PREDICTION OF CUTTING FORCE BY NUMERICAL SOLUTION AND STATISTIC METHOD IN END-MILLING OPERATION

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Abstract. *The present paper discusses the development of the first order models and finite element analysis for predicting the cutting force produced in end-milling operation of modified AISI P20 tool steel. The first order cutting force equations are developed using the response surface methodology (RSM) to study the effect of four input cutting parameters (cutting speed, feed rate, radial depth and axial depth of cut) on cutting force. The cutting force contours with respect to input parameters are shown and the predictive models analyses are performed with the aid of the statistical software package Minitab. The predictive models in this study are believed to produce values of the longitudinal component of the cutting force close to those readings recorded experimentally with a 95% confident interval. Explicit code Thirdwave AdvantEdge has been used to estimate cutting and thrust forces. These estimated results are compared with experiments performed in this study and predictive model developed in this paper. The result from the simulation results are agreed with experimental value and predictive value from RSM.*

Keywords: Cutting force, AISI P20, end milling, RSM, finite element analysis

Introduction

Cutting Force is one of the important factors for metal cutting process. Metal cutting process is common and important process for machining and fabrications. For a long time, manufacturing engineers and researchers have been realising that in order to optimise the economic performance of metal cutting operations, efficient quantitative and predictive models that establish the relationship between a big group of input independent parameters and output variables required for the wide spectrum of manufacturing processes, cutting tools and engineering materials currently used in the industry [1]. Furthermore, it has been observed that the improvement in the output variables, such as tool life, cutting forces, surface roughness, etc, through the optimisation of input parameters, such as feed rate, cutting speed and depth of cut, may result in a significant economical performance of machining operations [2].

One of these output variables that may have either direct or indirect effect on other variables such as tool wear rate, machined surface characteristics and machining cost, is cutting forces. Many researchers have conducted studies on predicting cutting forces produced in machining operations using theoretical and analytical approaches [3 - 6]. The problem with these approaches is that they are based on a big number of assumptions that are not included in the analyses. This may reduce the reliability of the calculated cutting force values found by these methods. In addition, these approaches may be successfully applicable for certain ranges of cutting conditions.

On the other hand, many other researchers have followed purely experimental approaches to study the relationship between cutting forces and independent cutting conditions. This has reflected on the increased total cost of the study as a large number of cutting experiments is required. Furthermore, with this purely experimental approach, researchers have investigated the effect of cutting parameters on cutting forces using machining experiments based on a one-factor-at-a-time design, without having any idea about the behaviour of cutting forces when two or more cutting factors are varied at the same time.

The present study considers the effect of simultaneous variations of four cutting parameters (Cutting speed, feed rate, radial depth of cut and axial depth of cut) on the behaviour of cutting forces. For this purpose, the response surface methodology RSM is utilised. RSM is a group of mathematical and statistical techniques that are useful for modelling the relationship between input parameters (cutting conditions) and output variables (cutting force) [7]. RSM saves cost and time on conducting metal cutting experiments by reducing the overall number of required tests. In addition, RSM helps describe and identify, with a great accuracy, the effect of the interactions of different independent variables on the response when they are varied simultaneously [8, 9, 10]. RSM has been extensively used in the prediction of responses such tool life, surface roughness and cutting forces. Up-to-date, few researches used RSM to study the effect of cutting conditions on cutting forces when end-milling of tool steels used to produce plastic injection moulds such as modified AISI P20 steel. Noordin et. al. [11] used the RSM to investigate the tangential cutting force in turning of AISI 1045. They found that feed rate, as a main factor, and side cutting edge angle, as a secondary factor, affected the response variable (tangential force).

In the past decade, the finite element method based on the updated-Lagrangian formulation has been developed to analyze the metal cutting process [12 - 18]. Several special finite element techniques, such as the element separation [12 - 18], modelling of worn cutting tool geometry [12, 13, 15 - 17], mesh rezoning [14, 16], friction modelling [12 - 18], etc. have been implemented to improve the accuracy and efficiency of the finite element modelling. Detailed work-material modelling, which includes the coupling of temperature, strain-rate, and strain hardening effects, has been applied to model the material deformation [14, 16, 17]. The finite element simulation results have also been validated by comparing with experimental measurements.

In this study, the cutting force developed when end-milling of modified AISI P20 tool steel is investigated using response surface method and finite element method. The first and predictive models are developed for four cutting conditions: feed rate, cutting speed, axial depth of and radial depth of cut. The received quadratic equation shows, as a result of the variance analysis, that the most influential input parameter was the feed rate followed by radial depth of cut, and axial depth cut and, finally, by the cutting speed. In addition, the interactions of radial depth of cut together with feed; and radial depth of cut with axial depth of cut were observed to be quite significant. The predictive models in this study are believed to produce values of the longitudinal component of the cutting force close to those readings recorded experimentally with a 95% confident interval. Both methods are agreed with experimental result.

Finite Element Model

The model is composed of a deformable workpiece and a rigid tool. The tool penetrates through the workpiece at a constant speed and constant feed rate. The model assumes plane-strain condition since generally depth of cut is much greater than feed rate. Thirdwave AdvantEdge uses six-nodded quadratic triangular elements by default. Figure 1 show the elements used.

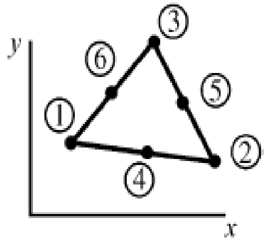


Figure 1: Six-node quadratic triangular elements

AdvantEdge is an automated program and it is enough to input process parameters to make a two-dimensional simulation of orthogonal cutting operation. The boundary conditions are hidden to the user. AdvantEdge uses the Coulomb friction model. The workpiece material used for simulation is P20 tool steel and the cutting tool is carbide coated with TiN. AdvantEdge uses an analytical formulation for material modelling. In a typical machining event, in the primary and secondary shear zones very high strain rates are achieved, while the remainder of the workpiece deforms at moderate or low strain rates. In order to account for this, Thirdwave AdvantEdge incorporates a stepwise variation of the rate sensitivity exponent:

$$\bar{\sigma} = \sigma_f\left(\varepsilon^p\right)\cdot\left(1+\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_o^p}\right)^{1/m_2}, \; if \;\; \dot{\varepsilon} \le \dot{\varepsilon}_t^p \qquad (4)$$

$$\bar{\sigma} = \sigma_f\left(\varepsilon^p\right)\cdot\left(1+\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_o^p}\right)^{1/m_2}\cdot\left(1+\frac{\dot{\varepsilon}_t}{\dot{\varepsilon}_o^p}\right)^{1/m_1} \;, \; if \;\; \dot{\varepsilon} \le \dot{\varepsilon}_t^p \qquad (5)$$

where $\bar{\sigma}$ is the effective Von Misses stress, σ_f is the flow stress, ε^p is the accumulated plastic strain, $\dot{\varepsilon}_o^p$ is a reference plastic strain rate, m_1 and m_2 are low and high strain-rate sensitivity exponents, respectively, and $\dot{\varepsilon}_t$ is the threshold strain rate which separates the two regimes.

Experimental Procedure

Experimental design for RSM

The parameters β_0, β_1, β_2 etc, appearing in Eq. 3, are determined using the method of least squares. The calculations are performed using MINITAB. To reduce numbers of cutting tests and allow simultaneous variation of the four independent factors, a well-designed experimental procedure has to be followed.

In machining research, the Box-Behnken design has found a broad application compared to other experiment designs used for RSM. The Box-Behnken design is based on the combination of the factorial with incomplete block designs. It does not require a large number of tests as it considers only three levels (-1, 0, 1) of each independent parameter [18]. The levels of the four input independent variables are given in Table 1. The Box-Behnken design is normally used for non-sequential experimentation, when a test is conducted only once. It allows an efficient evaluation of the parameters in the first order models. Using Minitab the cutting conditions of 29 experiments are generated and the experiments are conducted randomly to minimise errors. In order to calculate the experimental error, the 29 experiments consider five times repeating of central point of the cutting conditions. After a series of preliminary trial tests had been conducted and based on the recommendations given by the tool and workpiece manufacturers, the cutting conditions of the main experiments were established (Table 2).

Table 1: Levels of independent variables

Factors \ Coding of Levels	-1	0	1
Speed, V_c (m/s)	100	140	180
Feed, f (mm/rev)	0.1	0.2	0.3
Axial depth of cut, a_a, (mm)	1	1.5	2
Radial depth of cut, a_r, (mm)	2	3.5	5

Table 2: Conditions of cutting experiments according to Box-Behnken design

Experiment Number	Cutting speed, V_c (m/min)	Feed, f (mm/rev)	Axial depth of cut, a_a (mm)	Radial depth of cut, a_r (mm)
1	140	0.1	1	3.5
2	140	0.15	1	2
3	140	0.15	1	5
4	100	0.15	1	3.5
5	140	0.2	1	3.5
6	180	0.15	1	3.5
7	180	0.1	1.5	3.5
8	100	0.2	1.5	3.5
9	140	0.15	1.5	3.5
10	180	0.15	1.5	2
11	100	0.15	1.5	2
12	140	0.1	1.5	5
13	140	0.2	1.5	5
14	140	0.15	1.5	3.5
15	140	0.15	1.5	3.5
16	140	0.15	1.5	3.5
17	180	0.15	1.5	5
18	140	0.1	1.5	2
19	100	0.15	1.5	5
20	140	0.2	1.5	2
21	140	0.15	1.5	3.5
22	180	0.2	1.5	3.5
23	100	0.1	1.5	3.5
24	100	0.15	2	3.5
25	140	0.15	2	5
26	140	0.2	2	3.5
27	180	0.15	2	3.5
28	140	0.1	2	3.5
29	140	0.15	2	2

Test workpiece, tool material and experimental setup

The current study is concerned with investigating the effect of four factors (cutting speed, feed, axial- and radial depth of cut) on the cutting force generated when end milling of modified AISI P20 tool steel with coated carbide inserts. Generally, AISI P20 is a chromium-molybdenum alloyed steel which is considered as a high speed steel used to build moulds for plastic injection and zinc die-casting, extrusion dies, blow moulds, forming tools and other structural components. The modified form of AISI P20 is distinguished from normal P20 steel by the balanced sulphur content (0.015 %) which gives the steel better machinability and more uniform hardness in all dimensions. Modified AISI P20 possesses a tensile strength of 1044 MPa at room temperature and a hardness ranging from 280 to 320 HB. The workpiece used in this study was prehardened and tempered to a minimum hardness of 300 HB and was provided by ASSAB (Sweden). Table 3 shows the approximate chemical analysis.

Table 3: Chemical analysis of modified AISI P20, %

C	0.38
Si	0.30
Mn	1.50
Cr	1.90
Mo	0.15
S	0.015
Fe	balance

The cutting tool used in this study is a 0º lead – positive end milling cutter of 31.75–mm diameter. The end mill can be equipped with two square inserts whose all four edges can be used for cutting. The tool inserts were made by Kennametal and had an ISO catalogue number of SPCB120308 (KC735M). In this study, only one inserts per one experiment was mounted on the cutter. The insert had a square shape, back rake angle of 0º, clearance angle of 11º, and nose radius of 0.794 mm and had chip breaker. KC735M inserts are coated with a single layer of TiN. The coating is accomplished using PVD techniques to a maximum of 0.004–mm thickness.

The 29 experiments were performed in a random manner on Okuma CNC machining centre MX-45 VA and using a standard coolant. Each experiment was stopped after 85 mm–cutting length. Meanwhile, the data about cutting force component F_y, was acquired with the aid of a piezoelectric cutting force dynamometer provided by Kistler. Each experiment was repeated three times using a new cutting edge every time to obtain very accurate readings of the cutting force. A cutting pass was conducted in such a way that a shoulder, of depth ranging from 1 to 2 mm, and width of 2 to 5 mm, was produced.

Results and Discussion

Development of first order cutting force model

After conducting the first passes (one pass is equal to 85-mm length) of the 29 cutting experiments, the cutting force readings are used to find the parameters appearing in the postulated first order model (Eq. 2). To do the calculation of these parameters, the method of least squares is used with the aid of MINITAB. The first order linear equation for predicting the cutting force is expressed as:

$$\hat{y} = -163.7548 - 0.75x_1 + 1216.67x_2 + 117.92x_3 + 37.09x_4 \quad (6)$$

From this linear equation, one can easily notice that the response $\hat{y}$ (cutting force) is affected significantly by the feed rate followed by axial depth of cut and then by radial depth of cut, and lastly, by the cutting speed. Generally, the increase in feed rate, axial- and radial depths of cut will cause the cutting force to become larger. On the other hand, the decrease in cutting speed will slightly cause a reduction in cutting force. The proposed linear equation is valid only for cutting modified AISI P20 with a 0º lead end mill equipped with TiN coated KC735M carbide inserts and within the cutting conditions ranges used in the experimentation (see Table 3). Table 4 shows the cutting force values received by experimentation and the values predicted by the first order model. It is clear that the predicted values are very close to the experimental readings. This indicates that the obtained linear model is able to provide, to a great extent, accurate values of cutting forces.

The adequacy of the first order model was verified using the analysis of variance (ANOVA). At a level of confidence of 95%, the model was checked for its adequacy. As it is shown in Table 4, the lack-of-fit *F* –value of 3.50 is not significant with relative to the pure error. This implies that the model could fit and it is adequate. There is about a chance of 11.60% that the lack-of-fit *F*–value could occur due to noise.

Table 4: Analysis of variance ANOVA for first order equation (from Minitab)

Source of Variation	Degree of freedom, DF	Sum of squares, SS	Mean squares, MS	*F-Ratio*	*P-Ratio*
Zero order term	4	134060	134060	155.49	0.0000
Residual error	24	5173	215.5		
Lack-of-fit	20	4893	244.7	3.5	0.116
Pure error	4	280	280	70	
Total	28	139233			

The developed linear model (Eq. 4) was used to plot contours of the cutting force at different values of axial and radial depth of cut. Figure 2 shows the cutting force contours at three different combinations of axial- and radial depths (lowest "-1", middle "0", and highest values "+1"). It is clear that the reduction in cutting speed and increase in feed rate will cause the cutting force increase dramatically. For the other factors, the cutting force show proportional relationship.

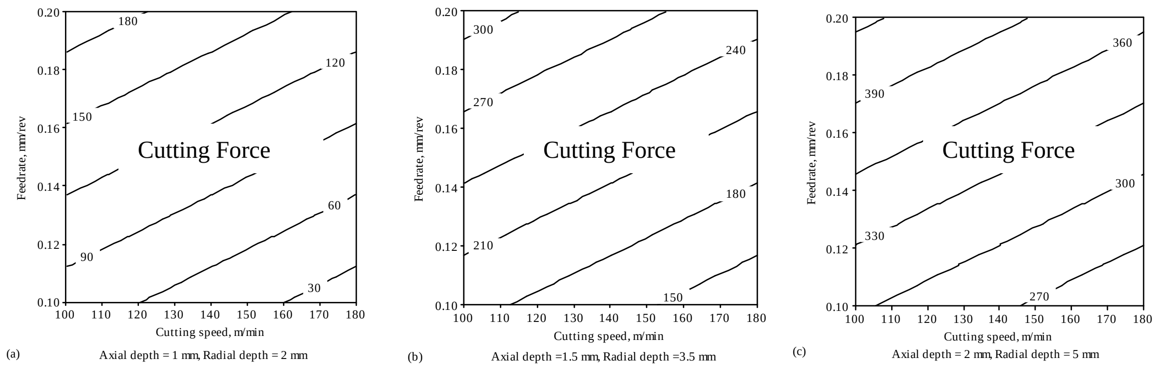


Figure 2: Cutting force contours in cutting speed–feed plane for different combinations of axial- and radial depths of cut plotted from first order model: (a) a_a =1 , a_r =2 mm (lowest values) (b) a_a =1.5 , a_r =3.5 mm (middle values) and (c) a_a =2 , a_r =5 mm (highest values).

The increase in axial depth of cut will cause a reduction in the cutting force. Another observation from this equation is that the interaction of the feed rate with axial depth of cut. It is noticed that this interaction has the most dominant effect on the cutting force was feed rate with the axial depth of cut. The cutting force readings obtained experimentally and predicted values by this equation are shown in Table 5. It can be concluded from the table that the equation can produce values close to those found experimentally. The analysis of variance shown in Table 6 indicates that the model is adequate as the *P*–values of the lack-of-fit are not significant.

Table 5: Comparison between experiment of cutting force and predicted results generated by first order model

No. of experiment	Cutting speed, V_c (m/min)	Feed, f (mm/rev)	Axial depth of cut, a_a (mm)	Radial depth of cut, a_r (mm)	Exp. results, F_y (N)	Predicted results, F_y (N)
1	140	0.1	1	3.5	110	100.64
2	140	0.15	1	2	127.46	105.84
3	140	0.15	1	5	225	217.10
4	100	0.15	1	3.5	190	191.47
5	140	0.2	1	3.5	210	222.30
6	180	0.15	1	3.5	140	131.47
7	180	0.1	1.5	3.5	130	129.60
8	100	0.2	1.5	3.5	320	311.26
9	140	0.15	1.5	3.5	210	220.43
10	180	0.15	1.5	2	145	134.80
11	100	0.15	1.5	2	210	194.80
12	140	0.1	1.5	5	210	215.23
13	140	0.2	1.5	5	320	336.89
14	140	0.15	1.5	3.5	220	220.43
15	140	0.15	1.5	3.5	200	220.43
16	140	0.15	1.5	3.5	210	220.43
17	180	0.15	1.5	5	240	246.06
18	140	0.1	1.5	2	100	103.97
19	100	0.15	1.5	5	315	306.06
20	140	0.2	1.5	2	200	225.64
21	140	0.15	1.5	3.5	200	220.43
22	180	0.2	1.5	3.5	260	251.26
23	100	0.1	1.5	3.5	190	189.60
24	100	0.15	2	3.5	320	309.39
25	140	0.15	2	5	350	335.02
26	140	0.2	2	3.5	360	340.23
27	180	0.15	2	3.5	270	249.39

28	140	0.1	2	3.5	200	218.56
29	140	0.15	2	2	210	223.76

Table 6: The results for the numerical method

No. of Exp.	Cutting speed, V_c (m/min)	Feed, f (mm/rev)	Axial depth of cut, a_a (mm)	Radial depth of cut, a_r (mm)	Exp. results, F_y (N)	RSM Results	AdvantEdge Results	Error by RSM (%)	Error by AdvantEdge (%)
1	140	0.1	1	3.5	110	114.47	98.75	-4.06	10.23
2	140	0.15	1	2	127.46	120.6	99.25	5.38	22.13
3	140	0.15	1	5	225	210.63	205.25	6.39	8.78
4	100	0.15	1	3.5	190	205.31	174.53	-8.06	8.14
5	140	0.2	1	3.5	210	206.14	193.15	1.84	8.02
6	180	0.15	1	3.5	140	145.31	117.48	-3.79	16.09
7	180	0.1	1.5	3.5	130	130.63	112.9	-0.48	13.15
8	100	0.2	1.5	3.5	320	312.3	305.44	2.41	4.55
9	140	0.15	1.5	3.5	210	208	196.74	0.95	6.31
10	180	0.15	1.5	2	145	143.64	129.26	0.94	10.86
11	100	0.15	1.5	2	210	198.64	192.88	5.41	8.15
12	140	0.1	1.5	5	210	204.06	195.74	2.83	6.79
13	140	0.2	1.5	5	320	330.73	304.23	-3.35	4.93
14	140	0.15	1.5	3.5	220	208	203.07	5.45	7.70
15	140	0.15	1.5	3.5	200	208	186.78	-4.00	6.61
16	140	0.15	1.5	3.5	210	208	197.44	0.95	5.98
17	180	0.15	1.5	5	240	249.9	223.76	-4.13	6.77
18	140	0.1	1.5	2	100	97.81	114.25	2.19	-14.25
19	100	0.15	1.5	5	315	314.9	327.56	0.03	-3.99
20	140	0.2	1.5	2	200	214.47	184.77	-7.24	7.62
21	140	0.15	1.5	3.5	200	208	183.48	-4.00	8.26
22	180	0.2	1.5	3.5	260	252.3	238.75	2.96	8.17
23	100	0.1	1.5	3.5	190	190.63	176.35	-0.33	7.18
24	100	0.15	2	3.5	320	323.23	306.01	-1.01	4.37
25	140	0.15	2	5	350	349.78	338.72	0.06	3.22
26	140	0.2	2	3.5	360	354.06	344.72	1.65	4.24
27	180	0.15	2	3.5	270	263.23	251.75	2.51	6.76
28	140	0.1	2	3.5	200	202.4	186.48	-1.20	6.76
29	140	0.15	2	2	210	217.3	198.73	-3.48	5.37

Numerical Method Result.

The results for the numerical method are shown in Table 6. Errors for most of the results are range 4 % to 10 %. But only for five simulations the error are more than 10 %. The error analysis graph is shown in Figure 3. From the graph, it shows that the RSM model predict more closely to the experimental results. For AdvantEdge, μ =0.5 has been selected. This code uses Coulomb friction model, in which frictional stress on the rake face is calculated from the normal stress acting on the same surface and not from the shear yield strength of the material. According to Halil Bil et. al. [19], friction parameters effects the simulation results for cutting force drastically. Figure 4 shows the simulation results for the experiment 3, 8 and 26.

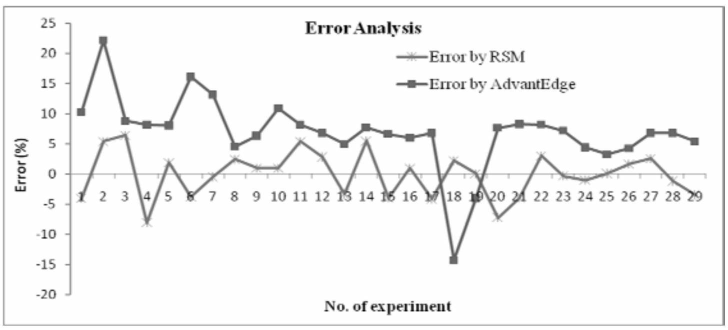
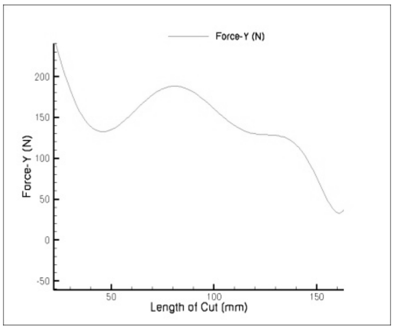
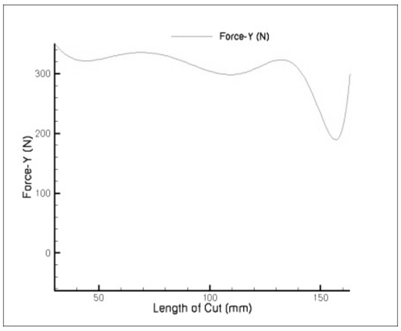


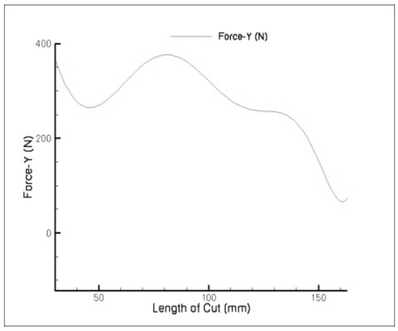
Figure 3: Error analysis graph



a) Experiment no. 3



b) Experiment no. 8



c) Experiment no. 26

Figure 4: Simulation result for a) experiment no. 3, b) experiment no. 8 and c) experiment no. 26

Conclusions

The following conclusions can be withdrawn from this study:

1. Response surface methodology has proved to be a successful technique that can be used to predict cutting force produced in end milling of modified AISI P20 with TiN coated inserts mounted on 0º lead cutters.
2. The first order equation developed by RSM using Minitab are able to provide accurately predicted results of the cutting force close to those values found in the experiments. The equations are checked for their adequacy with a confidence interval of 95%.
3. The two equations indicate that the feed rate was the most dominant cutting condition on the cutting force, followed by the axial depth, radial depth of cut and then by the cutting speed. The cutting force increases with increasing the feed rate, depths of cut but decreases with increasing cutting speed
4. Most of the results from the simulation are agreed with the experimental results but some of the simulation results are quite far from the experimental results. To get more accurate results from the simulation, the friction force must be calculated from the experimental results.

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