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Torque Prediction Model for Milling 618 Stainless Steel Using Response Surface Methodology

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Abstract: The aim of this study was to develop the first and second order torque prediction model for milling 618 stainless steel with coated carbides cutting tool, using response surface methodology with 4 factors. From the model the equation that relates the factors (cutting speed, feed rate, axial depth and radial depth) with response (torque) can be developed. Beside the relationship, the effect of the factors can be investigated from the equation developed. The model generated show that the torque reach the maximum value when cutting speed decreased and, feed rate, axial depth and radial depth are increased. The second order is more accurate based on the variance analysis and the predicted value is closer with the experimental result.

Key words: Torque, surface response methodology, first order

INTRODUCTION

In this study, experimental results were used for modeling using Response Surface roughness Methodology (RSM)[1]. The RSM is practical, economical and relatively easy for use and it was used by lot of researchers for modelling machining processes[2-4]. Mead and Pike[5] and Hill and Hunter[6] reviewed the earliest study on response surface methodology. Response Surface Methodology (RSM) is a combination of experimental and regression analysis and statistical inferences. The concept of a response surface involves a dependent variable y called the response variable and several independent variables $x_1, x_2, ..., x_k$[7].

It has also been recognized that improving the technological performance measures, such as the chip formation, forces, power and tool life, improves the economic performance of machining operations as assessed by the time per component, cost per component or other suitable economic measures[8]. The main aim of the paper is to develop the first and second order model by using Surface Response Methodology. From this model, the relationship between the factors and the response can be investigated.

TORQUE MODEL

The proposed relationship between the machining responses (torque) and machining independent variables can be represented by the following:

$$\tau = C\,(V^m F^n A_x^y A_r^z)\varepsilon' \qquad (1)$$

Where τ is the torque in Nm, V, F, A_x and A_r are the cutting speed (m s^{-1}), feed rate (mm rev^{-1}), axial depth (mm) and radial depth (mm). C, m, n, y and z are the constants. Equation 1 can be written in the following logarithmic form:

$$\ln\tau = \ln C + m\ln V + n\ln F + y\ln A_x + z\ln A_r + \ln\varepsilon' \qquad (2)$$

Equation 2 can be written as a linear form:

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \varepsilon \qquad (3)$$

Where, y is the torque, x_0 = 1(dummy variables), x_1= ln V, x_2 = ln F,

x_3 = ln A_x, x_4 = ln A_r and ε = ln ε,where ε is assumed to be normally-distributed uncorrelated random error with zero mean and constant variance, β_0 = ln C and β_1, β_2, β_3 and β_4 are the model parameters. The second model can be expressed as:

$$\begin{aligned} y'' = {} & \beta_0 x_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{11} x^2{}_1 \\ & + \beta_{22} x^2{}_2 + \beta_{33} x^2{}_3 + \beta_{44} x^2{}_4 + \beta_{11} x_1 x_2 \\ & + \beta_{12} x_1 x_3 + \beta_{13} x_1 x_4 + \beta_{14} x_2 x_3 + \beta_{15} x_3 x_4 \end{aligned} \qquad (4)$$

The values of β_1, β_2, β_3 and β_4 are to be estimated by the method of least squares. The basic formula is:

$$\beta = (x^T x)^{-1} x^T y \qquad (5)$$

Where x^T is the transpose of the matrix x and $(x^T x)^{-1}$ is the inverse of the matrix $(x^T x)$. The details of the solution by this matrix approach are explained[1,9]. The

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Table 1: Levels of independent variables

Levels	Low	Medium	High
Coding	-1.0	0.0	1.0
Speed v (m s^{-1})	100.0	140.0	180.0
Feed f (mm rev^{-1})	0.1	0.2	0.3
Axial depth d_a (mm)	1.0	1.5	2.0
Radial depth d_r (mm)	2.0	3.5	5.0

parameters have been estimated by the method of least-square using a Matlab computer package.

Experimental design: To develop the first-order, a design consisting 27 experiments was conducted. Box-Behnken Design is normally used when performing non-sequential experiments. That is, performing the experiment only once. These designs allow efficient estimation of the first and second-order coefficients. Because Box-Behnken Design has fewer design points, they are less expensive to run than central composite designs with the same number of factors. Box-Behnken Design do not have axial points, thus can be sure that all design points fall within the safe operating. Box-Behnken Design also ensures that all factors are never set at their high levels simultaneously[10-12].Preliminary tests were carried out to find the suitable cutting speed, federate, axial depth and radial depth (Table 1).

Experimental details: The 618 stainless steel work pieces were provided in fully annealed condition in sizes of 65x170 mm and produce by Sanyo Special Steel Co. Ltd. The tools used in this study are carbide inserts PVD coated with one layer of TiN. The inserts are manufactured by Kennametal with ISO designation of KC 735M. They are specially developed for milling applications where stainless steel is the major machined material.

The end-milling tests were conducted on Okuma CNC machining centre MX-45VA The cutting tests were carried out according to ISO standard. Dynamometer used to measure the torque. In dynamometer designs, strain gages are used as transducer and strain rings such as octagonal, semi-octagonal and circular sectioned are used as spring element in general[13]. Wheatstone bridges are constituted with strain gages fitted on the strain rings and force signals are measured from the bridge outputs. Two or tree component cutting force dynamometers which have high rigidity and capacity have been designed and manufactured[14]. It is necessary that analogue force signals coming from dynamometer for evaluation are converted into digital signals and record to a data recorder or a computer.

Every one passes (one pass is equal to 85mm), the cutting test was stopped. The same experiment has been repeated for 3 times to get more accurate result. Table 2 shows the experimental cutting conditions together with the measured torque.

Table 2: Experiment condition and results of measured torque

Run	Cutting speed (m s^{-1})	Feed (mm rev^{-1})	Axial depth (mm)	Radial depth (mm)	Exp. torque (Nm)
1	140	0.15	1.0	2.0	10
2	140	0.20	1.0	3.5	13
3	100	0.15	1.0	3.5	16
4	180	0.15	1.0	3.5	13
5	140	0.10	1.0	3.5	8
6	140	0.15	1.0	5.0	16
7	100	0.15	1.5	2.0	16
8	140	0.10	1.5	2.0	7
9	100	0.20	1.5	3.5	17
10	140	0.15	1.5	3.5	14
11	180	0.20	1.5	3.5	18
12	180	0.15	1.5	2.0	12
13	140	0.20	1.5	2.0	13
14	140	0.15	1.5	3.5	18
15	140	0.15	1.5	3.5	13
16	180	0.10	1.5	3.5	8
17	100	0.10	1.5	3.5	14
18	100	0.15	1.5	5.0	22
19	140	0.10	1.5	5.0	14
20	180	0.15	1.5	5.0	15
21	140	0.15	1.5	3.5	18
22	140	0.15	2.0	5.0	20
23	140	0.20	2.0	3.5	23
24	140	0.10	2.0	3.5	13
25	140	0.15	2.0	2.0	11
26	100	0.15	2.0	3.5	23
27	180	0.15	2.0	3.5	16

RESULTS AND DISCUSSION

First-order model: The torque first order model is:

$$y = 2.6215 - 0.1308x_1 + 0.2292x_2 + 0.1408x_3 + 0.2142x_4 \quad (6)$$

Table 3 shows the 95% confidence interval for the experiments. For the linear model, the p-value for lack of fit is 0.196 and the F-statistics is 5.1033.Therefore, the model is adequate (Table 4).

The transforming equations for each of the independent variables are:

$$x_1 = \frac{\ln(V) - \ln(v)\text{centre}}{\ln(v)\text{high} - \ln(v)\text{centre}}$$

$$x_2 = \frac{\ln(F) - \ln(f)\text{centre}}{\ln(f)\text{high} - \ln(f)\text{centre}}$$

$$x_3 = \frac{\ln(A_x) - \ln(a_x)\text{centre}}{\ln(a_x)\text{high} - \ln(a_x)\text{centre}}$$

$$x_4 = \frac{\ln(A_r) - \ln(a_r)\text{centre}}{\ln(a_r)\text{high} - \ln(a_r)\text{centre}} \quad (7)$$

Equation 6 describing the torque model can be transformed using Eq. 7 into the following form:

$$T = 315.23(V^{-0.5204}F^{0.796719}A_x^{0.489432}A_r^{0.60055}) \quad (8)$$

This result shows that feed rate has the most significant effect on the torque, follow by axial depth, radial depth and cutting speed. The equation shows that the torque increasing with reducing the cutting speeds and increasing the feed rate, axial depth and radial depth. Equation 5 is utilized to develop torque contour at the selected cutting speed and feed rate. Figure 1a to c show the torque contour with selected cutting speed and feed rate. These contours help to predict the torque at any zone of experimental zone.

From the contour, the torque reach the highest value at Fig. 1c where the value of cutting speed at its lower value, feed rate, axial depth and radial depth at their maximum value. The torque can reach more than 25Nm in Fig. 1c. The lowest torque is in Fig. 1a when the cutting speed at its maximum value and the other factors at its maximum value. From this contour plot, the safety zone of torque can be selected for any experiment.

The second-order model was postulated in obtaining the relationship between the cutting force and the machine independent variables. The model was based on the Box-Behnken Design method. The model equation is:

$$\begin{aligned} y'' = {} & 2.05074 - 0.031x_1 + 47.37x_2 + 2.97x_3 + 1.60x_4 + \\ & 0.00029x_1^2 - 50.17x_2^2 - 0.78x_3^2 - 0.14x_4^2 - 0.29x_1x_2 - \\ & 0.018x_1x_3 - 0.0094x_1x_4 + 24.3x_2x_3 + 12.8x_2x_4 + 0.80x_3x_4 \end{aligned} \quad (9)$$

Table 5 shows the 95% confidence interval for the experiments. For the second-order model, the p-value for lack of fit is 0.221 and the F-statistics is 4.5249 (Table 6). Therefore, the model is adequate. The second-order model

Table 3: The predicted result from the first order model

Run	Cutting speed (m s^{-1})	Feed rate (mm rev^{-1})	Axial depth (mm)	Radial depth (mm)	Exp. torque (Nm)	Pre. torque (Nm)
2	140	0.15	1.0	2.0	10	8.06
7	140	0.20	1.0	3.5	13	14.18
11	100	0.15	1.0	3.5	16	13.43
14	180	0.15	1.0	3.5	13	9.89
19	140	0.10	1.0	3.5	8	8.16
21	140	0.15	1.0	5.0	16	13.97
4	100	0.15	1.5	2.0	16	11.71
5	140	0.10	1.5	2.0	7	7.11
6	100	0.20	1.5	3.5	17	20.60
9	140	0.15	1.5	3.5	14	13.75
10	180	0.20	1.5	3.5	18	15.17
12	180	0.15	1.5	2.0	12	8.62
15	140	0.20	1.5	2.0	13	12.36
22	140	0.20	1.5	5.0	18	21.42
24	140	0.15	1.5	3.5	13	13.75
25	180	0.10	1.5	3.5	8	8.73
26	100	0.10	1.5	3.5	14	11.86
8	100	0.15	1.5	5.0	22	20.29
17	140	0.10	1.5	5.0	14	12.33
18	180	0.15	1.5	5.0	15	14.95
22	140	0.15	1.5	3.5	18	13.75
1	140	0.15	2.0	5.0	20	19.61
3	140	0.20	2.0	3.5	23	19.91
13	140	0.10	2.0	3.5	13	11.46
16	140	0.15	2.0	2.0	11	11.31
20	100	0.15	2.0	3.5	23	18.86
27	180	0.15	2.0	3.5	16	13.89

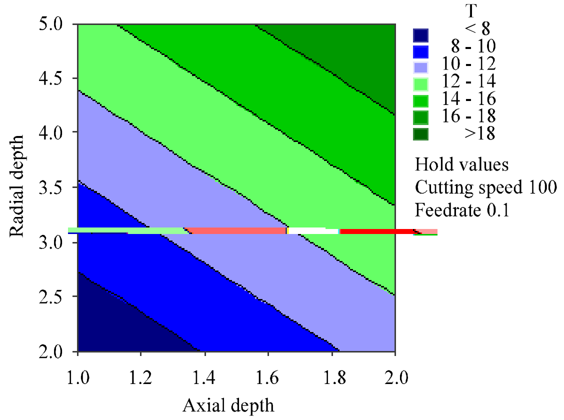

Fig. 1a: Torque contours in the Axial depth-radial depth plane for cutting speed 100 m s^{-1} and feed rate 0.1 mm rev^{-1}

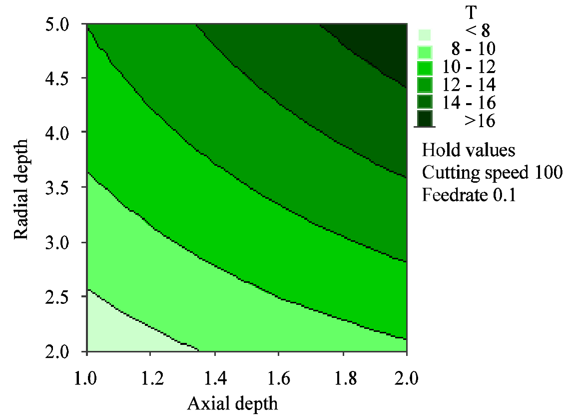

Fig. 2a: Torque contours in the Axial depth-radial depth plane for cutting speed 100 m s^{-1} and feed rate 0.1 mm rev^{-1}

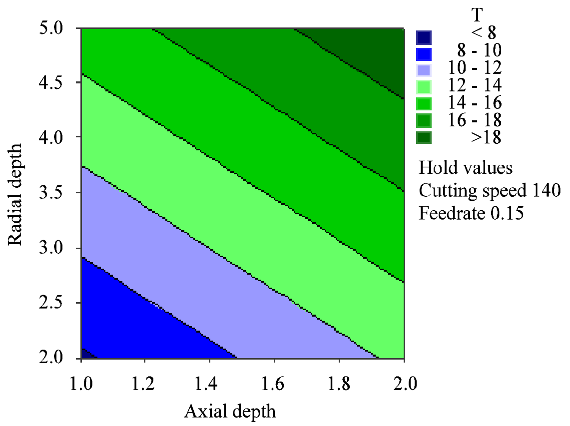

Fig. 1b: Torque contours in the Axial depth-radial depth plane for cutting speed 140 m s^{-1} and feed rate 0.15 mm rev^{-1}

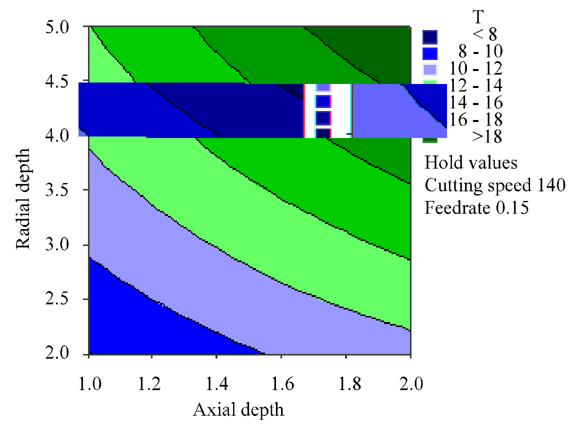

Fig. 2b: Torque contours in the Axial depth-radial depth plane for cutting speed 140 m s^{-1} and feed rate 0.15 mm rev^{-1}

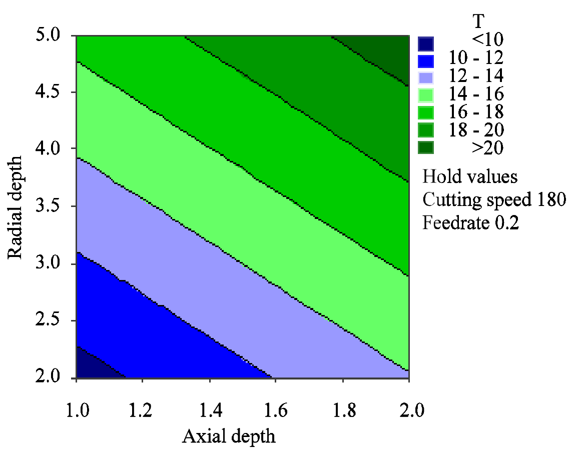

Fig. 1c: Torque contours in the Axial depth-radial depth plane for cutting speed 180 m s^{-1} and feed rate 0.2 mm rev^{-1}

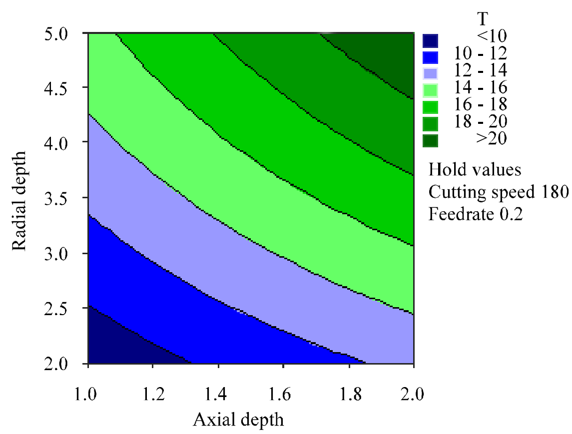

Fig. 2c: Torque contours in the Axial depth-radial depth plane for cutting speed 180 m s^{-1} and feed rate 0.2 mm rev^{-1}

Table 4: Analysis of variance from the first order model

Source	DF	Seq SS	Adj SS	Adj MS	F-value	p-value
Regression	4	434.746	434.746	108.687	186.37	0.000
Linear	4	434.746	434.746	108.687	186.37	0.000
Residual error	22	12.830	12.830	0.583		
Lack-of-fit	20	12.830	12.830	0.642	5.1033	0.196
Pure error	2	0.000	0.000	0.1258		
Total	26	447.576				

Table 5: The predicted result from the second order model

Run	Cutting speed (m s^{-1})	Feed rate (mm rev^{-1})	Axial depth (mm)	Radial depth (mm)	Exp. Torque (Nm)	Pre. torque (Nm)
2	140	0.15	1.0	2.0	10	7.94
7	140	0.20	1.0	3.5	13	14.21
11	100	0.15	1.0	3.5	16	13.51
14	180	0.15	1.0	3.5	13	9.97
19	140	0.10	1.0	3.5	8	8.09
21	140	0.15	1.0	5.0	16	13.98
4	100	0.15	1.5	2.0	16	11.84
5	140	0.10	1.5	2.0	7	6.98
6	100	0.20	1.5	3.5	17	20.45
9	140	0.15	1.5	3.5	14	13.75
10	180	0.20	1.5	3.5	18	15.05
12	180	0.15	1.5	2.0	12	8.72
15	140	0.20	1.5	2.0	13	12.39
22	140	0.20	1.5	5.0	18	21.55
24	140	0.15	1.5	3.5	13	13.75
25	180	0.10	1.5	3.5	8	8.87
26	100	0.10	1.5	3.5	14	11.97
8	100	0.15	1.5	5.0	22	20.20
17	140	0.10	1.5	5.0	14	12.30
18	180	0.15	1.5	5.0	15	14.82
22	140	0.15	1.5	3.5	18	13.75
1	140	0.15	2.0	5.0	20	19.73
3	140	0.20	2.0	3.5	23	19.98
13	140	0.10	2.0	3.5	13	11.44
16	140	0.15	2.0	2.0	11	11.30
20	100	0.15	2.0	3.5	23	18.78
27	180	0.15	2.0	3.5	16	13.81

Table 6: Analysis of variance for second-order model

Source	DF	Seq SS	Adj SS	Adj MS	F	p-value
Regression	14	447.358	447.358	31.954	1758.88	0.000
Linea	4	434.746	434.746	108.687	5982.52	0.000
Square	4	2.922	2.922	0.731	40.21	0.000
Interaction	6	9.690	9.690	1.615	88.90	0.000
Residual error	12	0.218	0.218	0.018		
Lack-of-fit	10	0.218	0.218	0.022	4.5249	0.221
Pure error	2	0.000	0.000	0.00486		
Total	26	447.576				

is more adequate, because the predicted result is much more accurate than the first model. The p-value show much bigger than the first order. Equation 9 is used to develop the contour plot (Fig. 2a-c).

From the contour 1a-c, the power reach the highest force when the cutting speed, feed rate, axial depth and radial depth at their maximum value. The lower power shown in contour 1a when the feed rate, cutting speed, axial depth and radial depth at their lower value.

CONCLUSIONS

Response surface methodology design of experiments actually safe lot of time and cost of the experiments. From this design of experiments, lot of useful information such as develops first order and second order of torque and contour plot. The torque equation show that feed rate, cutting speed, axial depth and radial depth plays the major role to produce the power. The higher the feed rate, axial depth and radial depth, the torque generates very high compare with low value of feed rate, axial depth and radial depth. The contour and the contour plot show the safe zone, to produce the optimum torque The second-order is more accurate because the predicted result is much closer with the experimental result.

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