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Multi Response Optimization of CNC End Milling Using Response Surface Methodology and Desirability Function

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Abstract

CNC end milling is the most important milling operation, widely used in most of the manufacturing industries due to its capability of producing complex geometric surfaces with reasonable accuracy and surface finish along with flexibility and versatility. Proper selection of machining parameter is an important step in process planning in order to build up a bridge between quality and productivity and to achieve the same in an economic way. This paper focuses RSM for the multiple response optimizations in CNC end milling operation to get maximum material removal rate, minimum surface roughness and less force. In this work, second-order quadratic models were developed for cutting forces, surface roughness and machining time; considering the spindle speed, feed rate, depth of cut and immersion angle as the cutting parameters using central composite design. Significant parameters are found out by analysis of variance test. The developed models were used for multiple-response optimization by desirability function in conjunction with response surface methodology to determine the optimum machining parameters.

1. Introduction

Milling is a very commonly used manufacturing process in industry due to its versatility to generate complex geometric shapes in variety of materials at high quality. Due to the advances in machine tool, CNC, CAD/CAM, cutting tool and high speed machining technologies the volume and importance of milling have increased in key industries such as aerospace, aeronautical, biomedical, die and mold, automotive and component manufacturing. However, with the inventions of CNC milling machine, the flexibility has been adopted along with versatility in end milling process. Only the implementation of automation in end milling process is not the last achievement. It is also necessary to improve the machining process and machining performances continuously for effective machining and also for the fulfillment of requirements of the industries.

Despite recent advances in machining technology, productivity in milling is usually reduced due to the process limitations such as high cutting forces and less stability. If milling conditions are not selected properly, the process may result in violations of machine limitations and part quality, or reduced productivity. The usual practice in machining operations is to use experience-based selection of cutting parameters which may not yield optimum conditions. The cutting forces affect the quality and the precision of the final component; therefore precise prediction of milling forces becomes an important factor to improve machining performance.

Surface roughness is another key factor in the machining process while considering machining performance and that is why in many cases, industries are looking for maintaining the good surface quality of the machined parts. The processing time of the work piece, is another important factor that greatly influences production rate and cost. It is also necessary to study the production time along with surface roughness in CNC end milling process. Both the surface roughness and machining time greatly vary with the change of cutting process parameters.

The present study highlights optimization of CNC end milling process parameters to provide good surface finish and high productivity in energy efficient manner. Optimization of more than one response simultaneously to find a setting of input factors from a number of alternatives is known as multiple response optimizations. In the present study multi response optimization of cutting forces, surface roughness and machining time in end milling is done using central composite design of response surface methodology and desirability function.

2. Response Surface Methodology

RSM is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response[2]. RSM is useful for developing, modeling and optimize the response variables. The procedure for RSM includes six steps. These are,(1) define the independent input variables and the desired output responses, (2) adopt an experimental design plan, (3) perform regression analysis with the quadratic model of RSM, (4) calculate the statistical analysis of variance (ANOVA) for the independent input variables in order to find parameters which significantly affect the response, (5) determine the situation of the quadratic model of RSM and decide whether the model of RSM needs screening variables or not and finally, (6) optimize, conduct confirmation experiment and verify the predicted performance characteristics.

2.1 Identifying the input variables and output responses

By the theoretical method of force analysis and by the practical knowledge cutting speed, feed rate, depth of cut and immersion angle are selected as input variables and cutting forces, surface roughness and machining time are selected as responses.

2.2 Experimental design

Central Composite rotatable Design is selected for experimental design, in which standard error remains the same at all the points which are equidistant from the centre of the region. The upper and lower limits and their levels of the parameters are given in the table1 and ccd matrix is given in table 2.

Table 1: Parameters and their levels.

Sl. No:	Parameters	Units	Notations	Factor Levels				
				-2	**-1**	**0**	**1**	**2**
1	Depth of cut	mm	D	.4	.8	1.2	1.6	2
2	Feed rate	mm/sec	F	.3	.6	.9	1.2	1.5
3	Cutting speed	m/min	V	56	84	112	140	224
4	Immersion angle	degree	A	90	120	180	270	360

3. Mathematical modeling by regression analysis

Second order quadratic models were developed by least square regression method. Mathematical equations for cutting forces in tangential F_x, radial F_y and axial F_z , surface roughness R_a and machining time T_m are given in coded factors :

$$F_x = 22.79- 0.21A + 2.75B - 0.053C + 0.34D + 0.44AB + 0.081AC + 0.041AD +0.22BC - 0.21BD +0.42CD -0.082A^2-1.04B^2+ 0.004C^2 -0.097D^2 \quad (1)$$

$$F_y = 45.3 – 0.82A + 6.7B – 0.22C + 0.86D + 1.38AB + 0.55AC – 0.15AD + 0.55BC – 1.03BD+ 2.04CD - 0.027A^2 – 5.88B^2 + 0.25C^2 – 0.027D^2 \quad (2)$$

$$F_z = 13.53 – 0.13A + 5.50 B – 0.0021C +0.79D + 0.31AB + 0.51AC – 0.33AD + 0.55BC + 0.129BD+0.15BD+0.59CD-0.12A^2+0.46B^2-0.038C^2-0.078D^2 \quad (3)$$

$$R_a = 1.27-0.31A+0.32B+0.13C+0.21D -0.20AB + 0.058AC - 0.067AD + 0.047BC +0.19BD + 0.086CD + 0.019A^2- 0.036B^2 - 0.081C^2 + 0.073D^2 \quad (4)$$

$$T_m = 1.22 + 0.096A + 0.048B – 0.52C -0.31D 0.072AB -0.072AC - 0.14AD -0.14BC -0.072BD +0.013CD -0.040A^2 – 0.040B^2 + 0.20C^2 + 0.13D^2 \quad (5)$$

Table 2: Central Composite Design Matrix.

Sl. No:	Depth of cut,mm	Feed rate, mm/sec	Speed m/min	Im. Angle degree	Fx N	Fy N	Fz N	Ra um	Tm min
1	0.8	0.6	84	132	19.868	34.903	9.0466	1.13	0.72
2	1.6	0.6	84	132	19.868	35.075	9.245	1.09	2.45
3	0.8	1.2	84	132	23.385	47.69	17.386	0.86	1.3
4	1.6	1.2	84	132	23.385	47.393	17.543	1.75	0.72
5	0.8	0.6	140	132	18.718	30.392	4.703	0.55	2.45
6	1.6	0.6	140	132	15.373	20.086	4.555	0.83	2.45
7	0.8	1.2	140	132	24.053	46.873	19.201	0.66	1.3
8	1.6	1.2	140	132	24.271	48.075	19.806	0.76	1.3
9	0.8	0.6	84	224	21.051	39.246	10.455	0.7	1.53
10	1.6	0.6	84	224	17.603	25.82	5.668	2.74	1.53
11	0.8	1.2	84	224	24.72	49.091	22.061	1.13	0.72
12	1.6	1.2	84	224	24.72	47.811	20.59	2.57	0.72
13	0.8	0.6	140	224	20.69	37.396	10.023	0.57	1.53
14	1.6	0.6	140	224	21.14	39.456	10.513	0.68	1.53
15	0.8	1.2	140	224	24.203	48.595	20.695	1.04	0.72
16	1.6	1.2	140	224	24.726	49.571	22.073	1.75	0.72
17	0.4	0.9	112	178	22.013	43.656	12.503	0.74	1.28
18	2	0.9	112	178	22.26	44.218	12.756	1.81	1.28
19	1.2	0.3	112	178	11.566	10.788	5.715	0.87	3.68
20	1.2	1.5	112	178	25.011	29.863	24.181	1.32	0.82
21	1.2	0.9	56	178	22.426	44.478	12.851	2.08	1.28
22	1.2	0.9	168	178	22.508	45.176	13.038	0.91	1.28
23	1.2	0.9	112	86	22.506	45.408	13.168	1.32	2.92
24	1.2	0.9	112	270	21.645	42.468	12.405	2.1	1
25	1.2	0.9	112	178	22.208	42.638	12.475	1.29	1.28
26	1.2	0.9	112	178	22.611	43.975	12.818	1.32	0.89
27	1.2	0.9	112	178	22.711	45.902	13.075	1.2	1.28
28	1.2	0.9	112	178	22.876	46.388	13.546	1.3	1.28
29	1.2	0.9	112	178	23.271	46.386	14.895	1.23	1.28
30	1.2	0.9	112	178	23.09	46.536	14.356	1.3	1.28

4. Analysis of Variance Test

The analysis of the experimental data was done to statistically analyze the significance of the parameters depth of cut (D), feed (F), speed (V) and immersion angle (A) on the response variables surface roughness and machining time. The model has been developed for 95% confidence level.

Table 3: ANOVA for response surface quadratic model for F_x.

Source	Sum of Squares	Degree of Freedom	Mean Square	F-value	P-value	
Model	223.92	14.00	15.99	9.54	< 0.0001	significant
A-Depth of cut	1.09	1.00	1.09	0.65	0.4332	
B-Feed rate	181.73	1.00	181.73	108.43	< 0.0001	significant
C-Speed	0.07	1.00	0.07	0.04	0.8449	
D-Imm. angle	2.81	1.00	2.81	1.68	0.2151	
AB	3.14	1.00	3.14	1.87	0.1915	
AC	0.10	1.00	0.10	0.06	0.8061	
AD	0.03	1.00	0.03	0.02	0.9015	
BC	0.77	1.00	0.77	0.46	0.5080	
BD	0.71	1.00	0.71	0.43	0.5236	
CD	2.85	1.00	2.85	1.70	0.2117	
A^2	0.19	1.00	0.19	0.11	0.7442	
B^2	29.90	1.00	29.90	17.84	0.0007	significant
C^2	0.00	1.00	0.00	0.00	0.9985	
D^2	0.26	1.00	0.26	0.16	0.6991	
Residual	25.14	15.00	1.68			
Lack of Fit	24.43	10.00	2.44	17.31	0.0029	significant
Pure Error	0.71	5.00	0.14			
Core Total	249.06	29.00				

Table 4: ANOVA for response surface quadratic model for R_a.

Source	Sum of Squares	Degree of Freedom	Mean Square	F-value	P-value	
Model	8.182	14.000	0.584	11.782	< 0.0001	significant
A-Speed	2.325	1.000	2.325	46.872	< 0.0001	significant
B-Depth of cut	2.451	1.000	2.451	49.415	< 0.0001	significant
C-Feed rate	0.408	1.000	0.408	8.229	0.0132	significant
D-Imm.angle	1.088	1.000	1.088	21.934	0.0004	significant
AB	0.612	1.000	0.612	12.344	0.0038	significant
AC	0.054	1.000	0.054	1.090	0.3156	
AD	0.072	1.000	0.072	1.443	0.2512	
BC	0.035	1.000	0.035	0.709	0.4151	
BD	0.589	1.000	0.589	11.875	0.0043	significant
CD	0.117	1.000	0.117	2.365	0.1481	
A^2	0.010	1.000	0.010	0.201	0.6614	
B^2	0.035	1.000	0.035	0.714	0.4134	
C^2	0.180	1.000	0.180	3.622	0.0794	
D^2	0.145	1.000	0.145	2.932	0.1106	
Residual	0.645	13.000	0.050			
Lack of Fit	0.637	10.000	0.064	24.188	0.0119	significant

The Model F-value for surface roughness of 11.78 implies the model is significant. There is only a 0.01% 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. In this case A, B, C, D, AB & BD are significant model terms.

5. Multi response Optimization by Desirability Function

Multi response optimization of CNC end milling by simultaneous optimization of forces, surface roughness and machining time is done to obtain the optimum cutting conditions at low cost, high quality and easily deliverable in the market. Once the function is defined for each of the ‘m’ responses of interest, an overall objective function (the total desirability) is defined as the geometric mean of the individual desirability:

$$D(X) = [\, d_1 Y_1(X) d_2(Y_2(X) \ldots d_m(Y_m(X)]^{1/m} \qquad (6)$$

To minimize a response, the individual desirability is calculated as [2]:

$$\begin{array}{lll} d_i = 0 & i > H_i & \\ d_i = [(H_i - i)/(\mathrm{H_i} - \mathrm{T_i})]^{ri} & & T_i \le i \le H_i \\ d_i = 1 & i < T_i & \end{array} \qquad (7)$$

The optimum cutting conditions are shown by ramp diagram in fig.1.

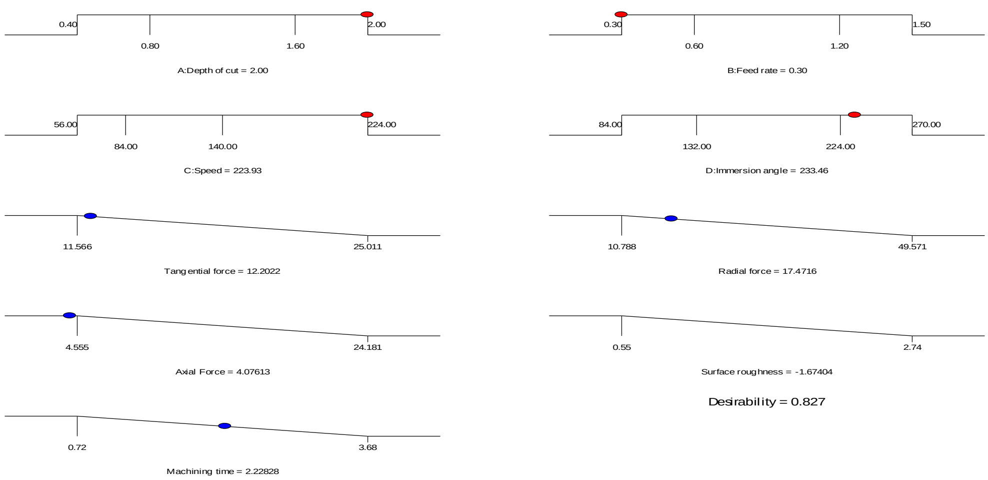

Fig. 1: Ramp diagram for optimum solution.

6. Conclusions

The optimum cutting conditions obtained by multiresponse optimization for maximum desirability are: depth of cut 2mm, feed rate .3mm/sec, cutting speed 224 m/min, immersion angle 233 degree. It is found that feed has significant effect on cutting force and it has to be kept minimum for least force and better surface finish and machining time. Cutting speed has significant effect on machining time and surface roughness. Speed has to be kept maximum for combined optimization of forces, roughness and machining time. With less power good surface finish is obtained at minimum time if cutting speed is kept maximum and depth of cut minimum.

References

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