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Optimization and Prediction of Effect of Turning Parameters on Tool Wear Rate and Surface Roughness using Response Surface Methodology

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Abstract— This present study tackled an optimization and prediction problem by the application of Response Surface Methodology Approach through a case study in straight turning of EN8 mild steel bar using HSS cutting tool. The study aimed at evaluating the best process environment which could simultaneously satisfy requirements of quality of turned components. The predicted optimal setting ensured minimization of the rate of cutting tool wear (TWR) and surface roughness (Ra), through CCD using version 7.0 of Design Expert software. The ENC lathe machine was used to carry out the turning operation, with work piece, measuring 100 mm diameter and length 60 mm. A total of 20 experimental runs were done. The experimental results (data) were recorded and RSM was used to analyze them. The results obtained revealed an R^2 value of 0.9887 and 0.9929 for TWR and Ra respectively. Sspindle speed and depth of cut, followed by feed rate, have significant influence on TWR. However, only feed rate is found to have significant influence on surface roughness. From the numerical optimization solution, it observed that optimum machining setting of spindle speed of 143.36 rpm, feed rate of 0.12 mm/rev and a depth of cut of 0.5 mm will result in a turning process with an optimum (minimized) tool wear rate of 0.079251 and surface roughness of 0.883829 µm, with a composite desirability value of 99%.

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Index Terms— Response surface methodology, surface roughness, central composite design, machining time, feed rate

1 Introduction

Machining operations are accomplished using cutting tools. The high forces and temperatures during machining create a very harsh environment for the tool. If cutting force becomes too high, the tool fractures. If cutting temperature becomes too high, the tool material softens and fails. If neither of these conditions causes the tool to fail, continual wear of the cutting edge ultimately leads to failure. Fracture and temperature failures result in premature loss of the cutting tool. These two modes of failure are therefore undesirable. Of the three possible tool failures, gradual wear is preferred because it leads to the longest possible use of the tool, with the associated economic advantage of that longer use. Product quality must also be considered when attempting to control the mode of tool failure. When the tool point fails suddenly during a cut, it often causes damage to the work surface. This damage requires either rework of the surface or possible scrapping of the part. The damage can be avoided by selecting cutting conditions that favor gradual wearing of the tool rather than fracture or temperature failure, and by changing the tool before the final catastrophic loss of the cutting edge occurs.

A mathematical model was developed by Samir *et al*. [1] using Response Surface Methodology, to study the effects of machining parameters of cutting speed, feed rate and depth of cut, in finish hard turning of AISI 52100 bearing steel with CBN tool on the performance characteristics of tool life, surface roughness and cutting forces are analyzed. The feed rate and cutting speed were found to strongly influence the surface roughness. Bouacha *et al.* [2] carried out an experimental investigation to show the effects of cutting speed, feed rate and depth of cut on surface roughness and cutting forces, in hard turning of AISI 52100 bearing steel, using CBN cutting tool. Response Surface Methodology (RSM) was used to carry out the optimization and concluded that the feed rate and cutting speed are the most influencing parameters on surface roughness. Suresh *et al.* [3] carried out an experimental investigation and validation of optimal cutting parameters of cutting speed, feed rate and depth of cut, for least surface roughness in EN24 with response surface method. It was found that feed rate has the highest significance than cutting speed and depth of cut. 3D plots were drawn to find out the optimum setting for minimum surface roughness. An experiment was conducted

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by Sahoo [4], using Response Surface Method and Genetic algorithm to estimate the effects of depth of cut, feed rate and spindle speed on surface roughness in a CNC turning of AISI 1040 steel. They concluded that the roughness value increases with increasing feed rate. Orthogonal hard turning tests were conducted by Attanasio *et al.* [5] to study the effects of cutting parameters (cutting speed and feed rate) on flank tool wear during the turning of white and dark layer formation in hardened AISI 52100 bearing steel, using PCBN inserts. The prediction was carried out using Finite elements (FE) model and authors found out that cutting speed is the most influencing parameter. Rahul and Jitendra [6] carried out Parametric Analysis and Optimization of Tool Life in Dry Turning of EN24 Steel, using Taguchi Method. Spindle speed, feed rate and depth of cut were taken as machining parameters. The authors concluded that spindle speed is the most influencing parameter to optimize tool life in dry turning of EN24 steel

2 Materials and Methods

2.1 Materials

EN8 mild steel of size 100 mm diameters and length 60 mm was selected for this research work. M42 HSS single point cutting tool is used for turning operation. ENC lathe machine (Fig. 1), with a spindle speed range from 100 to 2500 rpm was utilised for the experiment. The machining centre was driven by 10kW electric motor. The experiment was carried out under dry machining environment. The surface roughness (R_a) of the machined work-piece was measured using portable surface roughness Tester-TR100 (Fig. 2).

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Fig. 1 CNC Lathe machine

Fig. 2 TR100 Ra Tester

Fig. 3 Turned Samples

2.1 Methods

2.2.1 Identification of Important Process Parameters

Three main cutting parameters such as spindle speed (A) in rev/min, feed rate (B), in mm/min and depth of cut (C), in mm, each at two levels were considered for the turning process. Table 1 shows the process variables and their level.

Table 1. Process Variables and their Level

Factor	Range	
	Low	High
Spindle speed, A, (rpm)	105 rpm (32.99m/mim)	220 rpm (61.12m/min)
Feed rate, B, (mm/mim)	0.12mm/mim	0.18mm/min
Depth of cut, C, (mm)	0.50mm	1.50mm

2.2.2 Development of Design Matrix

The Design of Experiment (DOE) is used to develop a design matrix. The central composite second order rotatable design was utilized, using Design Expert 7.0 software. The design matrix, consists of two-level, three factor central composite rotatable factorial design (CCD) consisting of 20 sets of coded conditions. The upper limit of a given parameter was coded as (+1) and the lower limit was coded as (–1). Thus, all the 20 experimental runs to allow the estimation of the main, quadratic and two way interactive effects of the process parameters. Turning operations were carried out based on the experimental design matrix and the responses (machining time, tool wear rate and surface roughness) were measured and recorded. Empirical formula for tool wear rate, developed by Al-Hossainy *et al.* [7], was adopted for this study. This formula is presented as in equation 1.

$$TWR = KV^{\alpha} f^{\beta} d^{\gamma} t^{\sigma} \quad (1)$$

Where, k, $\propto$, β, γ and σ are constants, whose values were determined empirically, using regression analysis as 8.2961X10^{-5}, 2.747, 1.473, 1.261 and 0.43 respectively. The variable t represents the length of time in minutes spent in cutting under the cutting conditions specified by the cutting speed (V) in m/min, the feed rate (f) in mm/rev, and the initially adjusted depth of cut (d), in mm.

Table 2 shows the experimental design matrix and the measured responses of machining time and surface roughness.

Table 2. Experimental Design Matrix and Output Response ors (Tool wear rate and Surface Roughness)

Std.	Run	Block	Factor			Response		
			Spindle speed (rpm)	Feed rate (mm/rev)	Depth of cut (mm)	Machining Time(Min)	Tool Wear Rate (mm^3/min)	Av. Surface Roughness, Ra (µm)
13	1	Block 1	162.5	0.15	0.16	2.46	0.029	1.4
18	2	Block 1	162.5	0.15	1	1.59	0.368	1.4
10	3	Block 1	259.2	0.15	1	1.53	1.113	1.41
3	4	Block 1	105	0.18	0.5	3.17	0.067	2.03
20	5	Block 1	162.5	0.15	1	2.11	0.402	1.3
17	6	Block 1	162.5	0.15	1	2.01	0.348	1.42
5	7	Block 1	105	0.12	1.5	4.76	0.177	0.9
19	8	Block 1	162.5	0.15	1	2.46	0.273	1.33
9	9	Block 1	65.8	0.15	1	6.36	0.041	1.41
12	10	Block 1	162.5	0.2	1	1.83	0.501	2.55
11	11	Block 1	162.5	0.1	1	3.77	0.236	0.6
7	12	Block 1	105	0.18	1.5	3.18	0.27	2.03
15	13	Block 1	162.5	0.15	1	2.46	0.307	1.3
8	14	Block 1	220	0.18	1.5	1.52	1.496	2.03
1	15	Block 1	105	0.12	0.5	4.76	0.044	0.9
4	16	Block 1	220	0.18	0.5	1.52	0.374	2.03
16	17	Block 1	162.5	0.15	1	1.94	0.393	1.5
14	18	Block 1	162.5	0.15	1.84	2.46	0.807	1.41
6	19	Block 1	220	0.12	1.5	2.27	0.98	0.9
2	20	Block 1	220	0.12	0.5	2.27	0.245	0.9

3 Results and Discussion

The experimental results were analysed with ANOVA, to identify the factor(s) that significantly influence the performance measure, as shown in Tables 3 and 4. Quadratic model was suggested from the sequential model sum of squares [Type II] for the two responses.

Table 3. ANOVA Prediction of Tool Wear Rate (TWR)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	2.83	9	0.31	97.53	< 0.0001	significant
A-Spindle Speed	1.38	1	1.38	427.82	< 0.0001	
B-Feed Rate	0.11	1	0.11	33.07	0.0002	
C-Depth of cut	0.9	1	0.9	278.48	< 0.0001	
AB	0.035	1	0.035	10.85	0.0081	
AC	0.29	1	0.29	89.71	< 0.0001	
BC	0.026	1	0.026	8.1	0.0174	
A^2	0.092	1	0.092	28.52	0.0003	
B^2	5.47E-04	1	5.47E-04	0.17	0.689	
C^2	8.07E-03	1	8.07E-03	2.5	0.1447	
Residual	0.032	10	3.22E-03			
Lack of Fit	0.02	5	3.92E-03	1.55	0.3213	not significant
Pure Error	0.013	5	2.53E-03			
Cor Total	2.86	19				

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Table 4. ANOVA prediction of surface roughness (Ra)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	4.53	9	0.5	155.46	< 0.0001	significant
A-Spindle Speed	0	1	0	0	1	
B-Feed Rate	4.45	1	4.45	1377.23	< 0.0001	
C-Depth of cut	2.07E-05	1	2.07E-05	6.40E-03	0.9378	
AB	0	1	0	0	1	
AC	0	1	0	0	1	
BC	0	1	0	0	1	
A^2	1.94E-03	1	1.94E-03	0.6	0.4568	
B^2	7.00E-02	1	7.00E-02	21.79	0.0009	
C^2	1.39E-03	1	1.39E-03	0.43	0.5266	
Residual	0.032	10	3.23E-03			
Lack of Fit	7.93E-04	5	1.59E-04	0.025	0.9995	not significant
Pure Error	0.032	5	6.31E-03			
Cor Total	4.56	19				

Table 3 depicts the ANOVA generated at 95% confidence level for the cutting parameters and the response (Tool Wear Rate). The present model F-value of 97.53 implies the model is significant and it is noted that there is only a 0.01% chance that a Model with an F-Value, this large, could only occur due to noise. The factors possessing values of Prob > F less than 0.0500 indicate that model terms are significant. In this model, it is observed that A, B, C, AB, AC, BC and A^2 are the significant model terms for the minimization of Tool Wear Rate. Also, the probability value associated with the lack of fit is 0.3213, which is not significant. It is desirable to have an insignificant lack of fit (P>0.1).

Table 4 depicts the ANOVA for testing the significance of quadratic model in predicting surface roughness (Ra). The model has a P values of 0.0001, implying that it is significnt. In this model, it is observed that B and B^2 are the significant model terms for the minimization of surface roughness. Also, the probability value associated with the lack of fit is 0.9995, which is not significant and desirable.

To check how well the quadratic model fits the observed data and its ability to predict the TWR and surface roughness (Ra), the goodness of fit statistics presented in Tables 5 and Table 6 were employed.

Table 5. GOF statistics for validating model significance towards minimizing TWR

Std. Dev.	0.057	R-Squared	0.9887
Mean	0.42	Adj R-Squared	0.9786
C.V. %	13.4	Pred R-Squared	0.9347
PRESS	0.19	Adeq Precision	36.114

Table 6. GOF statistics for validating model significance towards minimizing Ra

Std. Dev.	0.057	R-Squared	0.9929
Mean	1.44	Adj R-Squared	0.9865
C.V. %	3.96	Pred R-Squared	0.9887
PRESS	0.051	Adeq Precision	47.769

Table 5 shows that the R^2 value of 0.9887 for TWR is greater than 0.9, implying a high correlation. This means the model can explain 98.87% of the variability in TWR. The adjusted R-squared and predicted R-squared should be within approximately 0.20 of each other to be in reasonable agreement, their respective values showed they are in good agreement. Adequate precision is a measure of the range in predicted response relative to its associated error, in other words a signal to noise ratio. Its desired value is 4 or more. In this case, it is more than 4, implying it can be used to navigate the design space. Table 6 depicts the ANOVA that validated the use of quadratic model in minimizing surface roughness.

3.1 Mathematical Modeling

The mathematical models of Tool wear rate and surface roughness deduced from this work are shown in Equations 2 and 3.

$$TWR = +0.35 + 0.32 * A + 0.088 * B + 0.26 * C + 0.066 * A * B + 0.19 * A * C + 0.057 * B * C + 0.080 * A^2 + 6.1633 - 003 * B^2 + 0.024 * C^2 \quad (2)$$

$$Ra = +39734 - 1.13981E - 003 * A - 4.27372 * B - 0.076158 * C * 0.00000 * A * B + 0.00000 * A * C + 0.00000 * B * C + 3.50710E - 006 * A^2 + 77.70183 * B^2 + 0.039310 * C^2 \quad (3)$$

3.2 Optimization

Numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, we asked design expert to minimize the tool wear rate (TWR) and surface roughness (Ra) and determine the optimum spindle speed, feed rate and depth of cut. The numerical optimization produces about twenty-two (22) optimal solutions as presented in Table 7. The three-dimensional (3D) response surface, showing the expected TWR as a function of machining parameters of spindle speed (A), feed rate (B) and depth of cut (C) and the associated contour plot are presented in Figure 4 through Figure 9 respectively. It can be inferred from the figures that TWR increases significantly with increase in spindle speed and depth of cut, followed by feed rate.

Table 7: Numerical optimization solution

Number	Spindle Speed (rpm)	Feed Rate (mm/min	Depth of cut (mm)	Tool Wear Rate (TWR) (mm3/min)	Surface Roughness (SR) (µm)	Desirability	
1	**143.36**	**0.12**	**0.5**	**0.079251**	**0.883829**	**0.99**	**Selected**
2	142.42	0.12	0.5	0.079137	0.883974	0.99	
3	141.26	0.12	0.5	0.079032	0.884142	0.99	
4	139.5	0.12	0.5	0.079082	0.884396	0.99	
5	138.74	0.12	0.5	0.079142	0.884547	0.99	
6	150.65	0.12	0.5	0.081595	0.883044	0.99	
7	134.24	0.12	0.5	0.079924	0.88537	0.99	
8	133.01	0.12	0.5	0.080322	0.885627	0.99	
9	161.56	0.12	0.5	0.089981	0.882541	0.99	
10	105.01	0.12	0.92	0.093814	0.885632	0.99	
11	105.04	0.12	0.91	0.093823	0.885633	0.99	
12	105.57	0.12	0.9	0.094318	0.885515	0.99	
13	105.05	0.12	0.84	0.094205	0.886157	0.99	
14	168.08	0.12	0.5	0.097594	0.882653	0.99	
15	108.28	0.12	0.85	0.096348	0.884765	0.99	
16	113.31	0.12	0.73	0.096763	0.884634	0.99	
17	111.23	0.12	0.77	0.096877	0.884692	0.99	
18	105.01	0.12	1.08	0.096777	0.886035	0.99	
19	105	0.12	1.18	0.101214	0.887318	0.99	
20	105	0.12	1.21	0.10279	0.887862	0.989	
21	179.15	0.12	0.5	0.115372	0.883521	0.989	
22	105	0.12	1.36	0.113302	0.891461	0.989	

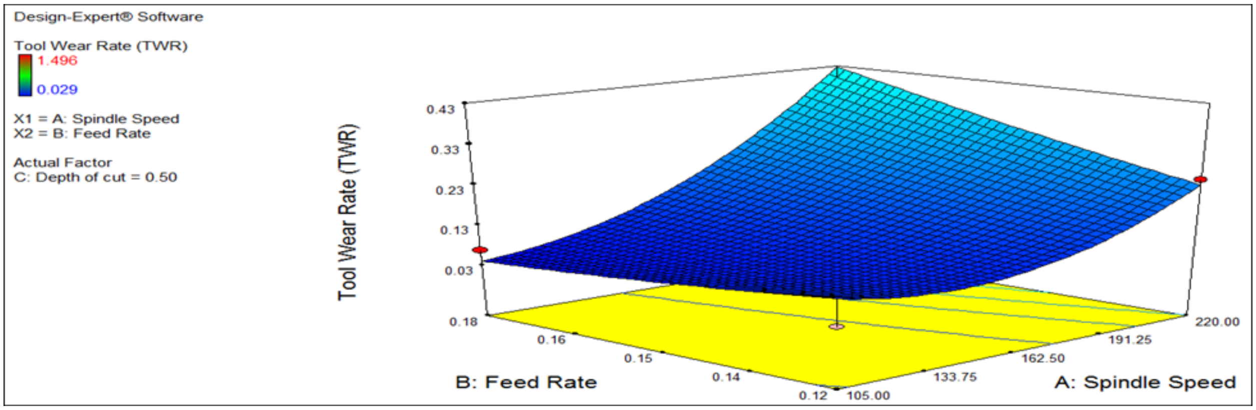

Fig.4 D response surface plot, showing the expected TWR as a function of A and B.

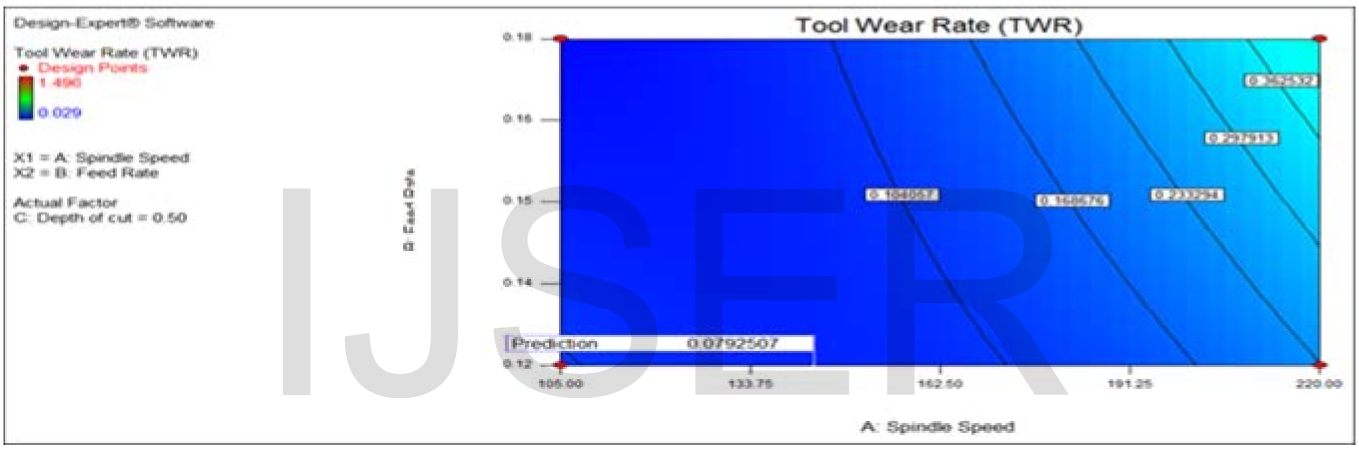

Fig.5 Contour plot showing the effect of spindle speed and feed rate on tool wear rate

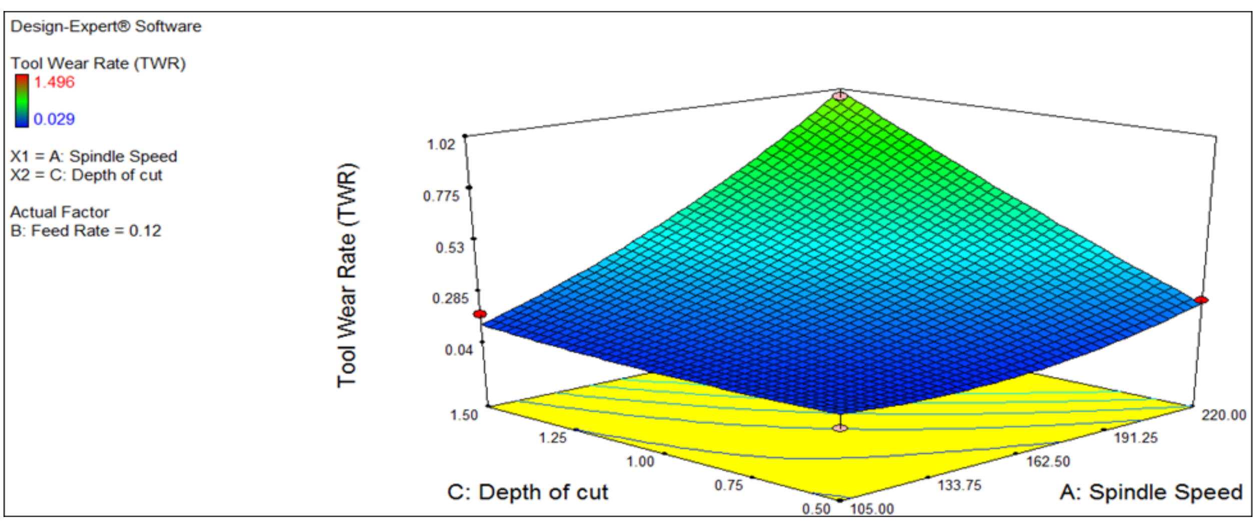

Fig.6 3D response surface plot, showing

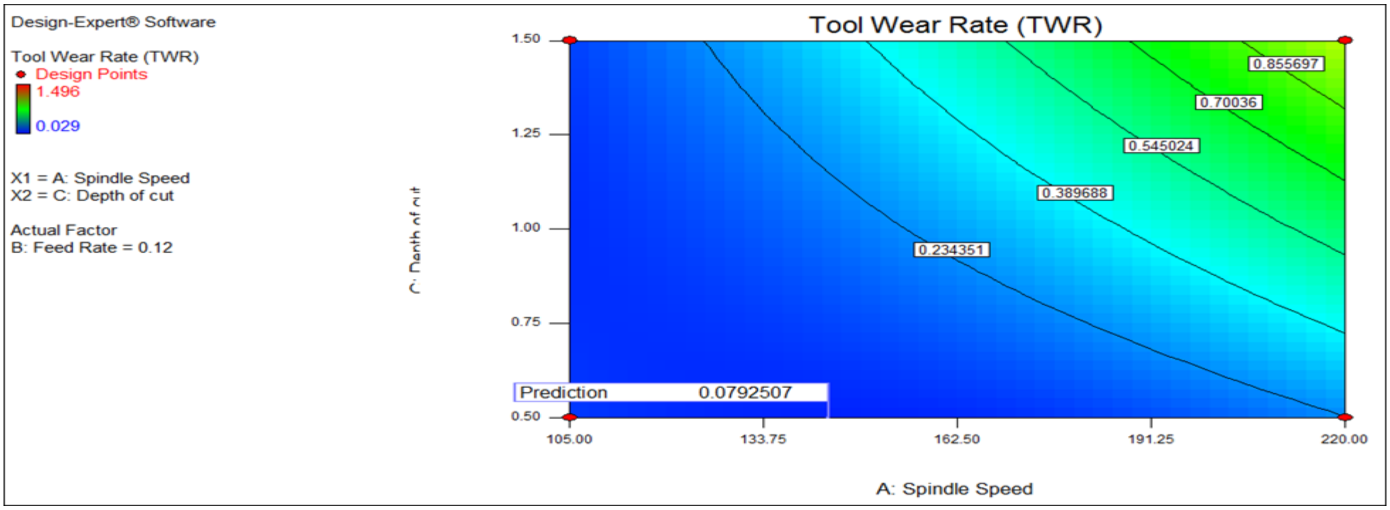

Fig.7. Contour plot showing the effect of spindle speed and depth of cut on tool wear rate

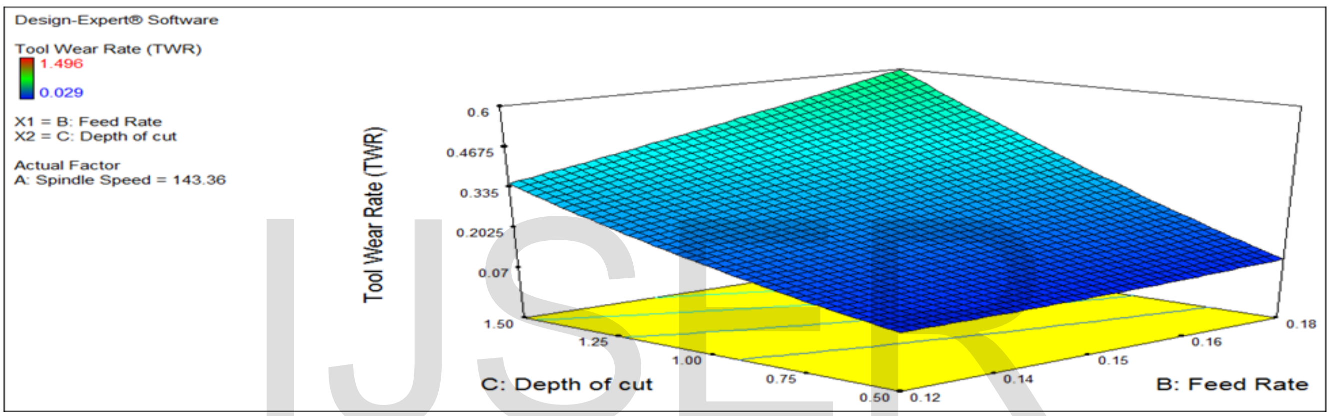

Fig.8. 3D response surface plot, showing the expected TWR as a function of B and C.

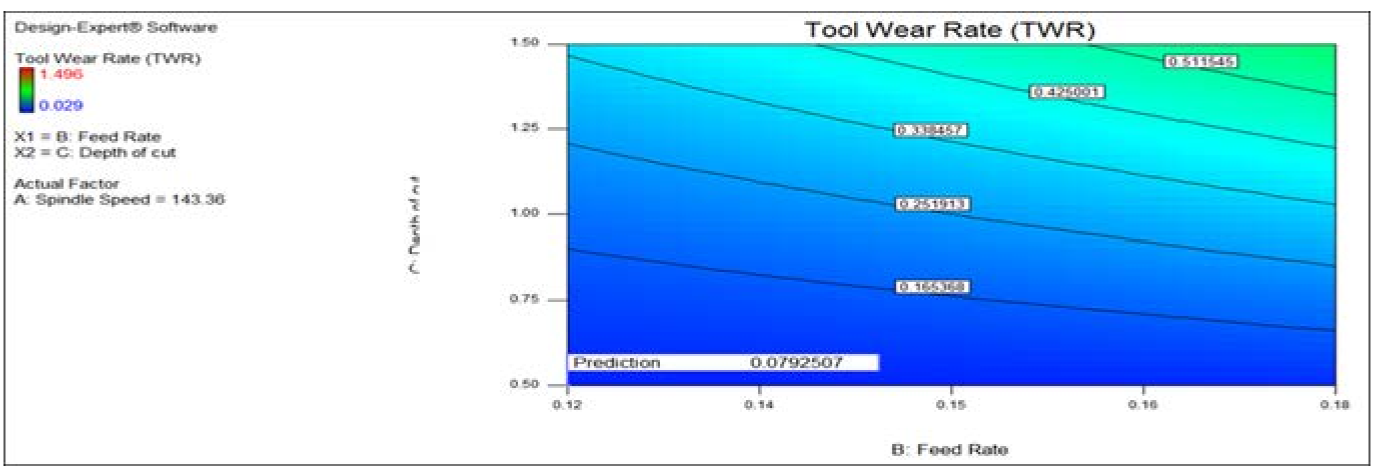

Fig. 9 Contour plot showing the effect of feed rate and depth of cut on tool wear rate

The 3D response surface, showing the expected surface roughness (Ra) as a function of spindle speed (A) and feed rate (B) and the associated contour plot are presented in Figures presented in Figures 10 and 11 respectively. It is predicted that only feed rate has significant influence in the minimization of surface roughness. From Figure 11, predicted Ra is 0.883829µm at an optimal machining setting of A (143.36 rpm), B (0.12 mm/min) and C (0.50 mm). The Contour plot showing the composite desirability of the optimization process is presented in Figure 12.

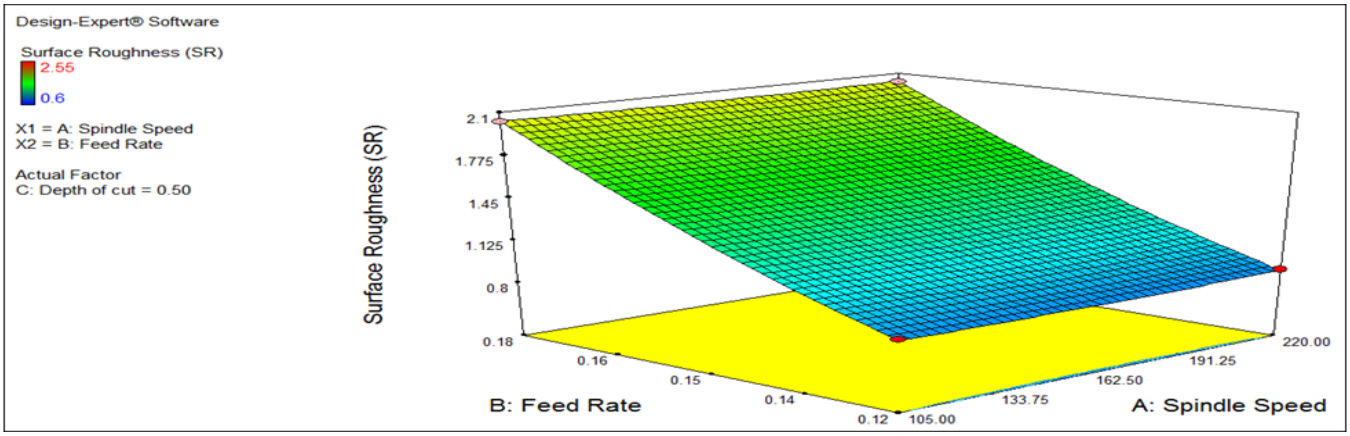

Fig. 10. 3D response surface plot, showing the expected Ra as a function of A and B

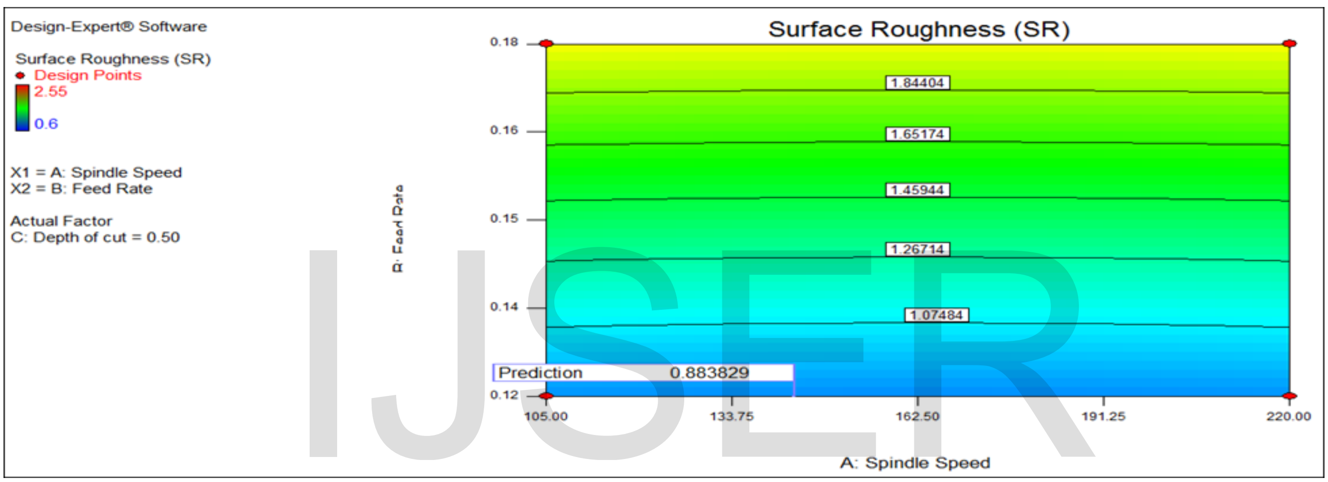

Fig. 11. Contour plot showing the effect of spindle speed and feed rate on surface roughness

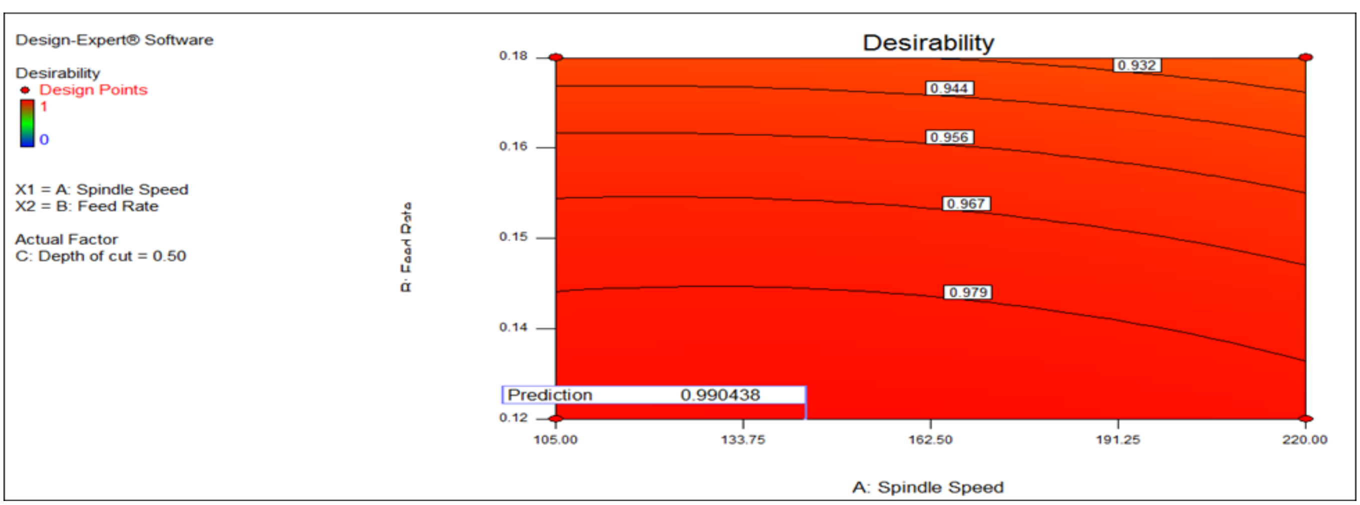

Figure 11: Contour plot showing the composite desirability of the optimization

4 Conclusion

In this study, we investigated the effect and optimization of machining parameters on Tool wear rate and surface roughness using response surface methodology. The results obtained from the ANOVA Table 3 revealed that the spindle speed, feed rate and depth of cut have significant influence on Tool wear rate. Also, from Table 4, only feed rate is found to have significant influence on surface roughness. It was also observed that optimum machining setting of spindle speed of 143.36 rpm, feed rate of 0.12 mm/rev and a depth of cut of 0.5 mm will result in a turning process with an optimum (minimized) Tool wear rate of 0.079251 and surface roughness of 0.883829 µm, with a composite desirability value of 99%.

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