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Force Modeling in Ball-end Milling and its Application to Sculptured Surface Machining

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Abstract—*Ball-end Milling is one of the most effective machining processes for components with sculptured surfaces such as dies, molds and automotive components. Force modeling has been an important tool to estimate tool life, predict chatter and tool deflection, monitor tool condition in manufacturing. This paper presents an empirical formulation of modeling cutting forces in ball-end milling and proposes a method to apply it to force modeling in sculptured surface machining. The workpiece is selected of mild steel and the ball-end mill of HSS. The experiment is designed as Central Composite Rotational Design, and the forces in X-, Y- and Z-directions are measured corresponding to the cutting parameters of depth of cut, feed and RPM. Empirical equations are generated to predict the cutting forces, and the equations are validated for a different set of data. Now a method is proposed based on literature survey to use the equations to predict the cutting forces for machining a sculptured surface where the tool can have arbitrary path in cutting.*

1. INTRODUCTION

For machining sculptured surfaces, that is surfaces with geometry having complex shapes such as in aircraft structural parts, automobiles parts, turbine blades, stamping dies etc, ball-end milling is used. It is a type of mill which consists of a hollow cylindrical shell (ball nose) rotating about its axis for the production of curved surface. Precision parts with curved surfaces such as dies and molds are required in many manufacturing industries. The ball-end milling cutter is one of the most widely used cutting tools in the machining of parts with 3-D sculptured surfaces such as dies and molds.

In general, prediction of forces in flat end milling is not complex problem. But in the case of ball-end milling, it is difficult due to complex geometry of ball-end milling either for force modeling or geometric modeling. Force modeling is important tool to estimate tool life, predict chatter and tool deflection, monitor tool condition in manufacturing.

For force modeling based on mechanistic methods, the cutting forces are calculated on the basis of the engaged cut geometry, the undeformed chip thickness distribution along the cutting edges, and the empirical relationship that relate the cutting forces to undeformed chip geometry. Now these empirical relations should be estimated by real force values obtained by conducting experiments. Feng and Menq [1] designed a cutting force model and determined empirical cutting force coefficients using numerical polynomial fit. VenkateswaraSharma and Manu [2] developed an empirical modeling of cutting forces in ball-end milling using experimental design, in which the force modeling was done according to the mechanistic principles of metal cutting, in which the forces acting on the ball end mill are directly proportional to the undeformed chip geometry. Azeem et al. [3] presented a simplified and efficient calibration of a mechanistic cutting force model for ball-end milling where a new approach is proposed to determine the cutting force coefficients for ball-end milling from only a single test cut. Instantaneous cutting forces are used instead of average forces to calibrate the empirical force coefficients. This single experiment significantly reduces the time and effort needed to determine the coefficients in order to cover a wide range of cutting conditions. Sun et al. [4] have developed a mechanistic method for estimating cutting forces in ball-end milling of sculptured surface for a general case of toolpath and varying federate by incorporation of a new chip thickness model. Based on the given cutter path and feedrate scheduling strategy, the trace modeling of the cutting edge used to determine the undeformed chip area resulted from the relative path-tool motion in milling. Validation tests were carried out on a sculptured surface with curved toolpaths practical cutting conditions.

1.1 Cutting Force Modeling

A number of different methods to predict the cutting forces have been developed for modeling the forces. These can be classified into four categories.
(a) Analytical
(b) Empirical
(c) Numerical
(d) Mechanistic

Out of all the above models, empirical models are the simples to predict the forces during cutting processes. The empirical methods are based on the study ofexperimental results which are collected in a large number to have a wide range for thevalidity of the model. They derive the cutting force coefficients by using the results of anumber of machining experiments conducted to obtain cutting forces, tool life, toolwear, and then relating them to the cutting conditions using proposed empiricalfunctions.

2. FORCE MODELING FOR BALL-END MILLING

The cutting force model was developed based on the empirical equation using numerical fitting procedure. The forces acting on the ball-end mill are modeled based on the equation from the paper given by Feng and Menq, in which the empirical relation is used to relate the cutting forces to the undeformed chip geometry.

2.1 Experimental work

A series of model building experiments was performed on CNC Milling Machine OKUMA ACE CENTER MBA-46 VAE-R vertical milling machine at IIITDM Jabalpur.The HSS ball-end mill with 12 mm diameter, four flutes was used. The ball-end mill was placed in tool holder and workpice was fitted on Dynamometer. The workpiece was Mild steel with a composition of 0.22% C, 0.24% Si, 0.64% Mn, 0.04% S, 0.05% P, 0.05%, Ni and 98.49% iron.

KISTLEAR dynamometer of type 9257B was used to measure the cutting forces during machining with charge amplifier of type 5070A for multi-component forces measurement. A total of 20 slots were cut and the analysis was carried out using CCRD model.

3. RESULTS AND DISCUSSION

Having selected the range of variation of the input parameters, experiments were conducted and results were recorded. The dynamometer recorded the forces in x-, y- and z- directions. The experimental results were obtained from the CCD runs.

3.1 Regression Analysis and Model fitting

After conducting the experiment, ANOVA of the results was carried out and regression model was studied. The model was created in terms of forces in X-, Y- and Z- direction. After neglecting the insignificant terms, the coefficient in the final equation for F_X, $F_Y$and F_Z are given below.

F_X =+155.51+5.84*d_c+0.6408*f -0.4725*RPM -0.8010*d_c*f -1.59099*10^{-3}*d_c*RPM - 2.12132*10^{-4}*f*RPM +10.49*d_c^2 +0.0290*f^2+3.52194*10^{-4}* RPM^2

Fy=-483.48+ 284.11*d_c+ 16.44*f -0.3414 *RPM -3.44*d_c*f+ 0.0285*d_c*RPM+ 4.19*10^{-3}*f*RPM -8.17827*d_c^2 -0.0332 *f^2-9.29*10^{-5}*RPM^2

Fz=-34.93773 +129.43*d_c +14.22*f -0.5577*RPM -2.66*d_c*f +0.0158*d_c*RPM +1.89446*10^{-3}*f*RPM +9.23*d_c^2-0.0340*f^2+2.77002*10^{-4}*RPM^2

where d_c is the axial depth of cut, f is the feed and RPM is the Revolution per Minute.

3.2 Effect of input parameters on Forces

After generating the calibrated equation, the quadratic response can be plotted. The variation of forces with the factors of axial depth of cut, feed and RPM is presented below in form of surface plots.

Variation of force in *X*- direction:

The surface plots are given below:

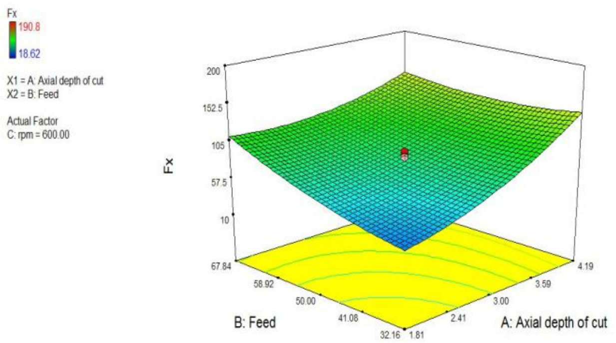

Fig. 1: Variation of F_X withd_c and f

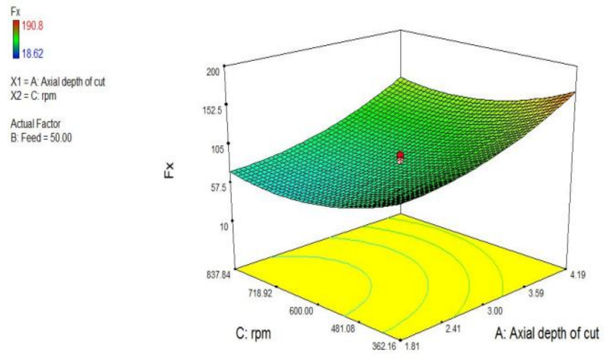

Fig. 2: Variation of F_X with d_c and RPM

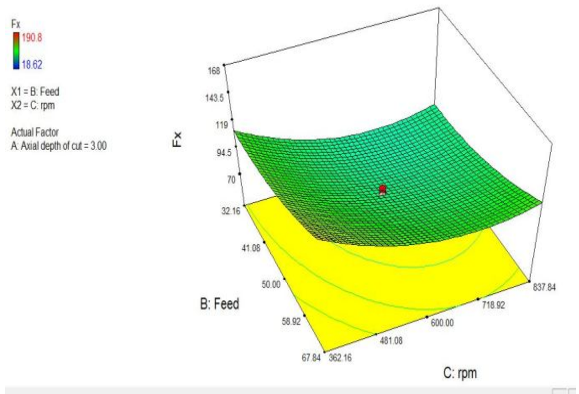

Fig. 3: Variation of F_X with f and RPM

Variation of force in *Y*- direction

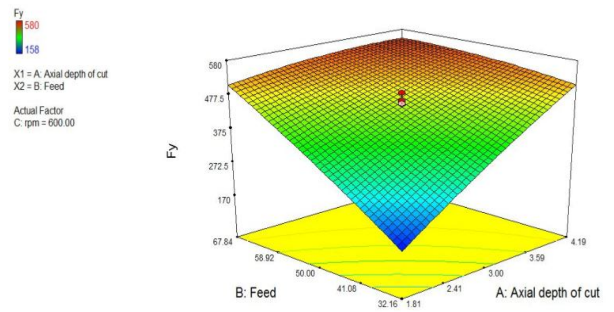

Fig. 4: Variation of $F_Y$with d_c and *f*

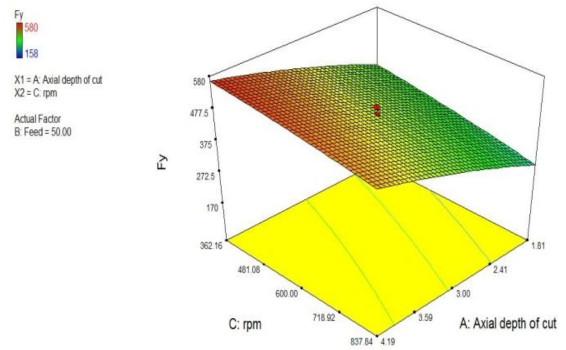

Fig. 5: Variation of $F_Y$with d_c and Rpm

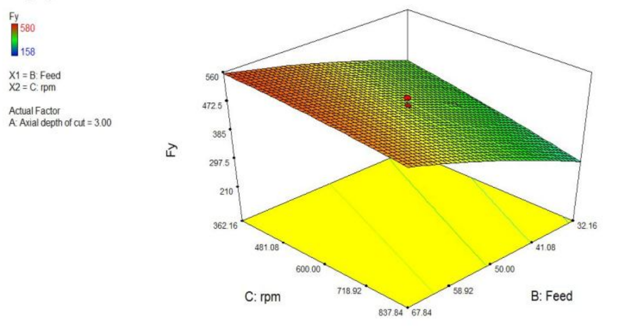

Fig. 6: Variation of $F_Y$with*f* and RPM

Variation of force in *Z*- direction

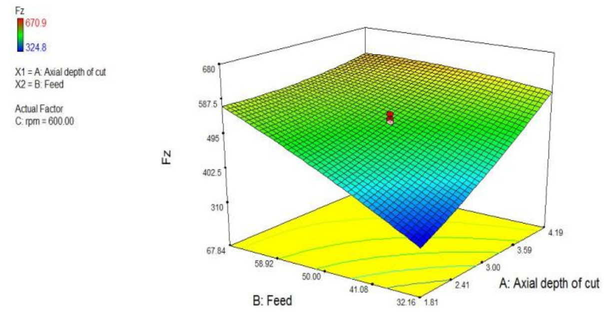

Fig. 7: Variation of force F_Z with d_c and *f*

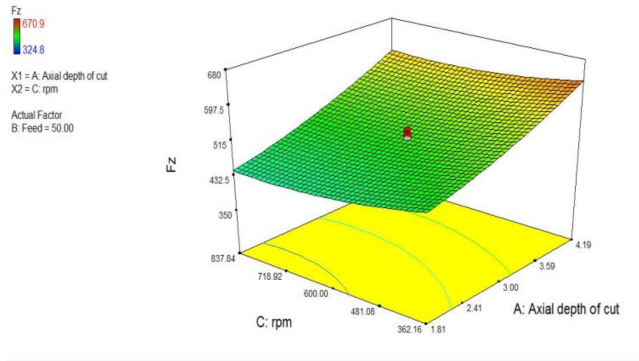

Fig. 3.8: Variation of $F_Z$with d_c and RPM

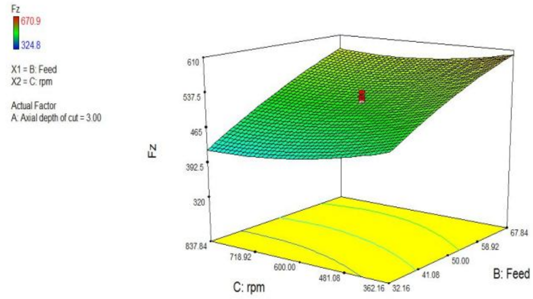

Fig. 9: Variation of force F_Z with*f* and RPM

3.3 Discussion of result

As we can see from figures above that when the axial depth of cut increases, forces also increase. This is because as the cutting tool penetrates deeper into the workpiece, more and more work material is removed, and hence higher forces are required.

As the feed increases, the cutting forces also increase. This is again because the force required to remove the additional material goes higher and higher.

As the RPM increases, the tip speed of the cutting tool increases. Thus the cutting force decreases. This can be clearly seen from the aboveFigures.

As the RPM increases, the tip speed of the cutting tool increases. Thus the cutting force decreases. This can be clearly seen from Figs.

3.4 Model validation

To validate the model, random values for axial depth of cut, feed, and RPM in the range of variation of parameters were selected and experiments were conducted. The results of the experiment were recorded and presented in Table 1.

The comparison of predicted and experimental values shows a good correlation with maximum error of 7.1 %. The model predicts the forces very closely in cutting of mild steel workpiece by HSS tool.

4. APPLICATION TO SCULPTURED SURFACE MACHINING

After conducting the force modeling in ball-end milling, the data is used for developing the force model for sculptured surface machining. For modeling the forces on sculptured surface, a mechanistic model is proposed as per the procedure used by Feng and Menq [1]. The size effect in metal cutting plays a significant role. Hence the cutting force can be estimated with the size effect as per the following:

$$F=Kbt^m$$

where$F$ is the principal cutting force responsible for the total energy consumed, b is the width of cut, t is the undeformed chip thickness, K is the cutting mechanics parameter, and m is a constant that varies between 0 and 1 for most of the metals. K includes the effect of all the process parameters except b and t, the undeformed chip geometry parameters. The instantaneous chip thickness is obtained as

$$t(\theta)=f\sin\theta$$

whereθ is the angular position of the cuttingedge.

Now the differential cutting forces in the tangential and radial directions can be written as:

$$dF_i=K(z)dz[t_i(\theta,z)]^m$$

Now, Feng and Menq [1] propose that the cutting mechanics parameters in the tangential and radial directions can be obtained as:

$$K_T(z) = a_0 + a_1\frac{z}{R} + a_2\left(\frac{z}{R}\right)^2 + a_3\left(\frac{z}{R}\right)^3$$

$$K_R(z) = c_0 + c_1\frac{z}{R} + c_2\left(\frac{z}{R}\right)^2 + c_3\left(\frac{z}{R}\right)^3$$

where z is the distance along the z-axis, R is the radius of the tool, and a_i and $c_i$are constants to be determined. Using the above formulation, the cutting forces in X- and Y- directions are obtained by geometric formulation and then averaged over a complete revolution. Now the experimental results obtained above are used to evaluate the constants present in the equations above. These constants determine the mechanistic equation. Now, these equations are used to predict the forces for machining of sculptured surfaces.

5. CONCLUSION

Force modeling has been an important tool to estimate tool life, predict chatter and tool deflection, monitor tool condition in manufacturing. The experiment is based on Central Composite Rotational Design, and the forces in X-, Y- and Z- directions are measured corresponding to the cutting parameters of depth of cut, feed and RPM. The above model could successfully predicted the forces developed during ball-end milling operations. This model coupled with the mechanistic equations can be applied to predict the forces in sculptured surface machining.

Table 1: Validation of proposed model

S. No.	d_c (mm)	f (mm/min)	RPM (rev/min)	Predicted Values			Experimental Values			% Error F_X	% Error F_Y	% Error F_Z
				F_X (N)	F_Y (N)	F_Z(N)	F_X (N)	F_Y (N)	F_Z(N)			
1	3.5	70	300	183.39	562.31	623.16	180.4	570.3	650.3	1.6	1.4	4.3
2	4.5	70	800	189.5	545.97	650.78	190.8	580	670.9	0.6	6.2	3.0
3	3.0	50	400	142.72	483.95	545.40	150	495	580.5	5.1	2.2	6.4
4	2.0	40	500	80.01	290.71	407.57	85.73	286.7	417.9	7.1	1.3	2.5

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