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Experimental and Numerical Study of Cutting Force in End-Milling Operation Using Statistical Method

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Abstract

The present paper explores the experimental and finite element study to predict the cutting force produced in end-milling operation for modified AISI P20 tool steel using statistical approach. The first order cutting force equations were developed utilizing the response surface methodology (RSM) to study the effect of input cutting parameters including the cutting speed, feed rate, radial depth and axial depth of cut. The explicit code was used to estimate the cutting and thrust forces. It can be seen that the longitudinal component of cutting force predicted by RMS and finite element analysis (FEA) are excellent agreement with the experimental results at 95% of confident interval. It can be observed that the range of the error for both methods within 10% except few and the more error occurred for higher cutting speed. At a level of confidence of 95%, the lack-of-fit *F* –value of 3.50 is not significant with relative to the pure error and zero order term and the model could fit and adequate. The acquired results show that the axial depth of cut, radial depth of cut and feed rate are strongly related with the cutting force. It can be seen that the increases of cutting force with increases of axial depth of cut, radial depth of cut and feed rate, however, the decreases of cutting speed. The cutting force obtained the highest value about 426 N at cutting speed 100m/min.

1. INTRODUCTION

Metal cutting process is an important process for the machining and fabrication operations. For a long time, the manufacturing engineers and researchers have been realizing that in order to optimize the economic performance of metal cutting operations, the 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. On the other hand, many other researchers have followed purely experimental approaches to study the relationship between cutting forces and independent cutting conditions. These have reflected on the increased total cost in order to conduct the 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 including the cutting speed, feed rate, radial depth of cut and axial depth of cut on the behaviour of cutting forces. For this purpose, the RSM was utilized. 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) [3]. The benefits of using RSM saves total 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 [4-6]. The RSM has been extensively used in the prediction of responses such tool life, surface roughness and cutting forces. Up-to-date, few researchers were used the 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. [7] was used the RSM to investigate the tangential cutting force in turning of AISI 1045. They found that the feed rate as a main factor and the side cutting edge angle as a secondary factor affected the response variable (tangential force).The finite element simulation results have also been validated by comparing with experimental measurements. In 2003, an analytical force model was presented by Wang and Yang [8] for a cylindrical roughing end mill with a sinusoidal profile in both the angle and frequency domains. Researchers were developed some methods of modelling structural properties of milling tools. [9]. Some investigation that first and second order 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 cut- ting speed [10]. The cutting force increases with increasing the feed rate, depths of cut but decreases with increasing cutting speed. The used of finite element and response surface methods to find the effect of milling parameters (cutting speed, feed rate and axial depth) on cutting force when milling Hastelloy C-22HS [11]. Based on variance analyses of First- and Second-Order RSM models, most influential design variable is feed rate. Cutting forces are mainly affected by cutting speed, feed rate, undeformed chip thickness, cutting tool material, tool geometry (approaching angle, rake angle, etc.), depth of cut and tool wear [12]. The study determined values of cutting force components [13] and specific cutting coefficient tables by using different rake angles, feed and speeds and offered applicable practical equations [14-16]. In this study, the cutting force developed in end-milling of modified AISI P20 tool steel is investigated using response surface method. The first predictive model is developed for four cutting conditions including the feed rate, cutting speed, axial depth of and radial depth of cut.

2. FINITE ELEMENT MODEL

The finite element analysis (FEA) model is composed of a deformable workpiece and a rigid tool. The tool penetrates through the workpiece at a constant speed and feed rate. The model assumes the plane-strain condition since generally depth of cut is much greater than feed rate. The six-nodded quadratic triangular elements are considered in this study. AdvantEdge is an automated program and it is enough to input process parameters to make a two-dimensional simulation of orthogonal cutting operation. The modified AISI P20 tool steel and carbide coated with TiN are used as a workpiece and cutting tool materials in this study. 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 is expressed as in Eq. (1):

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

where $\bar{\sigma}$ is the effective Von Misses stress, σ_f is the flow stress, ε^p is the accumulated plastic strain, $\dot{\varepsilon}^p$ is the rate of 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.

4. EXPERIMENTAL PROCEDURE

4.1. Experimental design for RSM

The model parameters are determined using the method of least squares. The calculations are performed using statistical software. 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 the 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 [17]. 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 and second order models. Using statistical software the cutting conditions of 29 experiments are generated and the experiments were conducted randomly to minimise the 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 were conducted and based on the recommendations given by the tool and workpiece manufacturers, the cutting conditions of the main experiments were established. Table 2 shows the conditions of cutting experiments according to Box-Behnken design.

4.2. Test workpiece, tool material and experimental setup

The present study is concerned with investigate the effect of the 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 of 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 composition of modified AISI P20.

Table 1: Levels of independent variables

Input cutting parameter	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 (m/min)	Feed (mm/rev)	Axial depth of cut (mm)	Radial depth of cut (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

Table 3: Chemical analysis of modified AISI P20 (%)

Chemical composition	**In percentage**
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 of 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. Figure 1 show the experimental setup employed in this study.

Fig. 1 Experimental setup

5. RESULTS AND DISCUSSION

5.1 Development of first order cutting force model

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

$$\hat{y} = -163.7548 - 0.75x_1 + 1216.67x_2 + 117.92x_3 + 37.09x_4 \quad (2)$$

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 are caused the cutting force to become larger. On the other hand, the decreases in cutting speed slightly reduce the 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 (Table 3). Table 5 shows the cutting force values received by experimentation and the values predicted by the first order model. It is clearly shown 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 and zero order term. This implies that the model could fit and adequate. There is about a chance of 11.60% that the lack-of-fit *F*–value could occur due to noise. The developed linear model (Eq. 1) was used to plot contours of the cutting force at different values of axial and radial depth of cut.

Table 4: Analysis of variance ANOVA for first order equation

Source of Variation	Degree of freedom, DF	Sum of squares, SS	*F*	*P(%)*
Zero order term	4	134060	155.49	0
Residual error	24	5173	-	-
Lack-of-fit	20	4893	3.50	11.6
Pure error	4	280	70.00	-
Total	28	139233	-	-

Figure 2 shows the cutting force contours at three different combinations of axial- and radial depths (lowest “-1”, middle “0”, and highest values “+1”). The range of axial depth of cut and radial depth of cut are specified 1 mm to 2 mm and 2 mm to 5 mm respectively. It is clearly shown that the axial depth of cut, radial depth of cut and feed rate are strongly related with the cutting force. It can be seen that the increases of cutting force with increases of axial depth of cut, radial depth of cut and feed rate, however, the decreases of cutting speed. The cutting force obtained the highest value about 426 N at cutting speed 100m/min.

5.2. Numerical Analysis Result

The comparison between the experiment, RSM and FEA predicted results are tabulated in Table 5. It can be seen that the RSM and FEA methods are excellent agreement with the experimental results. It can be observed that the range of the error for both methods within 10% except few. Four and six simulated error results more than 10 % for RSM and FEA respectively. It is also observed that the more error occurred for higher cutting speed due to the frictional stress on the rake face. For FEA, the frictional coefficient (μ) is considered 0.5. The frictional stress on the rake face is calculated from the normal stress acting on the same surface.

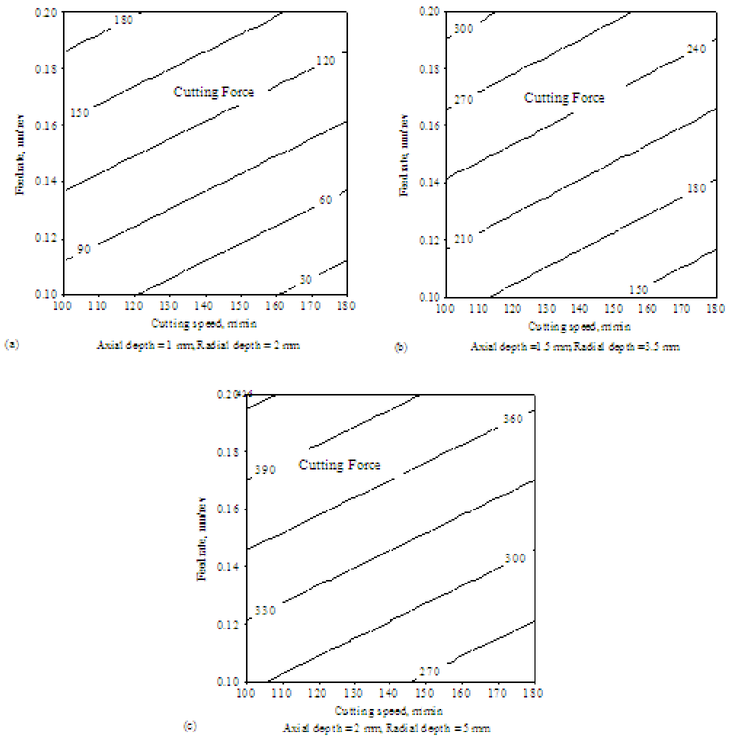

Fig. 4: Cutting force contours in cutting speed–feed plane for different combinations of axial- and radial depths of cut plotted from first order model: (a) a_a =1 , a_r =2 mm (lowest values) (b) a_a =1.5 , a_r =3.5 mm (middle values) and (c) a_a =2 , a_r =5 mm (highest values).

Table 5: The results of experiment, RSM and FEA Method

Expt. No.	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of Cut (mm)		Cutting force (N)			Error (%)	
			Axial	Radial	Expt.	RSM	FEA	RSM	FEA
1	140	0.10	1.0	3.5	110	100.64	98.75	8.51	10.23
2	140	0.15	1.0	2.0	127	105.84	99.25	16.96	22.13
3	140	0.15	1.0	5.0	225	217.10	205.25	3.51	8.78
4	100	0.15	1.0	3.5	190	191.47	174.53	-0.77	8.14
5	140	0.20	1.0	3.5	210	222.30	193.15	-5.86	8.02
6	180	0.15	1.0	3.5	140	131.47	117.48	6.09	16.09
7	180	0.10	1.5	3.5	130	129.60	112.9	0.31	13.15
8	100	0.20	1.5	3.5	320	311.26	305.44	2.73	4.55
9	140	0.15	1.5	3.5	210	220.43	196.74	-4.97	6.31
10	180	0.15	1.5	2.0	145	134.80	129.26	7.03	10.86
11	100	0.15	1.5	2.0	210	194.80	192.88	7.24	8.15
12	140	0.10	1.5	5.0	210	215.23	195.74	-2.49	6.79
13	140	0.20	1.5	5.0	320	336.89	304.23	-5.28	4.93
14	140	0.15	1.5	3.5	220	220.43	203.07	-0.20	7.70
15	140	0.15	1.5	3.5	200	220.43	186.78	-10.22	6.61
16	140	0.15	1.5	3.5	210	220.43	197.44	-4.97	5.98
17	180	0.15	1.5	5.0	240	246.06	223.76	-2.53	6.77
18	140	0.10	1.5	2.0	100	103.97	114.25	-3.97	-14.25
19	100	0.15	1.5	5.0	315	306.06	327.56	2.84	-3.99

20	140	0.20	1.5	2.0	200	225.64	184.77	-12.82	7.62
21	140	0.15	1.5	3.5	200	220.43	183.48	-10.22	8.26
22	180	0.20	1.5	3.5	260	251.26	238.75	3.36	8.17
23	100	0.10	1.5	3.5	190	189.60	176.35	0.21	7.18
24	100	0.15	2.0	3.5	320	309.39	306.01	3.32	4.37
25	140	0.15	2.0	5.0	350	335.02	338.72	4.28	3.22
26	140	0.20	2.0	3.5	360	340.23	344.72	5.49	4.24
27	180	0.15	2.0	3.5	270	249.39	251.75	7.63	6.76
28	140	0.10	2.0	3.5	200	218.56	186.48	-9.28	6.76
29	140	0.15	2.0	2.0	210	223.76	198.73	-6.55	5.37

6. Conclusions

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. The first order equation developed by RSM using statistical software and checked for their adequacy with a confidence interval of 95%. The 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. The experimental results are compared with the RSM and FEA 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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