Study of the Effect of Progressive Feed Rate on the Cutting Force in CNC End Milling of AISI 1045 Steel

K.S.Badrinathan [#1], L.Karunamoorthy [*2]

[#] Department of Mechanical Engineering, Sri Venkateswara College of Engineering,
Sriperumbudur – 602 105, India.
[1] badrinathan@hotmail.com
[*] Department of Mechanical Engineering, College of Engineering Guindy,
Anna University, Chennai - 600 025, India.
[2] karun@annauniv.edu

***Abstract* - This study focuses on the effect of cutting parameters on the cutting force in an end milling operation. Spindle speed, feed rate and depth of cut are the major factors which influence the cutting force. A concept of progressive feed rate, which is unlike the conventional constant feed rate, is introduced. AISI 1045 steel has been chosen as it is widely used in manufacturing. Design of Experiments (DOE) technique was adopted to conduct the experiments. Experiments were conducted and the mean cutting force was measured. A statistical model was developed using Design Expert software. The predicted values were compared with the experimental values and were found to be in close agreement. ANOVA technique was used to analyse the data for checking the model adequacy and for process optimization.**

Key words: End milling, Progressive feed rate, ANOVA, Design of Experiments (DOE), Mean cutting force

I. INTRODUCTION

End milling is one of the most common metal cutting processes used in manufacturing industries. High cutting forces may lead to faster tool wear which means high tooling cost, tool deflection leading to dimensional inaccuracy and poor surface finish leading to poor product quality. Also when conservative cutting parameters are chosen in order to avoid high cutting forces the productivity comes down. Higher cutting forces, in addition to damaging the cutting tool and the work piece, will also create vibration and chatter in the machine tool. The aim of this study is to investigate the effect of feed rate on the mean cutting force in machining of AISI 1045 steel.

When a part program is written, either manually or generated using CAM software, a single feed rate is selected for a particular cycle, say, for machining a pocket. When the rotating tool starts from its stationary position it accelerates from zero to the programmed feed rate instantly. This can create higher cutting forces, greater tool wear, and tool deflection and also will a leave a poor surface finish. In order to safeguard the machine tool, cutting tool and work piece the programmer might choose a conservative feed rate.

Various cutting parameters like spindle speed, feed rate, depth of cut influence the cutting force. H.Z. Li et al. [1] have analysed the cutting force variation along with the tool wear propagation. They found that the thermal effects could be a significant cause for the peak force variation within a single cutting pass. K.A. Abou-El-Hossein et al. [2] studied the effect of cutting speed, feed rate, radial depth and axial depth of cut on the cutting force and developed first and second order models for predicting the cutting force produced in end-milling operation of modified AISI P20 tool steel. Lei Zhang and Li Zheng [3] analysed the effect of the variable radial depth of cut, which is generally encountered as the end mill enters and exits the corner, on the cutting forces which further affects the contour accuracy of the milled pockets. They have developed an analytical model of cutting forces for steady state machining condition. Zhao-cheng Wei et al. [4] discretized the pocket into a series of small processes and each of the small processes was transformed into a steady-state machining using a new approximation method. Hyun-Chul Kim [5] optimized the generated tool path to maintain a constant MRR and thereby to achieve a constant cutting force and avoid chatter. He used pixel-based simulation technique to generate additional tool path segments. Sung-Joon Kim et al. [6] developed an algorithm, for indexable end mills, that calculates tool geometry data at an arbitrary axial position. They developed a cutting force model which uses cutting-condition-independent cutting force coefficients which considers run out, cutter deflection, geometry variation and size effect for accurate cutting force prediction. Han-Ul Lee and Dong-Woo Cho [7] developed a new method to obtain the most appropriate reference cutting force for rough milling. The reference cutting force was determined by considering the transverse rupture strength of the tool material and the area of the rupture surface. They used finite element method to accurately calculate the area of rupture surface. O. B. Adetoro and P. H. Wen [8] have used Finite Element Analysis (FEA) as a numerical tool to simulate the cutting process and determine both the average and instantaneous cutting force coefficients. They used Arbitrary Lagrangian and Eulerian (ALE) Formulation in FEM simulations. The cutting force coefficients were obtained using the least squares method. P Palanisamy et al. [9] have developed a dynamic cutting force model for end milling to predict the tangential cutting force and thrust force. Also they have used Oxley's energy partition function and Rapier's equation to study the thermal effect on the cutting force. Devi Kalla et al. [10] have utilized mechanistic modeling techniques for simulating the cutting of carbon fibre-reinforced polymers (CFRP) with a helical end mill. They have developed a methodology to predict the cutting forces by transforming specific cutting energies from orthogonal cutting to oblique cutting.

T . Radhakrishnan and Uday Nandan [12] used a regression model to fit the experimentally collected data and filtered out any abnormal data points. The final set of filtered data was analysed using neural networks to yield a final model. M. Kaymakci et al. [13] have developed a unified cutting mechanics model to predict cutting forces in milling, boring, turning and drilling operations. O.E.E.K. Omar et al. [14] have introduced a generic and improved model to simultaneously predict the conventional cutting forces along with 3D surface topography during side milling operation. Their model incorporates the effects of tool runout, tool deflection, system dynamics, flank face wear, and the tool tilting on the surface roughness. J. G. Li et al. [15] in their work have used an extended octree method to represent the work piece and tool swept volume to acquire the cutting depth and cutting width with high precision so that cutting forces can be predicted precisely. They have developed a framework of cutting force prediction based on virtual machining. Jian-Wei Dang et al. [16] have proposed a mechanistic cutting force model which considers the overall cutting forces contributed by both the flank edge and the bottom edge cuttings simultaneously. They found that the bottom edge cutting has a remarkable effect on the total cutting forces, when the axial depth of cut is relatively small. Zeki Yazar et al. [17] have developed a method for estimating the cutting forces in 3-axis milling of sculptured surface. The NC programmer can optimize the machining parameters especially the feed rate based on the predicted cutting force. Z.Z. Li et al. [18] have used heuristic methods for feed rate optimization based on cutting force prediction. Each cutting path segment is divided into micro-segments. Feed rates at several segments are determined together to make milling force satisfy various practical constraints of milling. Jeong Hoon Ko et al. [19] have developed a virtual machining system which can simulate real machining for a given set of NC codes. They have formulated an analytical model for off-line feed rate scheduling to regulate the cutting force and thereby improve the productivity and machining accuracy. W. A. Kline et al. [20] have developed a model which is based on chip load, cut geometry and the relationship between cutting forces and chip load. Both instantaneous and average force system are described as a function of cut geometry and feed rate. Force characteristics during cornering cuts are predicted by the model and are examined as a function of axial depth of cut and feed rate.

Most of the studies have focussed on the three cutting parameters, spindle speed, depth of cut and feed rate. With respect to feed rate a conventional way of programming the feed rate i.e. adopting a constant feed rate approach is used. To the authors knowledge hardly any attempt has been made to implement a progressive feed rate approach wherein the feed is applied gradually rather than instantly.

II. DESIGN OF EXPERIMENTS

Design of Experiments (DOE) [23] is a scientific and statistical approach to plan the conduct of experiments in an economical, less time consuming and cost effective way. DOE aids in generating data, analyse and interpret the data to arrive at valid conclusions. Taguchi defines the quality of product in terms of the loss to society caused by a product during its life cycle [21 - 23]. The experiments involve three factors, spindle speed, feed rate and depth of cut each at 3 levels. A standard L_{27} (3^{13}) full factorial orthogonal array (OA) [21] was chosen for the proposed method. This OA gives the effect of the individual factors on the response and also the interactions among the factors. Also L9 [21] orthogonal array was chosen for the conventional (existing) method of constant feed rate. This is to compare the results of the existing method with the proposed method.

III. EXPERIMENTAL DETAILS

A. Work Material

The work piece material was AISI 1045 steel flat of dimensions 150 mm x110 mm x10 mm. The work pieces were heat treated to have a uniform hardness. AISI 1045 steel is widely used in manufacturing. The mechanical properties of the material are given in Table I.

TABLE I
Mechanical Properties of AISI 1045 Steel

Property	Value
Ultimate tensile stress	515 Mpa
Yield stress	484 MPa
Young's Modulus	200 GPa
Poisson's ratio	0.29
Brinell Hardness	170 HB
Shear modulus	80 GPa

B. Tool Details

Parallel shank WIDIA M680 tool holder of 16 mm diameter with two flutes was chosen. WIDIA XDHT 090308-HX PVD coated PA 120 grade inserts were used for cutting.

C. Machine Details

ARIX VMC100, three axis CNC vertical machining centre was used for machining. The machine is shown in Fig. 1. Axis travel (X,Y,Z) –1000 x 500 x 500 mm; Spindle motor - 5 HP; Maximum feed rate - 4000 mm/min; Maximum spindle speed - 5000 rpm

Fig. 1. ARIX VMC100, 3 Axis Vertical Machining Centre

D. Experimental Design

Spindle speed (s), feed rate (f) and axial depth of cut (a) are considered as the major controllable cutting parameters. Experiments were conducted for the conventional constant feed rate and the proposed progressive feed rate and the results were compared. Climb milling with dry machining condition was chosen.

1) *Constant Feed Rate:* In normal machining conditions the feed rate is kept constant throughout the machining cycle, especially for a particular segment. Spindle speed, feed rate and depth of cut were taken each at three levels. Table II gives the details of the machining parameters.

TABLE II
Machining Parameters – Constant Feed Rate

Parameters	Levels		
Spindle speed, rpm	750	1000	1250
Depth of cut, mm	0.2	0.4	0.6
Feed rate, mm/min	40	60	80

2) *Progressive Feed Rate:* It is proposed to have a progressive feed rate wherein when a cut is initiated the feed rate starts from a low value and gradually accelerates to the final feed rate. The feed rate is increased in four steps (Fig. 2) and reaches the final feed rate. The progressive feed is applied through a distance equal to the radius of the cutter. When the tool travels through this distance the cutting width will be equal to the cutter diameter. In this case the cutter diameter is 16 mm and hence the progressive feed is applied through a distance of 8 mm. This distance of 8 mm is divided into four steps of 2 mm each. Beyond 8 mm the feed rate is constant.

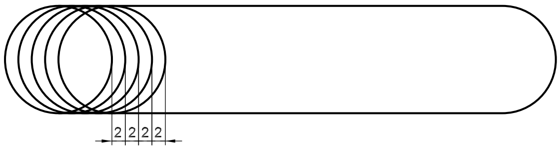

Fig. 2. Progressive Feed Rate steps

The starting feed rate is taken as the percentage of the final feed rate. The feed rate for the experiment is calculated as follows:

Level 1: Starting feed rate is taken as 15% of the final feed rate of 60 mm/min, which is 9 mm/min. Subsequent feed rates are taken as 16, 26, 36 mm/min and finally to 60 mm/min.

Level 2: Starting feed rate is taken as 25% of the programmed feed rate of 80 mm/min, which is 20 mm/min. Subsequent feed rates are taken as 30, 40, 50 mm/min and finally to 80 mm/min.

Level 3: Starting feed rate is taken as 35% of the programmed feed rate of 100 mm/min, which is 35 mm/min. Subsequent feed rates are taken as 45, 55, 65 mm/min and finally 100 mm/min.

The machining parameters and their values are given in Table III. The percentage for the starting feed rate is chosen such that the total machining time does not exceed that of the conventional machining method. The increments for the successive steps are chosen such that the difference in the feed rate between steps does not exceed 50%, which otherwise will increase the cutting force. Also the programmed feed rate has been taken as 60, 80 and 100 mm/min as against the 40, 60 and 80 mm/min given for constant feed rate. This is done considering two factors. One, a reduction in cutting forces is anticipated. Two, with progressive feed rate the machining time will increase and in order to maintain the machining time the feed rate values have been increased.

TABLE III
Machining Parameters – Progressive Feed Rate

Parameters	**Levels**		
Spindle speed, rpm	750	1000	1250
Depth of cut, mm	0.2	0.4	0.6
Starting feed rate, % of programmed feed rate	15	25	35

IV. CUTTING FORCE MEASUREMENT

The cutting force was measured using Kistler 3-component Dynamometer 9257B. The work piece mounted on the dynamometer is shown in Fig. 3.

Fig. 3 Work piece mounted on Dynamometer

The dynamometer was connected to the data acquisition system which in turn was connected to a personal computer to save the data. The setup is show in Fig.4. The calculated mean cutting force values for constant feed rate is given in Table IV and Table V gives the values for progressive feed rate.

Fig.4 Data acquisition system with personal computer

TABLE IV
Mean Cutting Force – Constant Feed Rate

Trial No	Spindle Speed, rpm	Feed, mm/min	Depth of Cut, mm	Mean Cutting force, N
1	750	40	0.2	22.4
2	750	60	0.4	45.8
3	750	80	0.6	85.9
4	1000	40	0.4	33.2
5	1000	60	0.6	60.0
6	1000	80	0.2	26.1
7	1250	40	0.6	49.6
8	1250	60	0.2	22.6
9	1250	80	0.4	45.0

TABLE V
Mean Cutting Force – Progressive Feed Rate

Trial No	Spindle Speed, rpm	Feed rate, %	Depth of Cut, mm	Mean cutting force, N
1	750	15	0.2	19.6
2	750	15	0.4	34.3
3	750	15	0.6	52.0
4	750	25	0.2	24.3
5	750	25	0.4	48.1
6	750	25	0.6	72.4
7	750	35	0.2	26.5
8	750	35	0.4	51.3
9	750	35	0.6	79.2
10	1000	15	0.2	15.6
11	1000	15	0.4	30.1
12	1000	15	0.6	45.2
13	1000	25	0.2	19.5
14	1000	25	0.4	38.7
15	1000	25	0.6	54.0
16	1000	35	0.2	22.4
17	1000	35	0.4	45.5
18	1000	35	0.6	71.4
19	1250	15	0.2	12.7
20	1250	15	0.4	24.1
21	1250	15	0.6	43.7
22	1250	25	0.2	16.5
23	1250	25	0.4	34.2
24	1250	25	0.6	48.8
25	1250	35	0.2	19.3
26	1250	35	0.4	38.5
27	1250	35	0.6	59.1

A. Constant Feed Rate vs. Progressive Feed Rate

The trials using constant feed rate were compared with the equivalent trials using progressive feed rate. The mean cutting force for the individual trials were compared to check for any reduction in cutting force. The values are tabulated in Table VI. The comparison of the mean cutting force values for both the methods is shown in Fig.5.

TABLE VI
Reduction in Mean Cutting Force

Trial No [CF]	Trial No [PF]	Mean cutting force, N		% Reduction
		Const. Feed	Prog. Feed	
1	1	22.4	19.6	12.5
2	5	45.8	48.1	-5.0
3	9	85.9	79.2	7.8
4	11	33.2	30.1	9.3
5	15	60.0	54.0	10.0
6	16	26.1	22.4	14.2
7	21	49.6	43.7	11.9
8	22	22.6	16.5	27.0
9	26	45.0	38.5	14.4
Overall improvement				11.30

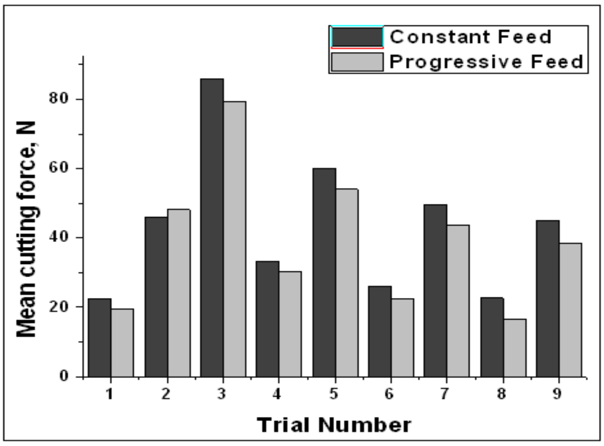

Fig.5 Mean cutting force - Constant feed rate vs. Progressive feed rate

B. Regression Mathematical Model

The regression model fitted for mean cutting force was obtained using Design Expert software and is represented by the Eqs. 1 – 3. Since the feed rate is taken as a percentage of the programmed feed rate it was considered as a categorical parameter, whereas the spindle speed and depth of cut were taken as numerical values. Hence three equations were arrived at.

Starting feed rate 15%:

$$N = 15.878 - 0.032 * s + 113.667 * a - 0.05 * s * a + 1.76E - 005 * s^2 + 17.5 * a^2 \quad (1)$$

Starting feed rate 25%:

$$N = 30.644 - 0.045 * s + 131.917 * a - 0.05 * s * a + 1.76E - 005 * s^2 + 17.5 * a^2 \quad (2)$$

Starting feed rate 35%:

$$N = 24.611 - 0.042 * s + 154.083 * a - 0.05 * s * a + 1.76E - 005 * s^2 + 17.5 * a^2 \quad (3)$$

Where ‘s’ is spindle speed in rpm, and ‘a’ is the axial depth of cut in mm.

The predicted mean cutting force values obtained using Eqs.1-3 were compared with the actual measured values and the percentage of error for each trial is given in Table VII. The comparision is graphically shown in Fig. 6. It can be clearly seen that the experimental values and the predicted values agree closely.

Table VII
Mean Cutting Force - Experimental vs Predicted Values

Trial No	Mean cutting force, N		% Error
	Experimental	Predicted	
1	19.6	17.6	10.0
2	34.3	34.9	-1.9
3	52.0	53.7	-3.2
4	24.3	26.1	-7.4
5	48.1	47.1	2.2
6	72.4	69.4	4.1
7	26.5	27.1	-2.3
8	51.3	52.5	-2.3
9	79.2	79.3	-0.1
10	15.6	14.8	5.1
11	30.1	29.6	1.6
12	45.2	45.8	-1.4
13	19.5	20.0	-2.4
14	38.7	38.4	0.7
15	54.0	58.3	-7.9
16	22.4	21.8	2.6
17	45.5	44.7	1.7
18	71.4	69.0	3.4
19	12.7	14.2	-11.7
20	24.1	26.5	-9.9
21	43.7	40.2	8.1
22	16.5	16.0	2.9
23	34.2	32.0	6.5
24	48.8	49.3	-1.0
25	19.3	18.8	2.8
26	38.5	39.1	-1.6
27	59.1	60.9	-3.0

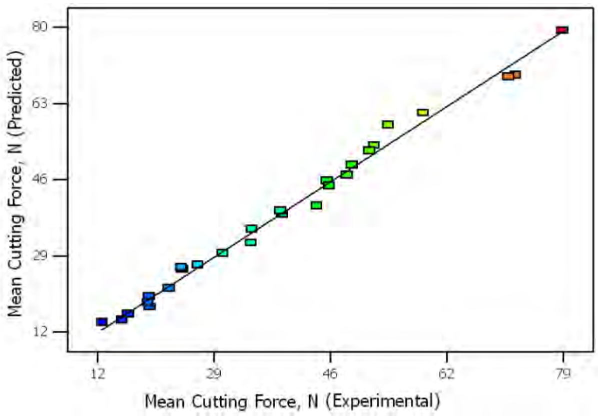

Fig. 6 Experimental vs Predicted values of mean cutting force

C. Adequacy of the Developed Model

Analysis of variance (ANOVA) technique [17,19,20] was used to check the accuracy of the model.The Model F-value of 153.75 implies that the model is significant. Values of "Prob > F" less than 0.05 indicates that the model terms are significant. Table VIII gives the details of ANOVA.

Table VIII
ANOVA for testing the adequacy of the model

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	8817.54	11	801.59	153.75	< 0.0001
Spindle Speed (s)	*682.04*	1	*682.04*	*130.82*	*< 0.0001*
Feed (f)	*1035.42*	2	*517.71*	*99.30*	*< 0.0001*
Depth of cut (a)	*6782.24*	1	*6782.24*	*1300.84*	*< 0.0001*
Residual	78.21	15	5.21		
Corrected Total	8895.75	26			

V. RESULTS AND DISCUSSION

The effect of machining parameters on the mean cutting force was considered. A new feed rate method, progressive feed rate, was introduced. Experiments were conducted and the mean cutting force values were measured using Dynamometer.

A. Constant Feed Rate vs. Progressive Feed Rate

The mean cutting force values for both constant feed rate and progressive feed rate were tabulated and compared. It was found that there was reduction in cutting force in all the trials except in trial 5 (Table 6). This reduction in the mean cutting force may be attributed to the fact that in case of constant feed rate the cutting tool accelerates from zero (at the start of the cut) to the programmed feed rate instantly. This instant acceleration creates higher cutting forces. Whereas in case of progressive feed rate the cutting tool starts from a low feed rate and gradually increases to higher values. This means that the feed rate increases gradually and hence the cutting force increases gradually.

B. Main Effects Plot for Progressive Feed Rate

Figures. 7 - 9 shows the effect of the cutting parameters on the mean cutting force.

1) Effect of Spindle Speed on Cutting Force: From the Fig. 7 it was observed that the cutting force decreased with the increase in the spindle speed. At lower spindle speeds the adhesion of work piece material to the tool tip takes place which reduces the effectiveness of machining thereby increasing the cutting force. However at high spindle speeds continuous reduction in the build up edge takes place and thus the cutting force comes down.

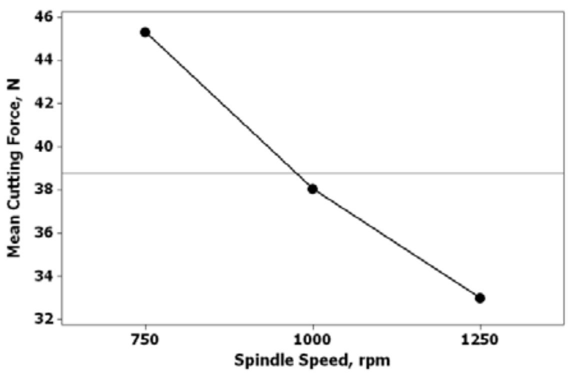

Fig. 7 Effect of spindle speed on mean cutting force

2) Effect of Feed Rate on Cutting Force: It was observed from Fig. 8 that the cutting force increased with the increase in the feed rate. Higher feed rate increases the material remove rate (MRR). Also with high feed rate the metal may be pushed instead of being cut. This will result in higher cutting force and higher temperature. The high temperature may lead to work harden of the work piece which in turn increases the cutting force.

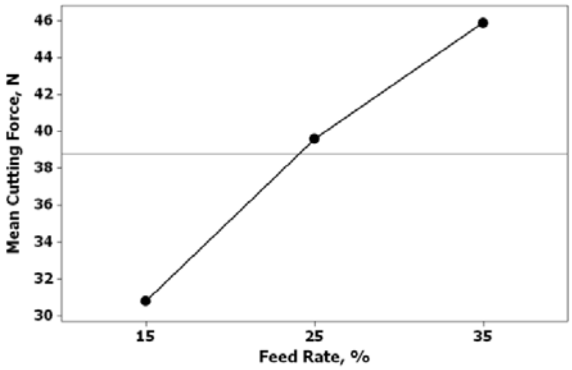

Fig. 8 Effect of feed rate on mean cutting force

3) *Effect of Depth of Cut on Cutting Force:* It was observed from the Fig. 9 that the cutting force increased with the increase in the depth of cut. Higher axial depth of cut increases the volume of metal removal and also leads to an increased contact area of the work piece, which increases the cutting force and induced mechanical load.

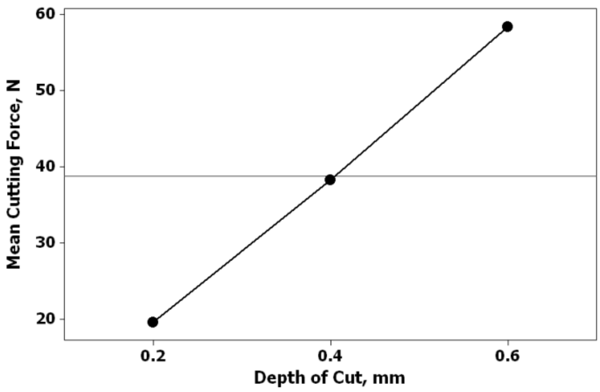

Fig. 9 Effect of depth of cut on mean cutting force

C. Interaction Effects for Progressive Feed Rate

Figures 10 - 12 shows the various interaction effects of the cutting parameters on the cutting force.

1) Effect of Spindle Speed and Depth of Cut on Cutting Force: Fig. 10 shows the interaction effect of spindle speed and depth of cut on the cutting force. It can be inferred from the graph that for a given depth of cut, increase in the spindle speed reduces the cutting force. This is in agreement with the discussion in section B. 1) that increase in the spindle speed reduces the cutting force. Also it can be observed that for a given spindle speed the increase in the axial depth of cut increases the cutting force. This relevance is given in section B. 3).

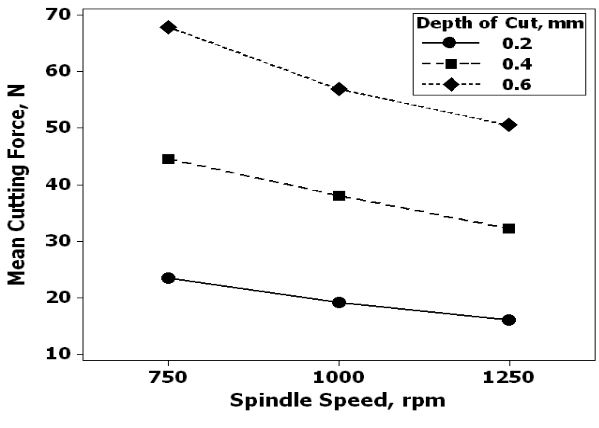

Fig. 10 Effect of spindle speed and depth of cut on mean cutting force

2) *Effect of Feed Rate and Spindle Speed on Cutting Force:* Fig. 11 shows the interaction effect of

feed rate and spindle speed on the cutting force. The graph shows that for a given spindle speed, increase in the feed rate increases the cutting force. This is as discussed in section B. 2) that increase in the feed rate increases the cutting force. Also it can be seen that for a given feed rate the increase in the spindle speed reduces the cutting force, which was discussed in section B. 1).

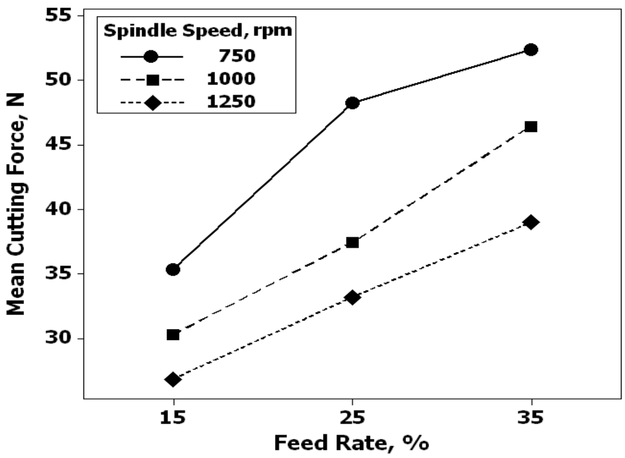

Fig. 11 Effect of feed rate and spindle speed on mean cutting force

3) *Effect of Depth of Cut and Feed Rate on Cutting Force:* Fig. 12 shows the interaction effect of axial depth of cut and feed rate on the cutting force. It can be seen that for a given feed rate the cutting force increases with the increase in depth of cut. This is in line with the discussion held in section B. 3) of this article. Also it is observed that for a given depth of cut increase in the feed rate increases the cutting force. This is in agreement with the discussion held in section B. 2).

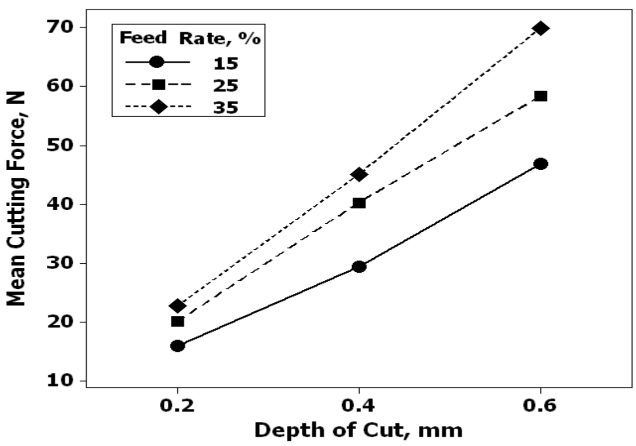

Fig. 12 Effect of depth of cut and feed rate on mean cutting force

VI. CONCLUSION

A new method of applying feed rate, progressive feed rate, which is unlike the conventional constant feed rate, was proposed. Experiments were carried out both for constant feed rate and for progressive feed rate and the mean cutting force were compared. Results show that experiments conducted using progressive feed rate gave a reduction in the mean cutting force to the tune of 11% (Table VI).

A regression mathematical model was developed using the data and the mean cutting force was predicted using the generated equation. The values were compared with the experimental data was found to be in good agreement, which shows the accuracy of the developed model (Fig. 6). The results indicate that the developed model can be effectively used for predicting the mean cutting force.

On testing the adequacy of the model using ANOVA it was found that the model was significant and the cutting parameters, spindle speed, feed rate and depth of cut have an influence on the mean cutting force.

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