

Modeling and Analysis of Ball End Milling Parameters of Inconel 718 Cantilevers Using RSM

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ABSTRACT: This paper is aimed at an experimental investigation of the ball end milling of Inconel 718 cantilevers, design and modeling of the process with the aid of the response surface methodology (RSM) utilizing the experimental data. The experiments were conducted according to the central composite design (CCD) with four factors of spindle speed, feed, workpiece thickness and workpiece inclination with toolpath orientation. The responses measured for each experiment were deflection (Def.) at free end, the experimental data was analysed to obtain the effect of various parameters on the response. The results of analysis of variance (ANOVA) indicated that the proposed mathematical models have been carried out to ensure the validity of the developed model. Confirmation test experiments have also been done to compare the experimental results and model result. The response surface model was found to be in good agreement.

KEYWORDS: Inconel 718, Ball-end milling, Cantilever, Workpiece Deflection, RSM, CCD,

I. INTRODUCTION

The superalloys are mostly used in the aerospace applications due to their ability to maintain excellent mechanical strength at elevated temperatures. Inconel 718 is one of the most commonly used super alloy in this class, in particular, it finds applications in aero-engines in the manufacturing of flexible web parts like discs, blades, sheets and rings [1-2]. The ball-end milling of thin-walled components is widely used for machining operation to generate three-dimensional complex profiles in aircraft industries [3-6]. The promising application of the process has prompted the focus of many researchers in the recent years. The paragraph below highlights the major findings of these researches on ball end milling of Inconel 718.

Sharamanet al. [7] performed high-speed ball nose end milling and found good surface finish while machining on 45° inclined workpieces. Authors also demonstrated the effect of cutter orientation and lead or tilt angles during five-axis ball end milling of turbine blade. The best surface finish was obtained during milling along horizontal inward direction with a 15° tilt angle to the cutter. Lee et al. [8] demonstrated the effect of workpiece inclination of 0°, 15° and 45° with different cutter orientations in a ball end milling operation. The minimum workpiece deflection and the better surface finish were observed at the workpiece tilt angle of 45° with vertical outward cutter orientation. Landers et al. [9] found that the optimal feed increases as the width-of-cut and depth-of-cut decrease, which results into higher surface roughness of the machined surfaces. Sonawane and Joshi [10] demonstrated the influence of process parameters on surface topography during ball end milling. The machined surfaces show formation of distinct bands along the periphery of cutter edge. Authors found the influence of chip compression and instantaneous shear angle on surface roughness and microhardness in those bands. Bouzakis et al. [11] have evaluated the undeformed chip geometry and cutting forces using initial part geometry, tool path and tool geometry as input parameters. Further, they have shown that the chip width and thickness of the cutting edge at its successive revolving positions are a function of two flute ball end mill in the case of down milling. Berra et al. [12] concluded that the cutting tool deflection has pronounced effect on the surface error than the workpiece deflection during machining of different parts. This is contrary to open-ended cantilever-type geometries, where the component of workpiece deflection is remarkably higher.

In this article, response surface methodology has been focused to develop non-linear mathematical experimental model for the computation of workpiece deflection and analyze the effect of machining parameters during ball end milling of Inconel 718 cantilevers. ANOVA test has been carried out to verify the adequacy of the developed model. It has been observed that the results of predicted and experimental are also quite similar.

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II. EXPERIMENTAL WORKS

Experimental design

In this work, the effect of independent machining parameters viz. cutting speed, feed, workpiece thickness, workpiece inclination and toolpath orientations on the machined the workpiece deflection is analysed, as shown in Figure 2. The ball-end milling was performed on inclined cantilever-shaped workpieces along two paths, horizontal outward and vertical upward, and at 45° and 15° workpiece inclination angles. In addition, tests were also performed on the flat horizontal (0°) workpieces to compare the results. The optimum parametric settings have been achieved to minimize the workpiece deflection using response surface methodology (RSM) in the framework of central composite design (CCD). A full-factorial blocked CCD was used and a total of 60 experiments were performed including a replication of each experimental run. Total 32 cube points, 8 centre points in cube, 16 axial points, and 4 centre points in axial position were considered in the design of experiments shown in Figure 1. The responses are graphically plotted and analysed using RSM. The parametric levels are decided based on the study of literature and preliminary experimental trials, as shown in Table 1. The deflection of the cantilever workpieces were measured at the free end. The variables are coded taking into account the capacity and limiting cutting conditions of the milling machine tool system. The coded values of the variables (Table 1) are obtained from the following transformation equation

$$x_1 = \frac{\ln x_n - \ln x_{n0}}{\ln x_{n1} - \ln x_{n0}} \tag{1}$$

where, x is a coded value of any factor corresponding to its natural value x_n , x_{n1} is a natural value at the +1 level and x_{n0} is the natural value of the factor corresponding to the base [13,16-17]

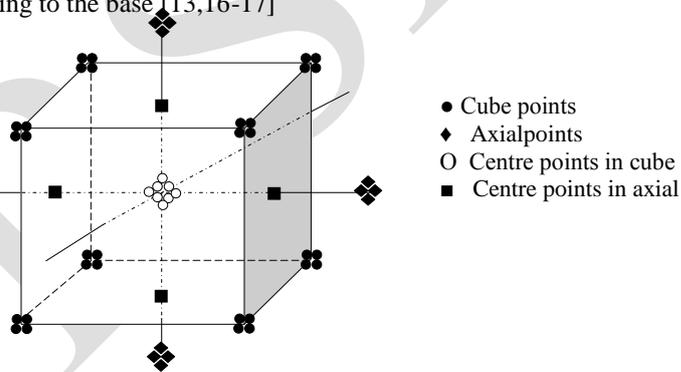


Figure 1. Central composite design for four factors

Experimental procedure: Fixture:

A fixture was designed to mount dynamometer and the cantilever work specimen at an inclination to the machine bed. Two mild steel plates were hinged at one end. On the top plate, the dynamometer was mounted and the bottom plate was fixed onto the machine table. The top plate was raised to a desired height from the other end, thereby positioning it to a desired angle at 15° and 45° with respect to the machine table (Figure 2). Additionally, a fixture was fabricated to hold the work specimens in cantilever position on the dynamometer surface (Figure 2).

Table 1. Factors and their levels

Sr. No	Machining parameters (Symbol) (unit)	Parametric level				
		-2 (Lowest)	-1 (Lower)	0 (Centre)	+1 (Higher)	+2 (Highest)
1	Spindle speed (V) (rpm)	1500	2000	3000	4000	4500

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2	Cutting feed (F) (mm/ tooth)	0.038	0.050	0.075	0.1	0.112
3	Workpiece thickness (T) (mm)	3.5	4	5	6	6.5
4	Workpiece angle and tool path orientation (D) (degree)	45 Horizontal	15 Horizontal	0 Horizontal	15 Vertical	45 Vertical

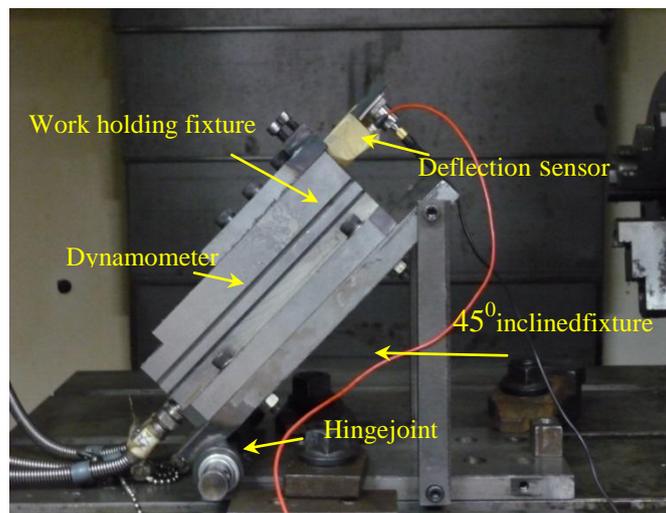


Figure 2. Close up view of experimental setup

Work specimen preparation

The work specimens were fabricated into thin rectangular plates (75mm × 25mm) of various thicknesses (3.5, 4, 5, 6 and 6.5mm). The selection of workpiece thickness was chosen based on the range of deflection sensor and workpiece thickness to length ratio. Thereafter, with consideration of parametric level designed by CCD, the final workpiece thickness have been chosen, which are also satisfying the industrial requirement for the machining of thin turbine blades at various workpiece inclination angles. All the Inconel 718 specimens were heat treated before machining to normalize the residual stresses generated while production of Inconel 718 cantilevers for a better analysis of the surface and subsurface qualities. They were solutionized at 1750⁰F to 1800⁰F (954⁰C to 982⁰C) for 1 hour and air cooled. Further, the solutionized samples were aged at 718⁰C for 8 hours and air cooled. The chemical composition of work material is 51.3% Ni, 20.14% Fe, 18.17% Cr, 4.8% Nb, 3.25% Mo, and balance C.

Cutting tools and machine tool

Solid carbide Ti-Al-N coated ball end mill cutters of 10mm diameter, 10⁰ rake angle and 30⁰ helix angle with two cutting flutes are used for the experiments (Figure 2). All the experiments were performed on a vertical CNC milling machine (HARDINGE-600II) under dry (without coolant) conditions [14-15].

Measurement of response variables

A deflection sensor was attached at the free end of the cantilever work specimen. It was connected to a deflection measuring (acquisition) software through an amplifier.

Operation details

The machining operation performed was slot milling along the length on the inclined cantilever type work specimens of various thicknesses. Ball end milling was carried out along two different cutting tool paths, vertically upward and horizontally outward. The slot was machined at a constant depth of cut of 1mm and over a cutting length of 40mm during each experimental run.

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III. RESULTS AND DISCUSSION

Development of Mathematical Models

Response surface modeling has been made to establish the mathematical relationship between response (y) and the various machining parameters. General second order response surface mathematical model which is considered to analyse the parametric influences on the various response criteria as follow [18].

$$y = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_i^2 + \sum_{j>1}^k b_{ij} x_i x_j \quad (2)$$

Where, y = output response, $x_i = (1, 2, 3, \dots)$ coded values for k quantitative parameters. The coefficient b_0 is the free term, the coefficient b_i is linear coefficient, the coefficient b_{ii} is quadratic term and the coefficient b_{ij} are the interaction terms.

Experiments have been carried out according to the experimental plan based on CCD. The input parameters and their coded values used in CCD matrix are as shown in Table 1. This coded values allotted to spindle speed, cutting feed, workpiece thickness and workpiece angle and tool path orientation at various levels. The Design Expert and Minitab software is used to analyse the experimental data during machining of Inconel 718 process.

The experimental values found using CCD matrix and developed the non-linear model for surface roughness (Ra) and workpiece deflection at free end (Def.). These experimental values tabulated shown in Table 2.

The non-linear mathematical model was developed as follows;

The following model will result the output in the coded form with the help of

$$\text{Deflection} = 0.086 + 0.00613 * V + 0.007 * F - 0.0024 * T + 0.0066 * D - 0.00673 * V * F - 0.0055 * V * T + 0.0021 * V * D + 0.0063 * F * T + 0.00103 * F * D - 0.0035 * T * D + 0.0072 * V^2 + 0.0025 * F^2 + 0.0028 * T^2 - 0.0018 * D^2 \dots\dots\dots(3)$$

From the developed models, it is evident that to spindle speed, cutting feed, and workpiece angle and tool path orientation are the significant factors for workpiece deflection. The calculated S values of the analysis for workpiece deflection of free end are obtained as 0.05 which are very small values and R-sq values for the response are 87.31%. The values of R-sq (adjusted) for Def. are 81%. All these values are close to unity and R-sq values is greater than R-sq (adjusted) values as a result the data for response is well fitted in the developed model.

Analysis of variance (ANOVA) technique is used to check the adequacy of the developed model for the desired confidence interval and given in Table 3. Here, the calculated F-value of the lack-of-fit for workpiece deflection at free end are 6.36 which are lower than the tabulated F-value confidence level. Furthermore, p-value of the source of regression, linear and square effects are lower than 0.01 for the response which implies the above model is significant.

Table 2. Experimental design matrix with response variable

Ext. No	V	F	T	D	Def. Free end (mm) Avg
1	1	1	1	1	0.56
2	0	0	0	0	0.45
3	1	1	-1	1	0.6
4	-1	1	1	1	0.62
5	0	0	0	0	0.42
6	-1	1	-1	-1	0.423
7	-1	-1	1	1	0.413
8	-1	-1	-1	1	0.444
9	1	-1	1	1	0.482
10	1	-1	-1	-1	0.501
11	1	1	1	1	0.511

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12	1	-1	-1	1	0.701
13	-1	-1	-1	-1	0.42
14	-1	-1	1	1	0.269
15	1	1	-1	-1	0.558
16	-1	1	1	-1	0.543
17	-1	1	-1	1	0.517
18	0	0	0	0	0.43
19	1	-1	1	-1	0.465
20	0	0	0	2	0.469
21	0	0	0	0	0.41
22	0	2	0	0	0.534
23	0	0	0	0	0.435
24	0	0	-2	0	0.455
25	-2	0	0	0	0.543
26	0	0	0	-2	0.29
27	0	0	2	0	0.489
28	0	-2	0	0	0.4
29	2	0	0	0	0.579
30	0	0	0	0	0.46

Table 3.Result of ANOVA for developed Models

Source	Def. _{free} model	
	F- value	P-value
Regration	195.17	0.000
Linear	298.16	0.005
Interaction	113.25	0.002
Lac-of-fit	6.36	0.0061

Influences of process parameters on workpiece deflection (Def.) in ball end milling of cantilevers of Inconel 718 performances has been analysed based on the mathematical model Equations was obtained as above (equation no. 3).

Analysis of parametric influence on Deflection

The forces are generated due to shearing and frictional resistance in the interface region in ball end milling operation. While milling of thin shaped cantilever plate, these forces are likely to caused eflexion in work piece. A concept of analytical model for the evaluation of instantaneous work piece deflection as the ball-endmill tool passes from the fixed-end towards the free-end of cantilever.

Effect of cutting speed and feed

The effect of interaction between cutting speed and feed on deflection is presented using a surface plot in Figure 3(a). It is observed that the interaction of cutting speed and feed has a significant impact on deflection of workpiece. At 0.038mm/tooth/rev of feed and 63m/mincutting speed, deflection is less than 0.43mm and for a 125.6m/min cutting speed, the deflection is greater than 0.70mm.

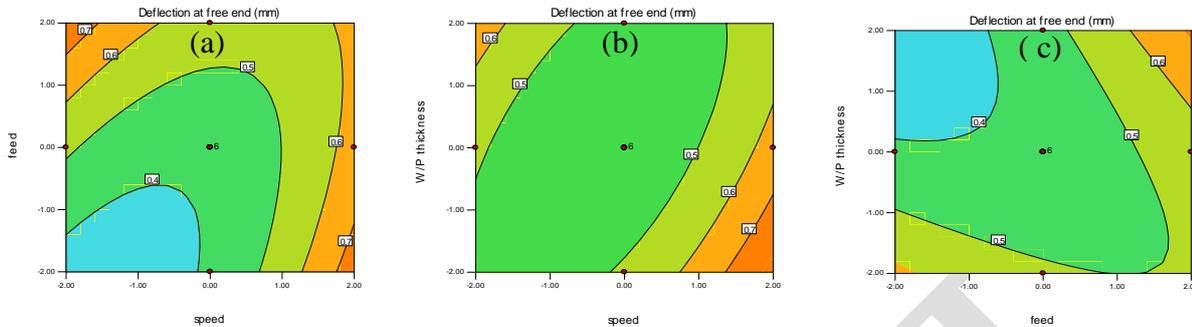


Figure 3. Contour plot of deflection at free end with (a) speed and feed (b) speed and w/p thickness and (c) feed and w/p thickness

However, with an increase in the feed to 0.112mm/tooth/rev with higher cutting speed the maximum deflection of workpiece of 0.74mm is observed. The feed has more dominant effect on the workpiece deflection than that of the cutting speed. An increase in the feed rate results into an increase in a chip load and thereby increases the overall thrust force during machining at the free-end of cantilever [20].

Effect of cutting speed and workpiece thickness

The effect of cutting speed as the workpiece thickness changes from 3.5mm to 6.5mm is analysed in Figure 3(b). A lower workpiece deflection of 0.41mm is observed on thicker > 5mm workpieces and at the moderate cutting speeds. The workpiece deflection increases as the workpiece thickness decreases. The highest workpiece deflection of >0.7mm is observed on thinner workpiece (3.5mm) and at higher cutting speed of 141m/min.

Effect of feed and workpiece thickness

The effect of interaction between cutting feed and workpiece thickness on deflection is presented using a surface plot in Figure 3c. It is observed that the interaction of workpiece thickness and feed has a significant impact on deflection of workpiece. The minimum deflection 0.35 is observed with 6.5mm workpiece thickness and at 0.075mm/tooth/rev of feed. The deflection is increases with increase in feed and decreases with workpiece thickness. The higher deflection observed at 3.5mm at thin workpiece and 0.112mm/tooth/rev of feed due to that the plate thicknesses decrease the decrease in the rigidity of the workpiece.

Validation of Models

Model validation is then extstep after the model is established. In order to validate the model L8 orthogonal experiments are performed with the input factors shown in Table 4. The comparison of experimental, model results for the response workpiece deflection at free end is shown in Table 5. It can be seen that model predicts satisfactory results. However, model is shown to gives results which is in close agreement to the experimentally obtained once.

Table 4. Input factors for confirmation experiment

Parameter	Level 1	Level 2
V	2000	4000
F	0.05	0.1
T	4	6
D	15° Horizontal	15° Vertical

The result of the validation experiments is presented in Table 5.

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Table5.Verification of model for surface roughness and deflection

Std.Run	Def.Exp.	Def. Model	% Error
1	0.44	0.435	1.13
2	0.38	0.41	-7.89
3	0.6	0.65	-8.33
4	0.46	0.43	6.52
5	0.445	0.415	6.78
6	0.6	0.53	11.66
7	0.65	0.59	9.28
8	0.55	0.53	4.02

IV. CONCLUSIONS

In this work, the deflection (Def.) mm in ball end milling process was modeled and analysed through RSM. Spindle speed, feed, workpiece thickness and workpiece inclination with toolpath orientation have been employed to carry out the experimental study, analysis of variance (ANOVA) was applied to ensure the validity of the developed models. Summarizing the main features, we drawn the following conclusions;

1. The developed non-linear response surface model for Deflection of workpiece using CCD matrix have been found adequate at 99% confidence level. It has been observed that regration coefficient, linear and square effects are significant for the model.
2. Developed models predicts that Def. is significantly affected by the spindle speed, feed, workpiece inclination with tool path orientations interaction effect of speed and feed, feed and workpiece thickness and workpiece thickness and workpiece inclination with toolpath orientations have been significantly affected factor for workpiece of deflection.
3. It has been observed that experimental values and predicted values are quite close which indicates that the developed model can be used effectively.

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