International Journal of Engineering

Journal Homepage: www.ije.ir

Cutting Force Prediction in End Milling Process of AISI 304 Steel Using Solid Carbide Tools

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PAPER INFO

Paper history:
Received 07 December 2013
Accepted in revised form 11June 2015

Keywords:
Logistic Network
End Milling
Helix Angle
Cutting force
AISI 304 Steel
Solid Carbide Tools

ABSTRACT

In the present study, attempt has been made to experimentally investigate the effects of cutting parameters on cutting force in end milling of AISI 304 steel with solid carbide tools. Experiments were conducted based on four factors and five level central composite rotatable design. Mathematical model was developed to predict the cutting forces in terms of cutting parameters such as helix angle of cutting tool, spindle speed, feed rate and depth of cut. Response surface methodology was employed to create a mathematical model and the adequacy of the model was verified using analysis of variance. The direct and interaction effect of the process parameters with cross feed forces were analysed, which helped to select cutting parameters in order to keep cutting forces at minimum, which ensures the stability of end milling process.

***doi**: 10.5829/idosi.ije.2015.28.07a.14*

1. INTRODUCTION

Milling is the most widespread cutting process in modern production. End milling is the fundamental and frequent metal cutting operation employed for making profiles, slots, engraves contours, pockets, etc., in various components. Cutting forces are critically important in cutting operations because they correlate strongly with cutting performance such as surface accuracy, tool wear, tool breakage, cutting temperature, self-excited, and forced vibrations, etc. Cutting forces generated in metal cutting operations cause deflections of the part, tool or machine structure and supply energy to the machining system which results in excessive temperatures or unstable vibrations. The excessive cutting forces are undesirable in milling, which results in poor surface finish, inaccurate dimensions and increases tool wear. Measured cutting forces are used to compare the machinability of materials and for real time control in monitoring a cutting process and tool wear and failure. Estimation of cutting forces was used to determine machine power requirements and bearing loads and to design fixtures.

The present study considers the effect of simultaneous variations of four cutting parameters (helix angle of end mill cutter, spindle speed, feed rate, and depth of cut) on the behaviour of cutting forces. For this purpose, the Response Surface Methodology (RSM) is utilized. RSM is a group of mathematical and statistical techniques that are useful for modelling the relationship between input parameters(cutting conditions) and output variable (cutting force).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 interactions of different independent variables on the response when they are varied simultaneously. An effective model to predict the cutting force becomes essential to ensure the stability in end milling process. In this study, the cutting forces were taken into account for analysis, to understand its effect on stability in end milling process and to determine its predictive model from process parameters by using response surface methodology. Various studies have been made on the cutting forces in end milling

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using various tools, work materials and experimental methods. The literature survey pertaining to the work of other researchers is indicated below.

Many researchers have conducted studies on predicting cutting forces produced in machining operations using theoretical and analytical approaches [1-4]. Zheng et al. [5] presented a generalised cutting force model in terms of material properties, tool geometry, cutting parameters and process configuration. The model specifies the interaction between work piece and multiple cutters, flutes by the convolution of cutting-edge geometry function with a train of impulses having the period equivalent to tooth spacing. They conducted experiments over various cutting conditions and the results were presented to verify the model fidelity.

Lai [6] explained the influence of dynamic radii, feed rate, radial and axial depths of cut on cutting forces. Tandon and El-Mounayri [7] employed neural network predictive model to predict cutting force in terms of machining parameters such as tool diameter, spindle speed, feed rate, number of flutes, rake angle, clearance angle, axial and radial depth of cut. They concluded that this model can accurately predict the cutting forces in three directions. Noordin et al. [8] used RSM to investigate the tangential cutting force in turning of AISI 1045. They found that feed rate, as a main factor, affected the response variable. Palanisamy et al. [9] developed a cutting force model to predict the tangential and thrust cutting force in end milling of AISI 1020 steel. The model prediction was validated with the experimental cutting forces during machining. Haci et al. [10] developed a model to calculate various components of cutting forces and analysed the effect of cutting parameters and tool geometry on cutting force. Le et al. [11] presented an experimental study on cutting force variations in the end milling of Inconel 718 with coated carbide inserts. They concluded that the tool wear propagation was responsible for the increase of the main peak force. Guosong Lin et al. [12] also dealt with the application of response surface methodology in developing mathematical model and plotting graphs relating primary input variables namely the cutting speed (V), the feed rate (F), depth of cut (A), and rotation angle in the end milling process. Ganesh babu et al. [13] developed a mathematical model to predict cutting forces in terms of depth of cut, feed, cutting speed and immersion angle by using response surface methodology in end milling of composite material. They analysed direct and interaction effect of the machining parameter with cutting forces. Sharma et al. [14] proposed a network model to predict cutting forces in terms of cutting parameters such as approaching angle, speed, feed and depth of cut. Gonzalo et al. [15] presented a mechanistic model to predict the milling forces. The experimental work was substituted for virtual experiments, carried out using a finite element method model of the cutting process. This methodology had been validated for end milling operations in AISI 4340 steel. K.A.Abou- El.Hossein et al. [16] predicted the cutting force in end milling operation of mild steel AISI P20 tool steel using RSM. Sivasakthivel et al. [17] developed a cutting force model to predict the cutting force using RSM. This work deals with the end milling operation on the aluminium AI 6063 material with high speed steel end mill cutter.

The literature indicated above reveals that the predictive model of cutting forces is mostly based on empirical model with arbitrary assumptions. The geometrical variations of the tool materials have not been included in most of the models. The effect of helix angle has not been explored in detail. It is also noted that not much work is reported on prediction of cutting force in metal cutting AISI 304 steel with carbide end mill cutter.

In this study, Response Surface Methodology is used to develop a mathematical model to predict the crossfeed force when milling of AISI 304 steel using solid carbide end mill cutter. The process parameters selected for this work were helix angle of the cutting tool, spindle speed, feed rate, and depth of cut. The mathematical model helps us to study the direct and interaction effect of each of these process parameters.

2. CUTTING FORCE MEASUREMENTS

In milling process, force components are related to the axes of motion of the machine tool. Three resolved component of the force are infeed force, crossfeed force and thrust force. The infeed force acts tangent to the rotating tool and in the x direction of the machine tool. Crossfeed force acts normal to the rotating tool and in the y direction of the machine tool. Thrust force acts parallel to the axis of the tool and in the z direction of the machine tool. In our study, milling tool dynamometer made by Syscon instruments was mounted between the workpiece and machine tool. The workpiece was mounted rigidly on a specially designed vice containing sensors to measure the cutting forces. These sensors are connected to a digital force indicator to displace the force values. Among the previously mentioned forces, the principal crossfeed force is the most important one, because it raises the vibrations and other related problems. In this work, the crossfeed force is considered to evaluate the cutting condition during the machining process.

3. RESPONSE SURFACE METHODOLOGY

Response surface methodology is the most informative method of analyzing the result of a factorial experiment. The response crossfeed force (FY) in normal direction of the machine tool can be expressed as a function of process parameters (Table 1): helix angle (α), spindle speed (S), feed rate (F) and depth of cut (D), as shown in Equation (1).

$$\text{Crossfeed force}(\mathrm{F_y}) = \psi(\alpha_{iu}, S_{iu}, F_{iu}, D_{iu}) + e_u \tag{1}$$

where, ψ = response surface, eu = residual, u = no of observations in the factorial experiment and iu represents level of the i^{th} factor in the u^{th} observation. When the mathematical form of ψ is unknown, this function can be satisfactorily approximated by polynomials within the experimental region in terms of process parameter variables. To conduct the experiments, a central composite rotatable design was chosen as the design matrix. This design matrix [18] comprised of a full replication of 2^4 (=16) factorial design plus seven center points and eight star points as given in Table 2. While all the machining parameters at the intermediate levels (0) constituted the center points and the combination of each machining parameters at either its highest value (+2), or lowest value (−2), with other three parameters of the intermediate level (0) constituted the star points. Thus, the 31 experimental runs allowed the estimation of linear, quadratic, and two-way interactive effects of the process parameters on crossfeed force. The upper limit of the parameter is coded as +2, its lower limit as -2, and the coded values for intermediate values were calculated from Equation (2) [19].

$$X_i = \frac{2(2X - (X_{\max} + X_{\min}))}{(X_{\max} - X_{\min})} \tag{2}$$

where:
X_i –The required coded value of a variable X
X–any value of the variable from X_{min} to X_{max}
X_{min}–the lower limit of the variable
X – the upper limit of the variable
The intermediate values were coded as -1, 0, and 1.

4. EXPERIMENTAL SETUP

The experiments were conducted on a HASS vertical machining centre: model tool room mill with uncoated solid carbide end mill cutter under dry condition. The end mill cutter used in the experiment had12 mm diameter, with four flutes. The workpiece material was AISI 304 commonly available machineable metal. The workpiece specimen was 32 mm × 32 mm in cross section and 50 mm in length. The cutting forces: crossfeed force was measured by using Syscon instruments milling tool dynamometer. The photograph of the experimental set-up is shown in Figures1and 2. The data is acquired in the data acquisition software and observations are tabulated to obtain the mathematical model (Table 3).

5. DEVELOPMENT OF MATHEMATICAL MODEL

The values of the coefficients of the polynomials were calculated by multiple regression method. Statistical software QA Six Sigma DOE PC IV [20] was used to calculate the values of these coefficients. The second order mathematical model was developed by neglecting the insignificant coefficients of the cutting forces: in feed force measured in the X, direction:

$$\begin{aligned} \text{Crossfeed force } (\mathrm{F_y}) &= 152 - 45.458S + 2.042F \\ &+ 25.458d + 10.615\alpha^2 + 12.615S^2 - 19.260F^2 \\ &+ 6.385D^2 + 2.188\alpha F + 1.938\alpha D - 1.562SF \end{aligned} \tag{3}$$

α = helix angle in (°)
S = spindle speed in rpm,
F = feed rate in mm/rev,
D= depth of cut in mm

TABLE 1. Parameters and levels in milling

Parameters & Notations	Units	Levels				
		-2	**-1**	**0**	**1**	**2**
Helix angle (α)	Degree (°)	25	30	35	40	45
Spindle speed (S)	rpm	700	1400	2100	2800	3500
Feed rate (F)	mm/rev	0.03	0.06	0.09	0.12	0.15
Depth of cut (D)	mm	0.2	0.4	0.6	0.8	1.0

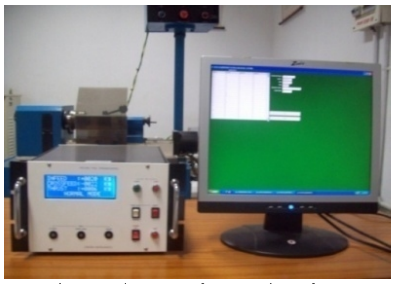

Figure 1. Experimental setup for cutting force measurement with Syscon tool dynamometer

Figure 2. Experimental setup- Machine tool connected with syscon tool dynamometer

6. THE ADEQUACY OF THE DEVELOPED MODEL

The adequacy of the model was tested using the analysis of variance techniques (ANOVA). As per the ANOVA technique, it is desired that the calculated value of the F-ratio of the model developed should not exceed the standard tabulated value of the F-ratio for a desired level of confidence (say 95%). Also, if the calculated value of the R-ratio of the model developed exceeds the standard tabulated value of the R- ratio for the desired level of confidence (say 95 %), then the model can be considered to be adequate within the confidence limit [21]. From the values in Table 3, it can be deduced that the current model is adequate. It is evident from the Table 2 that the error between the experimental value and predicted value is small.

7. RESULT AND DISCUSSION

A mathematical model was developed to predict the infeed force in X cutting direction by relating it with process parameters such as helix angle, spindle speed, feed rate and depth of cut. The direct and the interaction effects of these process parameters on cutting forces were calculated and plotted. The cause and effect were analysed. The trends of the plotted direct and the interaction effect of these process parameters help to determine which parameters and parameter interactions are statistically significant in the cutting forces.

7. 1. Direct Effect of Helix Angle From Figure 3, it is understandable that the increase in helix angle from 250 to 350^{o} resulted in decreasing trend in cutting forces. From the figure it is observed that helix angle from 350 to 450^{o}, the cutting force is decreased. By increasing in helix angle, the magnitude of the shock load was produced [22]. It is evident from Figure 3 that the cutting forces: crossfeedforce, decreases by increasing the helical angle of the cutting tool and it is a minimum at 350^{o}.

7. 2. Direct Effect of Spindle Speed From Figure 4 it is understandable that the spindle speed has significant effect on crossfeed force. Increasing spindle speed resulted in decreased crossfeed force; Figure 4 shows that crossfeed force is minimum at 3500 rpm and maximum at 700 rpm.

7. 3. Direct Effect of Feed Rate Figure 5 indicates that the feed rate has a significant effect on crossfeed force. From 0.03 mm/rev to 0.09 mm/rev, increasing the feed rate, the cross feed forces is increased. From 0.09 mm/rev to 0.15 mm/rev, increasing the feed rate, the cross feed force value is decreased. The work and work holding device are substantial enough to support against the crossfeed force of cutter. The crossfeed force is minimum at 0.03 mm/rev and maximum at 0.09 mm/rev.

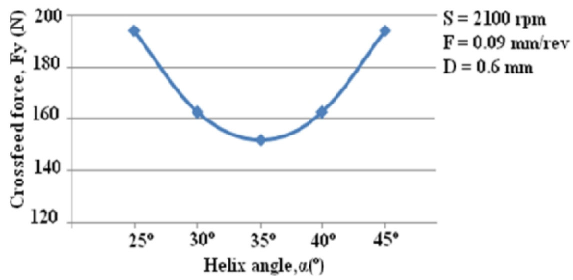

Figure 3. Direct effect of helix angle

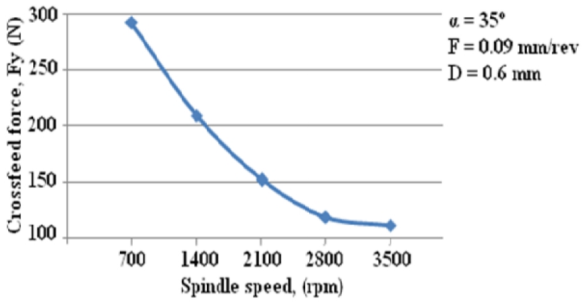

Figure 4. Direct effect of spindle speed

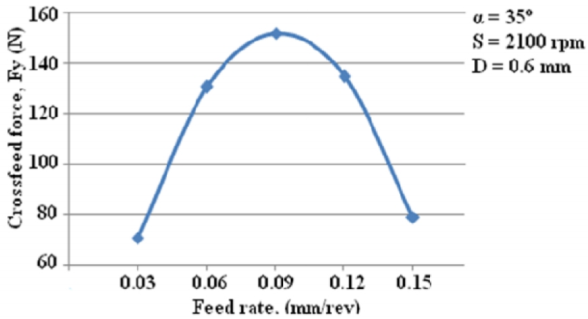

Figure 5. Direct effect of feed rate

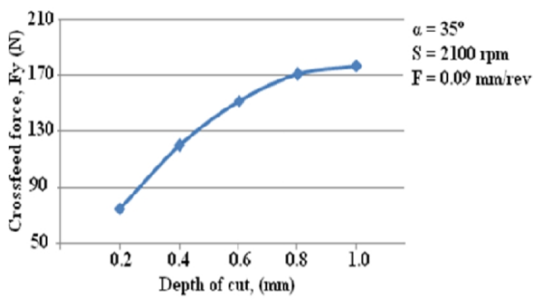

Figure 6. Direct effect of depth of cut

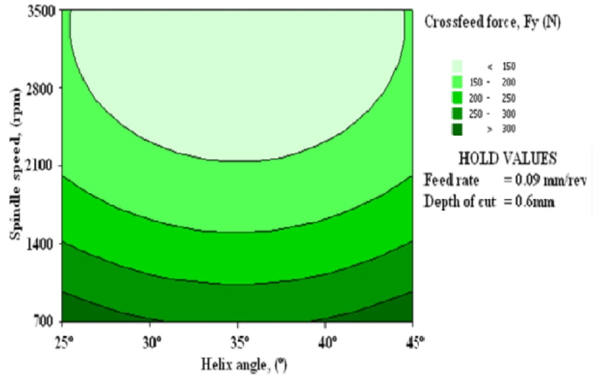

Figure 7. Interaction effect of helix angle and spindle speed for crossfeed force

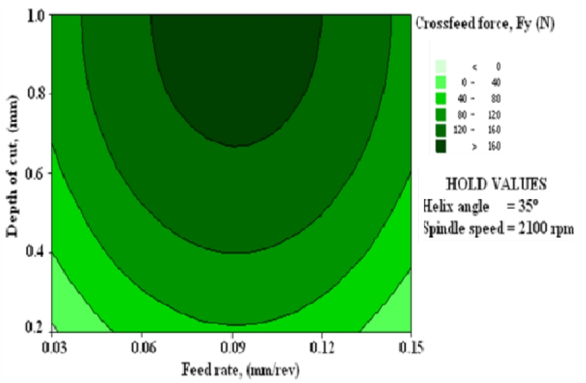

Figure 8. Interaction effect of feed rate and depth of cut for crossfeed force

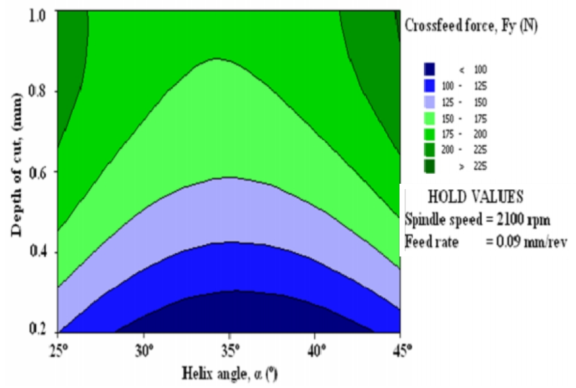

Figure9. Interaction effect of helix angle and depth of cut for crossfeed force

7. 4. Direct Effect of Depth of Cut The depth of cut has a significant effect on cutting forces, i.e. crossfeed force. From Figure 6, it is clear that the increase in depth of cut resulted in increased in feed. Deeper the depth of cut, more length of the flute will get engaged which results in higher cutting force. Increase in depth of cut, the length of the contact area in the cutting length in the rotating direction is increased, which resulted in increased force in normal direction.

8. INTERACTION EFFECTS OF VARIABLES

Strong interaction was observed between various process parameters for cutting forces measured in normal direction. For crossfeed force the most significant interaction effect was found to be helix angle with spindle speed, helix angle with depth of cut and feed rate with depth of cut. The contour graph between the most significant process parameter interactions are shown in Figures 7-9.

8. 1. Interaction Effect of Helix Angle and Spindle Speed for Crossfeed Force The interaction effect of helix angle and spindle speed on crossfeed force is shown in Figure 7, reveals that as helix angle increase, a decrease in crossfeed force results. It is also observed that ,spindle speed from 700 rpm to 3500 rpm, increase in helix angle resulted in decreases crossfeed force.

8. 2. Interaction Effect of Feed Rate and Depth of Cut for Crossfeed Force The interaction effect of feed rate and depth of cut on crossfeed force is shown in Figure 8, which reveals that as feed rate increase, it results in increase of crossfeed force. The same trend continues at change of level of depth of cut from 0.2 mm to 1.0 mm, increase in feed rate resulted in increase of crossfeed force.

8. 3. Interaction Effect of Helix Angle and Depth of Cut on Crossfeed Force The interaction effect of helix angle and depth of cut on crossfeed force is shown in Figure 9. It reveals that as helix angle increases from 25° to 30°,crossfeed force decreases. Further increasing the helix angle from 30° to 40°, results in increase in crossfeed force. Figure 9 also reveals that the increase in depth of cut from 0.2 mm to 1.0 mm, results in increase in feed force.

9. VALIDATION OF THE MODEL

The validity of the model is checked for the levels of the parameter which has not been included in the experimental design. The validations of the experimental data are shown in Table 4. It is evident from the Table 2 that the error between the experimental and predicted values is less than 5%, which confirms the validity of the model.

TABLE 2. Experimental design and response value

Exp. No	Control Factors				Crossfeed Force (N)		
	α	S	F	D	Observed value	Predicted value	Error %
1	-1	-1	-1	-1	172.59	170.10	1.10
2	1	-1	-1	-1	162.83	161.85	0.08
3	-1	1	-1	-1	79.88	82.31	-4.19
4	1	1	-1	-1	75.46	74.06	1.24
5	-1	-1	1	-1	174.28	172.94	0.60
6	1	-1	1	-1	178.25	173.44	2.56
7	-1	1	1	-1	80.10	78.90	1.37
8	1	1	1	-1	82.12	79.40	3.17
9	-1	-1	-1	1	216.23	217.14	-0.53
10	1	-1	-1	1	214.33	216.64	-1.23
11	-1	1	-1	1	126.56	129.35	-2.66
12	1	1	-1	1	132.99	128.85	2.38
13	-1	-1	1	1	218.86	219.98	-0.90
14	1	-1	1	1	230.79	228.23	0.76
15	-1	1	1	1	126.42	125.94	0.04
16	1	1	1	1	134.25	134.19	-0.14
17	-2	0	0	0	202.56	194.46	3.73
18	2	0	0	0	186.94	194.46	-4.54
19	0	-2	0	0	292.69	293.38	-0.47
20	0	2	0	0	112.41	111.54	0.40
21	0	0	-2	0	74.56	70.87	4.22
22	0	0	2	0	75.22	79.04	-5.39
23	0	0	0	-2	72.82	75.54	-4.92
24	0	0	0	2	180.56	177.37	1.45
25	0	0	0	0	150.26	152.01	-1.33
26	0	0	0	0	146.14	152.01	-4.10
27	0	0	0	0	150.57	152.01	-1.33
28	0	0	0	0	155.69	152.01	1.93
29	0	0	0	0	150.27	152.01	-1.33
30	0	0	0	0	155.45	152.01	1.93
31	0	0	0	0	158.86	152.01	3.79

TABLE 3. Adequacy of the model

Response	FactorsDf	Lack ofFit-df	PureError	F-ratio		R-ratio		Whether model is adequate
				Model	Standard	Model	Standard	
Crossfeed force (F_Y)	10	13	7	0.322	6.41	26.56	6.62	Adequate

TABLE 4. Result of Conformity test

Exp.No	Control Factors				Crossfeed force (Fy) in N		
	α	S	F	D	Observed value	Predicted value	Error %
1	2	2	2	2	387.46	391.01	-0.92
2	-2	-2	-2	-2	229.18	226.01	1.38

10. CONCLUSIONS

The following conclusions were arrived from the results of the present investigation:

The investigation presented a response surface methodology to develop a mathematical model to predict crossfeed force in terms of helix angle, spindle speed, feed rate, and depth of cut.

The helix angle and spindle speed are the most significant parameters which reduce the crossfeed force. Increasing the depth of cut also increased crossfeed force..

The interactions between the process parameters were analysed. The validity of the model is checked by conducting conformity test and the error is within 5%.

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PAPER INFO

Paper history:
Received 07 December 2013
Accepted in revised form 11 June 2015

Keywords:
Logistic Network
End Milling, Helix Angle
Cutting force
AISI 304 Steel
Solid Carbide Tools

چکیده

در مطالعه حاضر، تلاش شده است اثر متغیرهای برش بر روی نیروی برش فرز انتها تراش از جنس کاربید برای بریدن فولاد زنگ‌نزن AISI 304 به طور تجربی بررسی شود. آزمایش بر اساس چهار عامل و پنج سطح مرکب مرکزی طراحی قابل گردش انجام شد. مدل ریاضی برای پیش بینی نیروهای برش بر حسب پارامترهایی مانند زاویه مارپیچ ابزار، سرعت محور، میزان تغذیه و عمق برش تهیه شد. روش سطح پاسخ برای ایجاد یک مدل ریاضی به کار گرفته شد و کارایی مدل با استفاده از تحلیل واریانس تایید شد. اثر مستقیم و اثر متقابل پارامترهای فرایند با نیروهای تغذیه عرضی برای کمک به انتخاب پارامترهای برش به منظور کمینه کردن نیروهای برش و تضمین پایداری فرایند فرزکاری بررسی شد.

***doi**: 10.5829/idosi.ije.2015.28.07a.14*