy of the model in which calculated value of F should be greater than the F-table value. The model is adequate at 95% confidence Level since the F calculated value is greater than the F-table value. When the value of P from ANOVA table, is less than 0.05 (or 95% confidence), the obtained models are considered to be statistically significant [20].

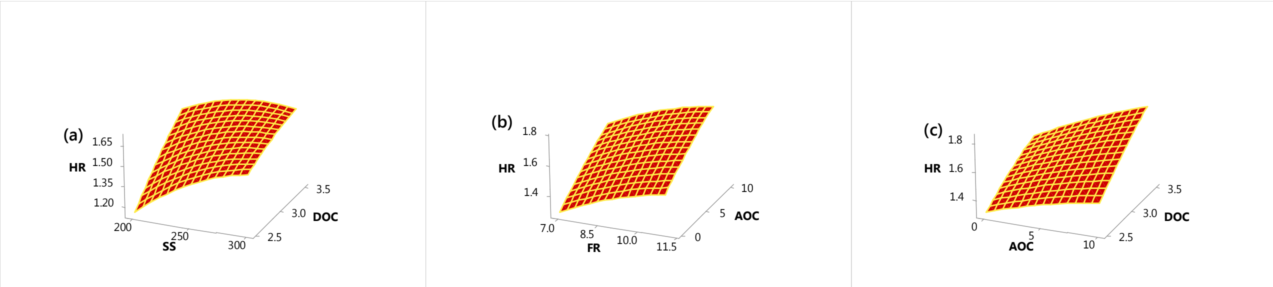

Fig.7 Response surface plot showing the effect of two variable on HR (the other variable is held at constant level) SS- spindle speed, FR- feed rate, AOC- angle of cut, DOC- depth of cut

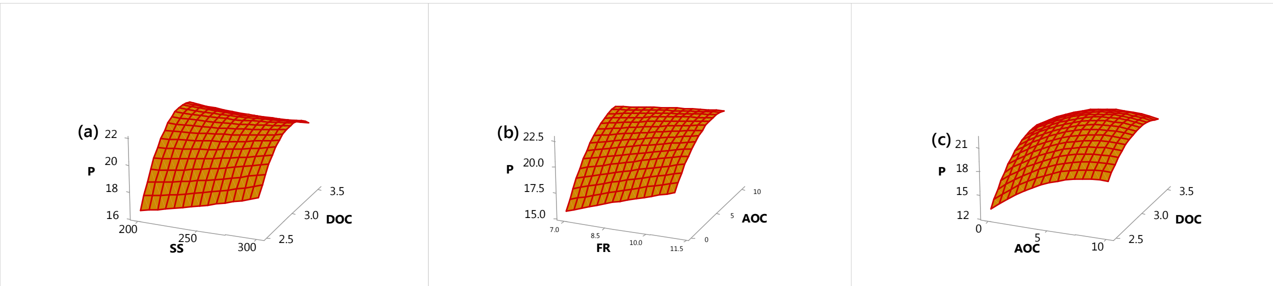

Fig.8 Response surface plot showing the effect of two variable on P (the other variable is held at constant level) SS- spindle speed, FR- feed rate, AOC- angle of cut, DOC- depth of cut

RESULTS AND DISCUSSION

Table 4 and 5 illustrates the results of analysis of variance (ANOVA) for HR and P**.** From the tables, it is clear that the first-order of spindle speed (SS), feed rate (FR), angle of cut (AOC) and depth of cut (DOC) have significant effect on HR and first –order of angle of cut (AOC) and depth of cut (DOC) have significant effect on P. On the other- end, quadratic and pair wise interaction of SS, FR, AOC, and DOC have no significant effect on the response parameters. All the parameters are found to significant for Material Hardness (HR) but angle of cut (AOC) and depth of cut (DOC) can be considered as the most significant factor for HR which explains 22.07% and 17.16% contribution of total variation respectively as shown in Table 4. In case of Pressure (P), angle of cut (AOC) and depth of cut (DOC) are found to be significant factor which explains 33.91% and 15.53% contribution of total variation respectively as shown in Table 5.

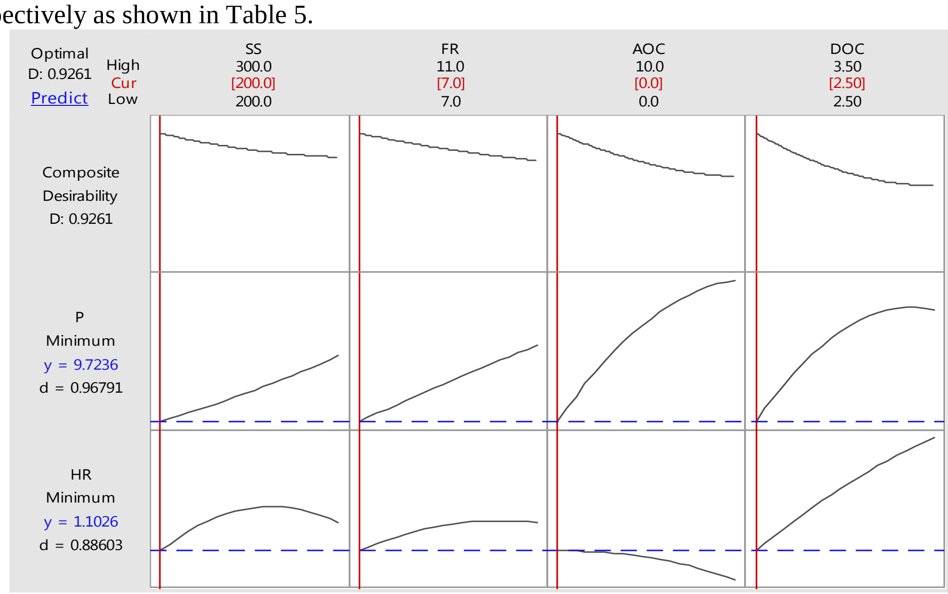

Fig. 9 Response optimization plot for HR and P

Table -7 Response Optimization for Surface Parameter Components

Response	Goal	Optimum Combination				Lower	Target	Upper	Pre. Response	Desirability
		SS (m/min.)	FR (mm/rev.)	AOC (degree)	DOC (mm)					
P	Minimum	200	7	0	2.5	9.3	9.3	22.5	9.7236	0.9261
HR	Minimum	200	7	0	2.5	1.0	1.0	1.9	1.1026	0.88603

Table -6 Regression Analysis for Material hardness (HR) & Pressure (P)

Term	Coefficient	P- Value
Constant	1.3233	0.000
SS	0.1283	0.008
FR	0.1058	0.022
AOC	0.1208	0.011
DOC	0.1233	0.010
SS*SS	0.0625	0.322
FR*FR	0.1013	0.120
AOC*AOC	0.1113	0.091
DOC*DOC	0.1100	0.094
SS*FR	0.0625	0.388
SS*AOC	0.1600	0.041
SS*DOC	-0.0375	0.601
FR*AOC	0.0325	0.650
FR*DOC	0.0675	0.353
AOC*DOC	0.0550	0.446

Term	Coefficient	P- Value
Constant	17.90	0.000
SS	0.642	0.517
FR	1.275	0.210
AOC	2.092	0.050
DOC	1.525	0.139
SS*SS	1.67	0.268
FR*FR	1.45	0.335
AOC*AOC	-0.02	0.986
DOC*DOC	-0.42	0.773
SS*FR	-0.70	0.682
SS*AOC	-0.03	0.988
SS*DOC	-0.40	0.814
FR*AOC	-0.33	0.849
FR*DOC	0.25	0.883
AOC*DOC	-1.13	0.512

SURFACE ROUGHNESS QUADRATIC MODEL

Estimated regression coefficients for surface roughness using data in uncoded units are shown in Table 6. The quadratic model of response equation in terms of actual factors for roughness parameters HR and P is:

HR=1.3233+0.1283.SS+0.1058.FR+0.1208.AOC+0.1233.DOC+0.0625.SS*SS+0.1013.FR*FR0.1113.AOC*AOC+ 0.1100. DOC*DOC+0.0625.SS*FR+0.1600.SS*AOC-0.0375SS*DOC0.0325.FR*AOC+0.0675.FR*DOC+0.0550AOC*DOC (4)

P=17.90+0.642.SS+1.275.FR+2.092.AOC+1.525.DOC+1.67.SS*SS+1.45.FR*FR-0.02.AOC*AOC-0.42DOC*DOC-.70.SS*FR -0.03.SS*AOC-0.40.SS*DOC-0.33.FR*AOC+0.25.FR*DOC -1.13.AOC*DOC (5)

The empirical Eq. 4 and 5 shows greater agreement than 90.13% and 83.82% in the fit values of HR and P respectively. Fig.10 and 11 shows the predicted values of HR and P respectively from quadratic model of response equation and measured values. These comparison results clearly show that the predicted values are much close to the recorded experimental values of HR and P.

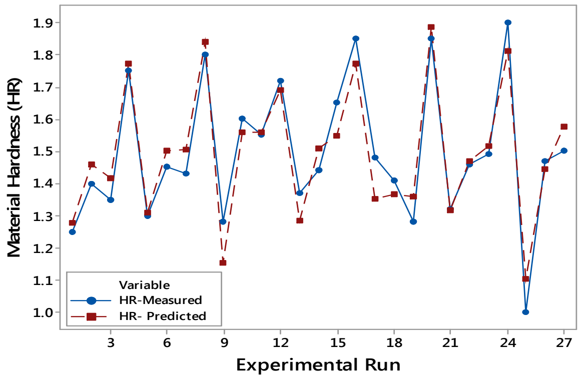

Fig.10 Measured vs. Predicted values of Material Hardness (HR)

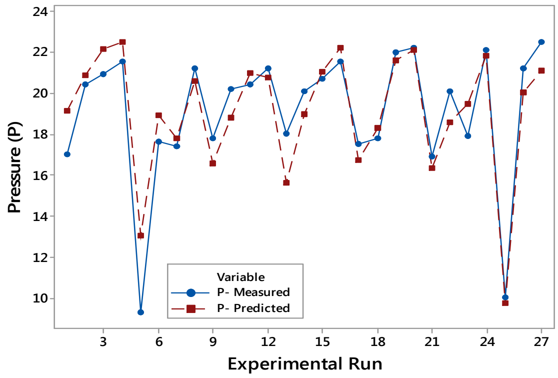

Fig.11 Measured vs. Predicted values of Pressure (P)

OPTIMIZATION OF RESPONSE

One of the most important objects of experiments related to manufacturing is to achieve the desired output of the optimal cutting parameters [21] and tool geometry. To achieve this, the response surface optimization methodology is an ideal technique to identify the best tool geometry combination in turning. Here, the goal is to minimize Material Hardness (HR) and Pressure (P). RSM optimization result for HR and P is shown in fig.9 and Table 6. Optimum cutting insert geometries obtained in Table 7 are found to be SS= 200 m/min, FR = 7 mm/rev, AOC = 0 degree, DOC = 2.5 mm and optimized Material Hardness (HR) is 1.1026. Similarly for P, optimum cutting inset is SS= 200 m/min, FR = 7 mm/rev, AOC = 0 degree, DOC = 2.5 mm and optimized Pressure (P) is 9.7236 kg/cm^2.

CONCLUSION

In the present study, the application of response surface methodology (RSM) on Hard Porcelain in carried out by turning with Al2O3 (R7.5,100) cutting tool. In addition, a quadratic model is established for Material Hardness (HR) and Pressure (P) so as to examine the influence of cutting parameters on it. Following are the results to be found:

- The result of ANOVA proved that the quadratic mathematical models allow prediction of Hardness (HR) and Pressure (P) with 90.13% and 83.82% confident interval respectively.
- In case of HR, all the cutting parameters have significant effect but angle of cut (AOC) and depth of cut (DOC) have the most significant effect with the contribution of 22.07% and 17.16% in the total variability of model, respectively.
- In case of P, angle of (AOC) and depth of cut (DOC) have significant effect with the contribution of 33.91% and 15.93% in total variability of model, respectively.
- ANOVA Table clearly shows that the interactions between the parameters have no significant on HR and P.
- Response optimization shows that the optimal combination of machining parameters for Material Hardness (HR) are (SS= 200 m/min, FR = 7 mm/rev, AOC = 0 degree, DOC = 2.5 mm) for spindle speed, feed rate, angle of cut and depth of cut respectively.
- Response optimization shows that the optimal combination of machining parameters for Pressure (P) are (SS= 200 m/min, FR = 7 mm/rev, AOC = 0 degree, DOC = 2.5 mm) for spindle speed, feed rate, angle of cut and depth of cut respectively.
- Significance of interactions and square terms of parameters are more clearly examined in RSM. The RSM represents the significance of all possible combination of interactions and square terms as shown in Table 4 & 5.

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