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

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Abstract: This study discussed the development of the first and second order power prediction model for milling 618 stainless steel with coated carbides cutting tool. The first and second order model has been developed by using response surface methodology with 4 factors. The surface methodology has been analysis by using statistical software Minitab. From the model the equation that relates the factors (cutting speed, feed rate, axial depth and radial depth) with the response (power) can be developed. Beside the relationship, the effect of the factors can be investigated from the equation develop. From the equation develop; the contour plot can be generated to predict the power at any zone of experimental zone. The model generated show that the power increases when cutting speed, feed rate, axial depth and radial depth are increased. The second-order is more accurate compare with the first order.

Key words: Power, surface response methodology, Minitab

INTRODUCTION

Response surface methodology can be simplified a huge number of experiments where it saves time and the cost of the experiments. By using this method the effect of the four factors can be investigated and produce an adequate functional relationship between factors and response.

Mead and Pike[1] and Hill and Hunter[2] reviewed the earliest work on response surface methodology. Empirical model building theory discussed by G. E. P. Box and Draper[3]. To construct a more general model of the original function; the method of experiment design[4,5] together with approximate model building[6-8] can be employed. 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 x1, x2,. . .,xk[9].

It has long been recognized that, in order to optimize the economic performance of machining operations, reliable quantitative technological performance data and equations are required for the wide spectrum of machining operations, tools and work piece materials used in practice[10,11]. 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[12].

Armarego and Desphande[13] and Armarego, Wang and Desphande[14] dealt with predictive models for end milling forces, torque and power and used the generic unified mechanics of cutting approach' and incorporated many tools and cut geometrical variables as well as tooth run out to develop a software module for the average and fluctuating force components in face milling. Sood, R. Guo, C., Malkin, S.[15] made a study of the specific energy where the power of machining is one of the parameter effect the specific energy.

Machining power model: The machining power is the product of cutting speed, υ and the cutting force, F_c. Thus the equation for the power is:

$$P = F_c \upsilon \tag{1}$$

where P is the power in watt, υ is the cutting speed in m/min and F_c is the cutting force in N.

The proposed relationship between the machining responses (power) and machining independent variables can be represented in linear form:

$$\begin{aligned} P &= m\text{Cuttingspeed} + n\text{Feedrate} \\ &\quad + p\text{Axialdepth} + q\text{Radialdepth} + C \end{aligned} \tag{2}$$

where P is the power in watt (w), C, m, n, p and q are the constants. Equation (2) can be written in the following form:

$$y = \beta_0 x_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 \tag{3}$$

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where y is the power, $x_0 = 1$ (dummy variables), x_1= cutting speed, x_2 = Feed rate, x_3 = Axial depth and x_4 = Radial depth. β_0 = C and β_1, β_2, β_3 and β_4 are the model parameters. The second model can be expressed as:

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

The second order is important to get more accurate prediction for the cutting force. The Box-Behnken Design method has been done by using Minitab software

Experimental design: To develop the first-order, a design consisting 27 experiments was conducted. This experiment conducted to measure the cutting force F_c and the cutting speed of the preliminary test. After the experiment, the power calculated using the equation (1) then generated the equation using Minitab. Box and Behnken[16], derived a series of three- level second-order designs that have been very popular, especially for a small number of factors. For t = 3 factors, the Box-Behnken (BB) design requires only 12 runs, plus a recommended n0 = 3 center point runs. The comparable central composite design requires 14 runs in addition to the center point replicates[16]. 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 does not have axial points, thus can be sure that all design points fall within the safe operating[3,16,17,18]. Preliminary tests were carried out to find the suitable cutting speed, federate, axial depth and radial depth. The suitable value of the factors after the preliminary test shown in Table 1.

Experimental details: The 618 stainless steel work pieces were provided in the 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 center MX-45VA with a maximum spindle rotary speed of 7000 RPM and maximum power of 10hp.The cutting tests were carried out according to ISO standard. Dynamometer used to measure the cutting force. In dynamometer designs, strain gages are used as a transducer and strain rings such as octagonal, semi-octagonal and circular sectioned are used as a spring element in general[19].

Table 1: Levels of independent variables

Levels	Low	Medium	High
Coding	-1	0	1
Speed v(m/s)	100	140	180
Feed f(mm/rev)	0.1	0.2	0.3
Axial depth d_a(mm)	1	1.5	2
Radial depth d_r(mm)	2	3.5	5

Table 2: Experiment condition and results

Run	Cutting Speed	Feed	Axial depth	Radial depth	Force
1	140	0.15	1	2	146.67
2	140	0.2	1	3.5	190
3	100	0.15	1	3.5	190
4	180	0.15	1	3.5	170
5	140	0.1	1	3.5	110
6	140	0.15	1	5	225
7	100	0.15	1.5	2	240
8	140	0.1	1.5	2	100
9	100	0.2	1.5	3.5	340
10	140	0.15	1.5	3.5	220
11	180	0.2	1.5	3.5	293.33
12	180	0.15	1.5	2	145
13	140	0.2	1.5	2	200
14	140	0.15	1.5	3.5	325
15	140	0.15	1.5	3.5	200
16	180	0.1	1.5	3.5	130
17	100	0.1	1.5	3.5	190
18	100	0.15	1.5	5	340
19	140	0.1	1.5	5	210
20	180	0.15	1.5	5	240
21	140	0.15	1.5	3.5	200
22	140	0.15	2	5	350
23	140	0.2	2	3.5	350
24	140	0.1	2	3.5	200
25	140	0.15	2	2	190
26	100	0.15	2	3.5	340
27	180	0.15	2	3.5	313.33

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[20]. 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. . Therefore the data transfer has been provided from dynamometer to a computer, the cutting force variation depends on changing of cutting parameters has been measured and modeling studies have been done about tool condition monitoring[21].

Everyone passes (one pass is equal to 85mm), the cutting test were stopped. The same experiment has been repeated for 3 times to get a more accurate result. Table 2 shows the experimental cutting conditions together with the measured cutting force and Table 3 shows the calculated power.

RESULTS AND DISCUSSION

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

$$y = -58285.4 + 142.706x_1 + 177832x_2 + 16560.9x_3 + 5187.01x_4 \qquad (5)$$

Table 3a: Calculated power using equation (1)

Run	Cutting speed	Feedrate	Axial depth	Radial depth	Ex.result	Power calc.
2	140	0.15	1	2	146.67	20533.8
7	140	0.2	1	3.5	190	26600
11	100	0.15	1	3.5	190	19000
14	180	0.15	1	3.5	170	30600
19	140	0.1	1	3.5	110	15400
21	140	0.15	1	5	225	31500
4	100	0.15	1.5	2	240	24000
5	140	0.1	1.5	2	100	14000
6	100	0.2	1.5	3.5	340	34000
9	140	0.15	1.5	3.5	220	30800
10	180	0.2	1.5	3.5	293.33	52799.4
12	180	0.15	1.5	2	145	26100
15	140	0.2	1.5	2	200	28000
22	140	0.2	1.5	5	325	45500
24	140	0.15	1.5	3.5	200	28000
25	180	0.1	1.5	3.5	130	23400
26	100	0.1	1.5	3.5	190	19000
8	100	0.15	1.5	5	340	34000
17	140	0.1	1.5	5	210	29400
18	180	0.15	1.5	5	240	43200
22	140	0.15	1.5	3.5	200	28000
1	140	0.15	2	5	350	49000
3	140	0.2	2	3.5	350	49000
13	140	0.1	2	3.5	200	28000
16	140	0.15	2	2	190	26600
20	100	0.15	2	3.5	340	34000
27	180	0.15	2	3.5	313.33	56399.4

Table 3b: The predicted result of the first order model

Run	Cutting speed	Feedrate	Axial depth	Radial depth	Ex.result	Power calc.	Pre. Power
2	140	0.15	1	2	146.67	20533.8	15303.2
7	140	0.2	1	3.5	190	26600	31975.3
11	100	0.15	1	3.5	190	19000	17375.5
14	180	0.15	1	3.5	170	30600	28791.9
19	140	0.1	1	3.5	110	15400	14192.1
21	140	0.15	1	5	225	31500	30864.2
4	100	0.15	1.5	2	240	24000	17875.4
5	140	0.1	1.5	2	100	14000	14692
6	100	0.2	1.5	3.5	340	34000	34547.6
9	140	0.15	1.5	3.5	220	30800	31364.2
10	180	0.2	1.5	3.5	293.33	52799.4	45964
12	180	0.15	1.5	2	145	26100	29291.9
15	140	0.2	1.5	2	200	28000	32475.3
22	140	0.2	1.5	5	325	45500	48036.3
24	140	0.15	1.5	3.5	200	28000	31364.2
25	180	0.1	1.5	3.5	130	23400	28180.8
26	100	0.1	1.5	3.5	190	19000	16764.3
8	100	0.15	1.5	5	340	34000	33436.5
17	140	0.1	1.5	5	210	29400	30253.1
18	180	0.15	1.5	5	240	43200	44852.9
22	140	0.15	1.5	3.5	200	28000	31364.2
1	140	0.15	2	5	350	49000	47425.2
3	140	0.2	2	3.5	350	49000	48536.3
13	140	0.1	2	3.5	200	28000	30753
16	140	0.15	2	2	190	26600	31864.1
20	100	0.15	2	3.5	340	34000	33936.4
27	180	0.15	2	3.5	313.33	56399.4	45352.9

Table 4: Analysis of variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	4	2888968111	2888968111	722242028	39.69	0.000
Linear	4	2888968111	2888968111	722242028	39.69	0.000
Residual Error	22	400285851	400285851	18194811		
Lack-of-Fit	20	395059184	395059184	19752959	7. 56	0.123
Pure Error	2	5226667	5226667	2613333		
Total	26	3289253962				

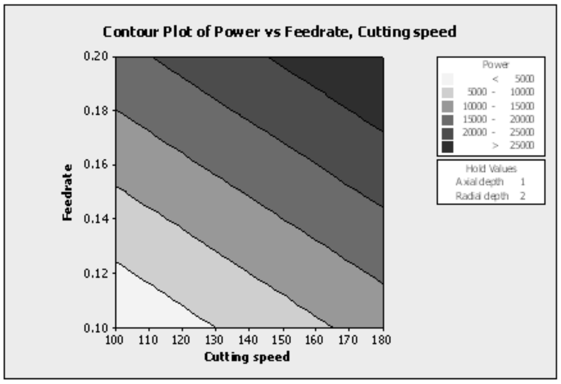

Fig. 1a: Power contours in the cutting speed-feed rate plan for axial depth 1 mm and radial depth 2mm

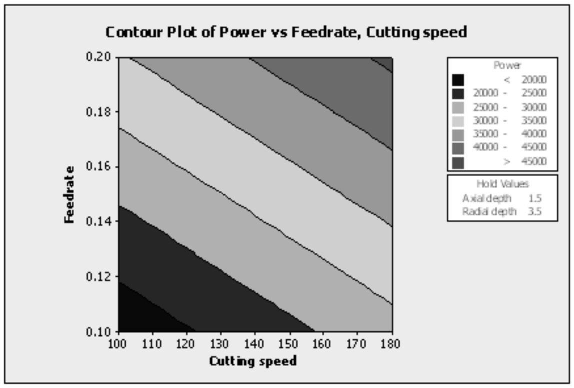

Fig. 1b: Power contours in the cutting speed-feed rate plan for axial depth 1.5 mm and radial depth 3.5mm

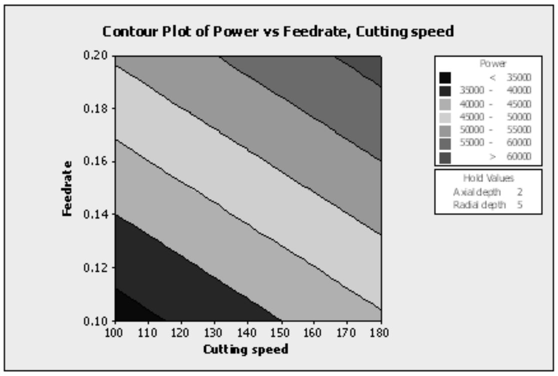

Fig. 1c: Power contours in the Cutting speed-feed rate plan for axial depth 2 mm and radial depth 5mm

Table 3 shows the 95% confidence interval for the experiments. The analysis of variance is shown in Table 4. For the linear model, the p-value for lack of fit is 0.123 and the F-statistics are 7.56. Therefore, the model is adequate.

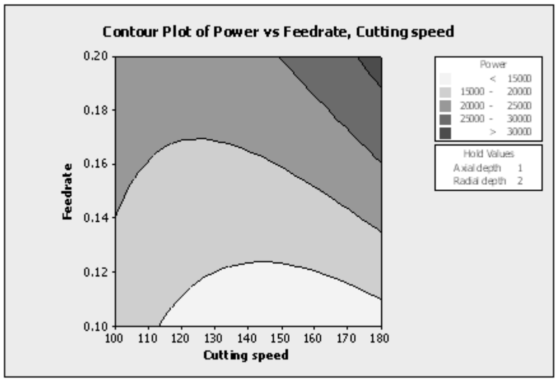

Fig. 2a: Power contours in the cutting speed-feed rate plan for axial depth 1 mm and radial depth 2mm

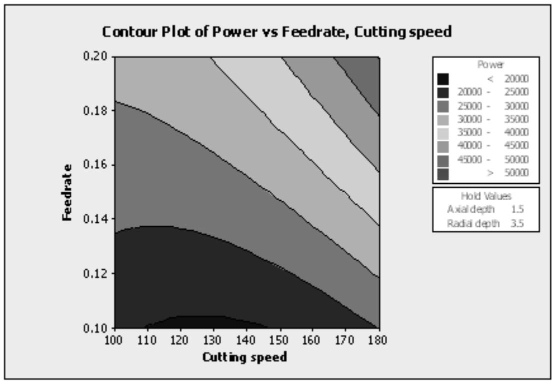

Fig. 2b: Power contours in the cutting speed-feed rate plan for axial depth 1.5 mm and radial depth 3.5mm

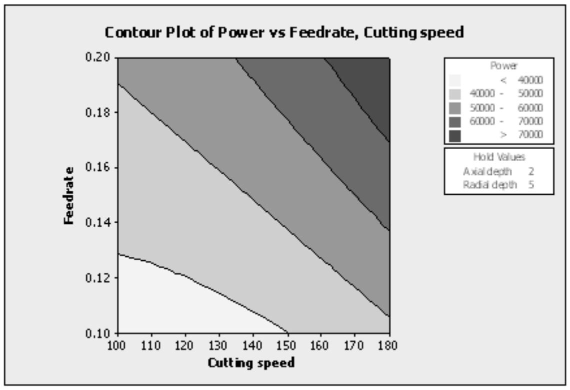

Fig. 2c: Power contours in the cutting speed-feed rate plan for axial depth 2 mm and radial depth 5mm

This result shows that feed rate has the most significant effect on the power, follow by axial depth, radial depth and cutting speed.

Table 5: The predicted result of the second order model

Run	Cutting speed	Feedrate	Axial depth	Radial depth	Ex.result	Power calc.	Pre. Power
2	140	0.15	1	2	146.67	20533.8	18269.8
7	140	0.2	1	3.5	190	26600	28791.7
11	100	0.15	1	3.5	190	19000	23266.6
14	180	0.15	1	3.5	170	30600	29283.4
19	140	0.1	1	3.5	110	15400	15908.4
21	140	0.15	1	5	225	31500	28113.9
4	100	0.15	1.5	2	240	24000	20991.8
5	140	0.1	1.5	2	100	14000	12633.5
6	100	0.2	1.5	3.5	340	34000	31447.3
9	140	0.15	1.5	3.5	220	30800	28933.3
10	180	0.2	1.5	3.5	293.33	52799.4	50063.4
12	180	0.15	1.5	2	145	26100	28858.2
15	140	0.2	1.5	2	200	28000	29366.7
22	140	0.2	1.5	5	325	45500	45977.7
24	140	0.15	1.5	3.5	200	28000	28933.3
25	180	0.1	1.5	3.5	130	23400	25080.5
26	100	0.1	1.5	3.5	190	19000	20863.7
8	100	0.15	1.5	5	340	34000	33002.8
17	140	0.1	1.5	5	210	29400	27144.5
18	180	0.15	1.5	5	240	43200	47969.3
22	140	0.15	1.5	3.5	200	28000	28933.3
1	140	0.15	2	5	350	49000	50391.8
3	140	0.2	2	3.5	350	49000	50252.6
13	140	0.1	2	3.5	200	28000	27569.4
16	140	0.15	2	2	190	26600	29113.8
20	100	0.15	2	3.5	340	34000	34427.8
27	180	0.15	2	3.5	313.33	56399.4	51244

Table 6: Analysis of variance for second –order model

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	14	3135916689	3135916689	223994049	17.53	0.000
Linear	4	2888968111	2888968111	722242028	56.52	0.000
Square	4	95558192	95558192	23889548	1.87	0.181
Interaction	6	151390386	151390386	25231731	1.97	0.149
Residual Error	12	153337273	153337273	12778106		
Lack-of-Fit	10	148110606	148110606	14811061	5. 67	0.159
Pure Error	2	5226667	5226667	2613333		
Total	26	3289253962				

The equation shows that the power increasing with increasing feed rate, axial depth and radial depth. Equation (5) is utilized to develop power contour at the selected axial depth, radial depth. Figure 1 (a) to 1 (c) show the cutting force contour and surface plot with selected axial and radial depth. These contours help to predict the cutting force at any zone of experimental zone.

From the contour, the power reaches the highest value at Fig. 1 (c) where the value of cutting speed, feed rate, axial depth and radial depth at their maximum value. The power can reach more than 60000w in Fig. 1 (c) .The low power is in Fig. 1 (b) when all the factor value in their minimum value. From this contour plot, the safety zone of power 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:

$$y'' = -124800 - 1033.15x_1 - 185985x_2 - 56710.9x_3 - 6793.44x_4$$
$$+2.14229x^2{}_1 - 198907x^2{}_2 + 8777.83x^2{}_3 + 1799.93x_1x_2 +$$
$$134.992x_1x_3 + 29.5833x_1x_4 + 98000x_2x_3 + 7000x_2x_4 + 3811.27x_3x_4$$

Table 5 shows the 95% confidence interval for the experiments. The analysis of variance is shown in Table 6. For the second-order model, the p-value for lack of fit is 0.159 and the F-statistics are 5.67. Therefore, the model is adequate. The second-order model 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 (4) is used to develop the contour plot as shown in Fig. 2 (a) to 2 (c).

From the contour 2 (a) to 2 (c), the power reaches the highest force when the cutting speed, feed rate, axial depth and radial depth at their maximum value. The lower power shown in contour 2 (a) when the feed rate, cutting speed, axial depth and radial depth of their lower value.

CONCLUSION

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

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