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OPTIMIZATION OF FACE MILLING PROCESS PARAMETERS USING RESPONSE SURFACE METHODOLOGY

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***Abstract-* Maintaining good surface quality usually involves additional manufacturing cost or loss of productivity. During the process high cutting frictional forces lead to rise in temperature at workpiece and tool interface which may affect the dimensional and surface quality of the product. Optimum machining parameters can reduce tool wear, to ensure better surface integrity and machining cost. In this paper, the machining parameters i.e. cutting speed (v), depth of cut (d) and feed rate (f) has been optimized for improved surface finish using response surface methodology (RSM). The optimization of the surface roughness (R_a) and tool wear (T_w) has been done simultaneously by multi response optimization technique and also a mathematical relation between response parameters and input process variables has been developed. The optimized process parameters obtained from machining through RSM were cutting speed of 175.7 m/min, feed rate of 400 mm/min and depth of cut of 0.50 mm, corresponding T_w and R_a were 49.44 µm, 11.38 µm respectively.**

***Keywords*— AISI 1050 Steel, Coated Tungsten Carbide Insert, RSM, Multi Response Optimization, Milling.**

I. INTRODUCTION

Surface roughness is an essential measure of the technological quality of a product and a parameter that significantly influences production cost. Surface roughness, cutting force, and tool wear are generally used to evaluate machinability. An indispensible part of machining process is tool failure [1, 2]. Surface roughness is a usually encountered issue in machined surfaces that has attracted the attention of researchers for better surface integrity [3]. It is defined as the finer irregularities of surface quality, which is the consequence of inherent action of the production process. Subsequently, surface roughness has a significant effect on product quality [4]. AISI 1050 is a medium carbon steel with reasonable strength and toughness which is used for manufacturing the brake discs, clutches, springs, washers and gears.

The main component of the milling process is cutting tool and tool breakage is a foremost source of unscheduled work stoppage in industrial sites using milling. Accumulation of tool damage over time commonly results in tool breakage, and has undesirable time loss and capital effects [5]. The three key elements in any elementary machining process are cutting speed, depth of cut and feed rate. The output cutting parameters in machining operation are the function of input cutting process parameters [6].

The correlation between one or more output variables and a set of input variables can be studied by employing response surface methodology. These approaches are often used after recognizing the manageable variables and the aim of this technique is to found the factor setting that optimizes the response parameter values. There is no fixed factorial or fractional design in the Box-Behnken design (BBD). The design points in Box-Behnken design are less than central composite designs, thus they have less number of trials with the same number of factors and thus less expensive.

II. LITERATURE REVIEW

In anticipating the performance of any machining process the surface roughness and tool wear are paramount factors. It is important to comprehend the current trend in this area for making and optimizing the tool wear (T_w) and surface roughness (R_a) model.

Reddy and Rao [7] conducted the experiments for end milling of medium carbon steel. The input parameters chosen for the research were cutting speed, tool geometry and feed rate to see the effect on machining performance. It was observed that as the value of speed increase the surface roughness reduces and increases as the value of feed rate increases. It was also depicted that R_a was minimum at 200 mm/min feed rate, 250 m/min speed, 0.8 mm nose radius and 10˚ radial rake angle. To obtain the machining parameters for best possible surface finish of this model, genetic algorithm has been found to be a very useful technique. Halim et al. [8] studied the comparison between ultrasonic assisted milling with conventional milling of carbon fiber reinforced plastic in relations of T_w, R_a, cutting temperature and cutting force. It was seen that the tool wear rate in ultrasonic assisted milling was more as compared to traditional milling. It was so because of severe friction at the interface between tool and surface which results in 25% higher R_a than conventional milling, but in former the cutting forces were less (10%) than traditional milling. It was proved that the optimum process variables obtained with the help of genetic algorithm (GA) technique yields minimum R_a. The value recommended by GA technique was 0.138 µm at low feed rate, high speed and high rake angle to acquire best possible predicted surface roughness [9]. The experimental study included the minimum quantity lubrication (MQL) and dry milling machining in addition to traditional flood cooling confirmed that near dry machining technique can be positively applied without upsetting the outcomes of machining process for cutting power and R_a [10].

Oktem et al. [11] investigated an effective methodology to get best machining conditions which produces least Ra in milling operation and it was deduced that the value of R_a was reduced from 0.412 µm to 0.375 µm which means the improvement of 10 % with the help of genetic algorithm. In face milling operation on a CNC machine by including depth of cut, feed rate and speed as input variables to detect the key elements affecting surface finish analysis of variance (ANOVA) was used. The outcomes of experimentations showed that in the current evaluation effects of feed rate and speed were more than depth of cut for face milling operation [12]. Kopac and Krajnik [13] studied grey-Taguchi methodology for optimizing flank milling conditions by employing integrated orthogonal array. It was determined that the optimized machining process parameters minimized machined surface roughness and resulting cutting force and maximized rate of material removal.

The experiments were conducted by employing dry machining in order to reduce environmental effect and it was concluded that to increase the rate of material removal the response parameters like speed, chip section and feed rate should be as large as possible with in the reasonable operational constraints of the tool [14]. To optimize the surface roughness carbide inserts were used for experiments under dry machining conditions and it was concluded that as the value of feed rate increases the R_a value increases whereas with an increased in speed the value of R_a decreases [15]. The input machining parameters selected were f, d and v. Three different materials were selected for experimentation - aluminium 6061, UNS C34000 brass and AISI 1040 mild steel so that the effect of variation of workpiece material can be find out. The response parameters considered were five roughness parameters. These were centre line average roughness, kurtosis, skewness, root mean square roughness and mean line peak spacing [16]. Rad and Bidhendi [17] studied multi-tool and single-tool milling machining operations and the parameters selected can be used by both CNC machines and conventional milling machines.

III. EXPERIMENTAL METHODOLOGY

The aim of the present work is to optimize the T_w and R_a value for AISI 1050 steel using RSM. During the experimentation work, AISI 1050 steel workpiece {Fe – (98.46 –98.91%) , C – (0.48-0.55%), Mn - (0.6-0.9% ma), P- (0.03%), S –(0.035%)} having dimensions (length 120 mm, thickness 100 mm and width 100 mm) was machined on HURCO vertical CNC milling machine with spindle motor power 11 kW using face milling cutter of 40 mm diameter.

The present work considered three levels of design of experiment. RSM based BBD Technique was used to develop the design of experiments by Design expert software. Three input variables of cutting speed 150.79, 175.92 and 201.06 m/min were selected with feed rate 400, 500 and 600 mm/min and depth of cut of 1.5, 1 and 0.5 mm. Commercially available TPKN2204PDR coated tungsten carbide inserts of given tool geometry (Shape – Triangular, Included angle = 60˚, Insert IC size = 12.70 mm, Thickness = 4.76 mm, Cutting edge = 3) were used to conduct the research work. The length of cut was taken constant at 300 mm.

Measurement of R_a was done by using Mitutoyo SJ 301 surface roughness tester and measurement of tool wear was done by Sipkon measurement system. SURFTEST instrument is a portable, self-contained instrument for the measurement of the surface profile. Evaluation of parameters is based on a processor. The surface roughness was measured thrice for a component and the average value was taken to determine the R_a value of the specimen. RSM based BBD technique was used for the optimization of process parameters. The measured response parameters values were incorporated into the model generated by RSM.

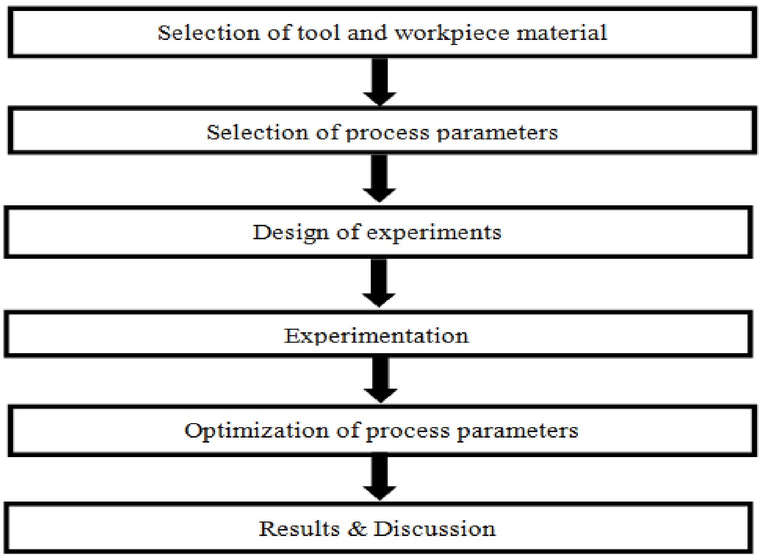


Figure 1 Flow Chart of Methodology

The framework of methodology adopted for the present work is shown in Figure 1. ANOVA was employed to study the performance characteristics of milling operation.

IV RESULTS AND DISCUSSION

The experiments were performed with variation in different process parameters using design of experiment approach and results were evaluated using response surface methodology. 27 experiments were designed by RSM based BBD technique. For each input parameter (*i.e.* cutting speed, feed rate and depth of cut) three levels were taken for experimentation and results were calculated as shown in Table 1. After conducting the experiments for CNC milling the surface roughness values of workpiece and flank wear value of tool insert were measured using Mitutoyo surface roughness tester and Sipkon measurement system respectively. Each run of the experiment contains three trial values for better output of the surface finish. For the analysis of optimization of input parameters average of these three trial values has been taken.

Table 1
Experimental design matrix

Run	A:Cutting speed (m/min)	B:Feed rate (mm/min)	C:Depth of cut (mm)	Surface Roughness (µm)	Tool Wear (µm)
1	175.925	500	1	10.97	52.3
2	201.06	500	1.5	16.13	112.5
3	175.925	500	1	12.14	53.3
4	175.925	500	1	11.94	56.5
5	150.79	500	0.5	13.16	44
6	175.925	500	1	11.48	51
7	175.925	500	1	10.92	53.7
8	175.925	600	1.5	14.56	108.5
9	201.06	600	1	12.01	46
10	150.79	500	1.5	13.48	90.12
11	175.925	500	1	11.21	48.65
12	150.79	400	1	12.81	75.5
13	175.925	500	1	11.56	56.2
14	175.925	600	0.5	11.21	48.65
15	175.925	500	1	11.21	51.9

16	175.925	500	1	11.34	54
17	150.79	600	1	13.10	78
18	175.925	400	1.5	12.98	86.5
19	175.925	500	1	11.67	50.3
20	175.925	500	1	12.02	51.9
21	201.06	400	1	11.37	71.5
22	201.06	500	0.5	13.16	49
23	175.925	500	1	11.62	57
24	175.925	400	0.5	10.25	49.57
25	175.925	500	1	11.78	55.6
26	175.925	500	1	11.56	54
27	175.925	500	1	12.09	52

4.1 Optimization of Surface Roughness and Tool Wear

The models were generated from the response parameter values in order to find the obtained models are productive or not. So, F-ratio test and ANOVA analysis has been performed. It was observed that the model generated for all the response parameters were significant.

4.1.1 Analysis of Surface Roughness and Tool Wear

The square root transformation was used for surface roughness model, therefore RSM suggests the desirability of the model is cubic as shown in Table 2. The power transformation was used for tool wear model, therefore RSM suggests the desirability of the model is cubic as shown in Table 3.

Table 2
Model significance of R_a using ANOVA

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	1.01	11	0.0921	29.88	< 0.0001	Significant
A-Cutting speed	0.2159	1	0.2159	70.05	< 0.0001	
B-Feed rate	0.0089	1	0.0089	2.90	0.1091	
C-Depth of cut	0.0933	1	0.0933	30.26	< 0.0001	
AB	0.0049	1	0.0049	1.57	0.2288	
AC	0.0015	1	0.0015	0.5008	0.4900	
BC	0.0140	1	0.0140	4.55	0.0499	

The model p-value of 0.0001 implies the significance of results. A “Model F-Value” 29.88 could occur due to noise only in 0.01 % cases. The value of “Prob >F” less than 0.0500 specify that model terms are significant for both R_a and T_w as shown in Table 2 and Table 3 respectively.

Table 3
Model significance of T_w using ANOVA

Source	Sum of Squares	DF	Mean Square	F-value	p-value	
Model	8122.66	12	676.89	116.70	< 0.0001	Significant
A-Cutting speed	2.25	1	2.25	0.3879	0.5434	
B-Feed rate	1.0000	1	1.0000	0.1724	0.6843	
C-Depth of cut	3409.39	1	3409.39	587.79	< 0.0001	
AB	600.25	1	600.25	103.49	< 0.0001	
AC	13.62	1	13.62	2.35	0.1478	
BC	131.33	1	131.33	22.64	0.0003	

4.1.2Mathematical Modeling And Regression Analysis

The results obtained by ANOVA model were formulated as a regression analysis equation for R_a and T_w by RSM and given in equation 1 and equation 2 respectively.

$$\sqrt{(\text{Surface Roughness})} = -45.54104 + (0.409834 * \text{Cutting speed}) + (0.150153 * \text{Feed rate}) + (14.48553 * \text{Depth of cut}) - (0.001036 * \text{Cutting speed} * \text{Feed rate}) + (0.001563 * \text{Cutting speed} * \text{Depth of cut}) - (0.064280 * \text{Feed rate} * \text{Depth of cut}) - (0.001208 * \text{Cutting speed}^2) - (0.000061 * \text{Feed rate}^2) + (0.354078 * \text{Depth of cut}^2) + (2.98511E-06 * \text{Cutting speed}^2 * \text{Feed rate}) + (0.000065 * \text{Feed rate}^2 * \text{Depth of cut})$$

…(1)

$$\text{Tool Wear} = 462.61911 - (5.71082 * \text{Cutting speed}) + (0.059769 * \text{Feed rate}) - (546.80920 * \text{Depth of cut}) - (0.004874 * \text{Cutting speed} * \text{Feed rate}) + (8.87290 * \text{Cutting speed} * \text{Depth of cut}) - (0.347000 * \text{Feed rate} * \text{Depth of cut} + 0.024959 * \text{Cutting speed2} + 0.000909 * \text{Feed rate2} - 194.07045 * \text{Depth of cut2} - 0.029410 * \text{Cutting speed2} * \text{Depth of cut} + 0.810822 * \text{Cutting speed} * \text{Depth of cut2} + 0.230800 * \text{Feed rate} * \text{Depth of cut2}$$

…(2)

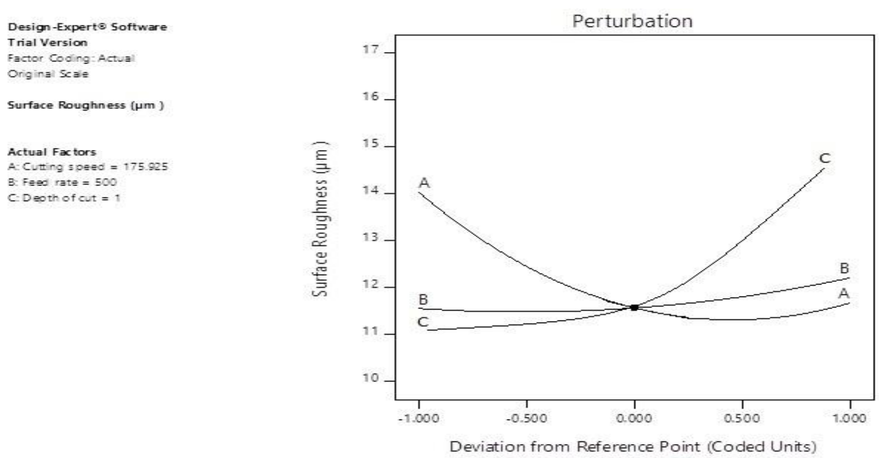
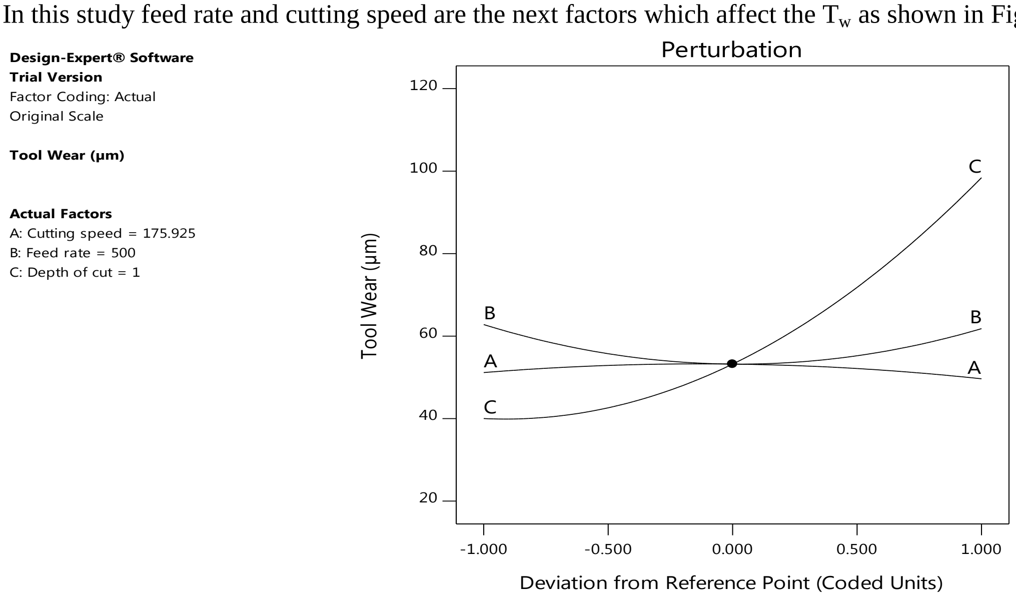


Figure 2 Perturbation plot for R_a

Figure 2 and Figure 3 shows the perturbation curve to study the effect of input variables on R_a and T_w respectively. It is evidently shown that the depth of cut is the most significant variable in governing R_a value, as depth of cut has steepest slope. In this case cutting speed is the next dominant factor which affects the R_a value and the feed rate has least influence on R_a which shows almost neutral behaviour as shown in Figure 2.

With the help of perturbation plot the influence of all the variables can be compared at a specific point in the design space. It is evidently shown that the depth of cut is the most significant variable in governing tool wear, as the slope is steepest for T_w. In this study feed rate and cutting speed are the next factors which affect the T_w as shown in Figure 3.



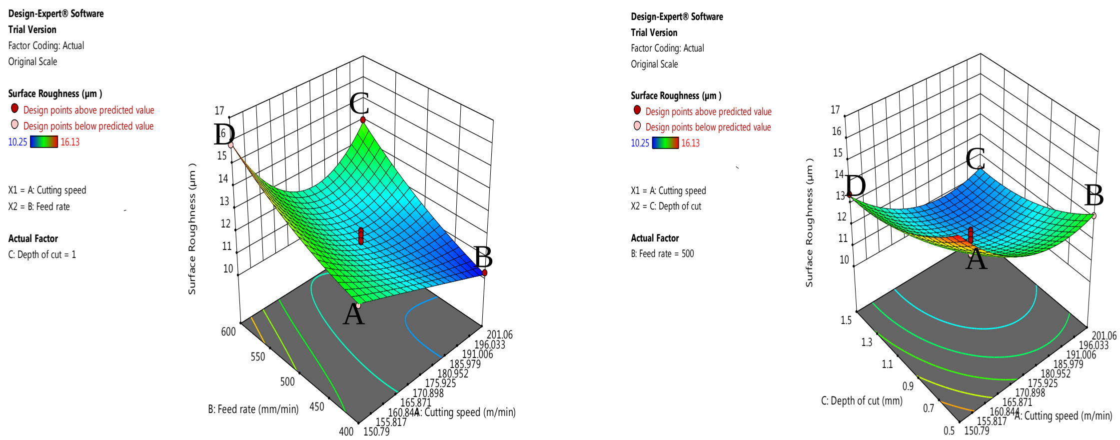
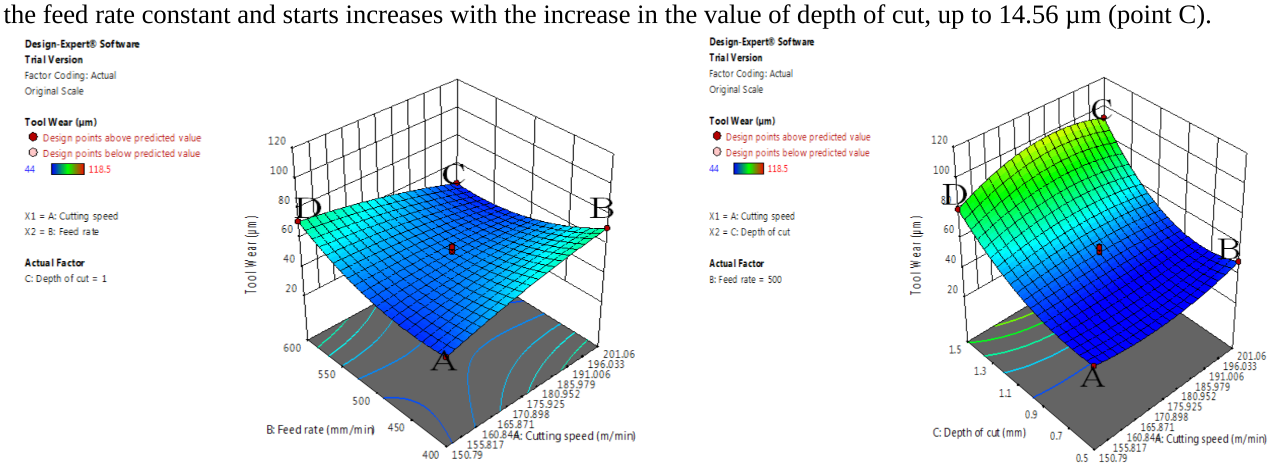
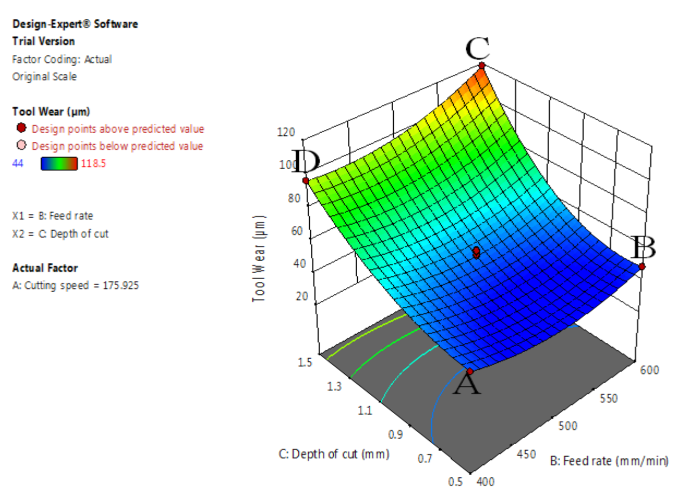


Figure 4 3D interaction plot showing effect between input parameters and surface roughness

Figure 4 (a) shows the minimum R_a of 10.25 µm (point B) at maximum speed of 201.06 m/min and minimum feed of 400 mm/min, it increases with decreases in cutting speed and increase in feed rate, up to 15.85 µm (point D). In Figure 4 (b) the minimum surface roughness of 11.30 µm (point C) at maximum cutting speed of 201.06 m/min and maximum depth of cut 1.5 mm, it increases with decrease in value of both the parameters up to 16.13 µm (point A). Combined effect of depth of cut and feed indicates that the minimum surface roughness of 11.21 µm (point B) at minimum depth of cut of 0.5 mm by keeping the feed rate constant and starts increases with the increase in the value of depth of cut, up to 14.56 µm (point C).



(a) Interaction between v, f and T_w



(c) Interaction between f, d and T_w

Figure 5 (a) shown below indicates the minimum tool wear of 46 µm (point C) at maximum feed rate 600 mm/min by keeping the feed rate constant and starts increases with decrease in cutting speed, up to 72 µm (point D) at minimum speed of 150.79 m/min. As the value of feed rate decreases, the value of tool wear also decreases and approaches to value of 48.5 µm (point A) at constant cutting speed of 150.79 m/min. In Figure 5 (b) the minimum tool wear of 44 µm (point A) at minimum depth of cut of 0.5 mm and at minimum cutting speed of 150.79 m/min. the maximum tool wear of 92.5 µm (point C) at maximum depth of cut 1.5 mm and maximum speed of 201.06 m/min. Combined effect of feed rate and depth of cut is shown in Figure 5 (c) indicates the minimum tool wear 48.65 µm (point D) at minimum depth of cut of 0.5 mm and maximum feed of 600 mm/min by keeping feed rate constant tool wear increases up to 118.5 µm (point C) with increases in the value of depth of cut.

4.2 Multi Response Optimization

A combination of factor levels were optimized simultaneously by selecting the required objectives for all response parameter to meet the requirements placed. The numerical multi response optimization criteria was employed to obtain the optimal input process parameter values for achieving minimum R_a and T_w. The importance for all input machining parameters is selected to be the same as shown in Table 4.

Table 4
Selected optimization criteria for RSM

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Cutting speed	is in range	150.79	201.06	1	1	3
Feed rate	is in range	400	600	1	1	3
Depth of cut	is in range	0.5	1.5	1	1	3
Surface Roughness	minimize	3.20156	4.01622	1	1	3
Tool Wear	minimize	44	118.5	1	1	3

Table 5
Optimized process parameters for machining

Cutting speed (m/min)	Feed Rate (mm/min)	Depth of Cut (mm)	Surface roughness (µm)	Tool wear (µm)	Desirability	
175.70	400	0.50	11.38	49.44	0.862	Selected

The optimal values of R_a and tool wear were 11.38 µm and 49.44 µm respectively at v of 175.7 m/min, feed of 400 mm/min, and depth of cut of 0.50 mm as optimum value of input process parameters. The numerical optimization found a point that gives the maximum desirability value as 0.862 which corresponds to the minimum values of R_a and T_w.

V. CONCLUSIONS

In the present work, milling of AISI 1050 steel was accomplished with coated tungsten carbide inserts to optimize the input process variables viz. cutting speed, feed and depth of cut for optimum T_w and R_a. The three level Box-Behnken Design was employed for developing mathematical models for calculating the optimized values of R_a and T_w. The conclusions extracted from the present work are discussed as follows:

a) The optimized process parameters obtained from machining through RSM were cutting speed of 175.7 m/min, feed rate of 400 mm/min and depth of cut of 0.50 mm.
b) Cutting speed and feed rate were found to have very less effect whereas depth of cut was found to have considerable impact on tool wear.
c) In case of surface roughness, depth of cut and cutting speed were found to be the most dominant parameters whereas feed rate has very less effect.

d) Better surface finish was found at low depth of cut and high cutting speed. The optimized value predicted for R_a was 11.38 μm.

e) Greater value of tool wear was produced at higher depth of cut. The optimized value predicted for tool wear was 49.44 μm.

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