Research Article

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PERFORMANCE ANALYSIS IN BALL NOSE END MILLING OF PREHEATED HSTR INCONEL 600 ALLOY

Rupesh Bangar[1], Vallabh Sakhare[1], Aishwarya Mahagaokar[1], Gopal Chavan[1], Raju Pawade[2]

[1]Graduate Student, [2]Associate Professor
Department of Mechanical Engineering, Dr. Babasaheb Ambedkar Technological University,
Lonere 402 103, Maharashtra, India. Email : [2]rspawade@dbatu.ac.in

Abstract : The paper reports the performance of ball nose end milling of preheated Inconel 600. The experiments designed using L8 orthogonal array were carried out on CNC milling machine using solid carbide ball end mill. The machining parameters (spindle speed, feed per tooth, depth of cut and number of flutes) were varied at two levels each and the surface roughness and material removal rate were measured. The analysis of results shows that the surface finish degrades at lower spindle speed. The chips welded on both sides of the slot retard chip flow, and cutting temperature will increase because the heat generated can not be dissipated with the chips leading to poor surface finish.

Keywords : Preheating, ball end milling, Taguchi, surface roughness, MRR, Inconel 600

1. Introduction

Inconel 600, a nickel based superalloy, finds applications in chemical processing (heaters, stills, bubble towers, and evaporator tubes), aerospace (lock wire, exhaust liners, and turbine seals) and nuclear industries (pressure vessels, heat exchanger tubing, steam generators). However, its excellent creep-rupture strength at elevated temperature leads to early cutting tool failures and metallurgical damage to the machined surface and sub-surfaces, and difficulty in machining [1,2]. Ball end milling is used to generate profiled surfaces on the components. The large radius of the ball end mill cutter facilitates uniform dissipation of heat at the higher speeds and feeds. Machining complex surfaces of Inconel 600 alloy is a challenge due to geometrical complicity of the parts, high tolerance and finish requirements. After the first machining pass, work hardening of this alloy tends to elastically deform either the workpiece or the tool on subsequent passes. These machining problems can be overcome to a certain extent by preheating the workpiece before machining that facilitates reduction in specific strength of the material [3]. The huge cost involved in machining of nickel alloys has prompted continued research and development of cutting processes and tool materials with minimum surface and sub-surface damage on the machined components [4].

Limited work has been published dealing with ball nose end milling of Inconel alloys. Sonawane et al. [5] have noticed that the chips get compressed significantly along their lengths during ball end milling of Inconel 718. In the case of chip width, the deformed chip width is larger in magnitude than the undeformed chip width [5]. In another experiment, similar observations have been noted in case of deformed chip thickness and width [6]. Ng et al. [7] have studied ball nose end milling of Inconel 718 at a workpiece angle of 45°. They have found that the chip edge length affects specific force acting on the cutting edge of the tool, and hence, the surface roughness. Further, the surface roughness has been the lowest in this orientation. Yang and Chen [8] have observed the smaller value of the surface roughness with a cutting distance of 0 to 1200 m, when a steel is machined using a superfinishing ball nose end mill. However, the surface obtained using the conventional cBN tool has been the highest. Abrari et al. [9] have conducted milling of aluminum by using two and four flute cutter to study effect of number of cutting flutes on the milling performance. Amin et al. [10] have shown that preheated machining facilitates up to 80% increase in tool life over conventional machining conducted using TiAlN coated carbide inserts. Hossain et al. [11] have investigated the effect of workpiece preheating with high frequency induction heating on improvement of machinability of Ti-6Al-4V during end milling using TiAlN coated PVD inserts. They have observed that preheating helps in lowering down the cutting force values significantly during cutting, and reducing acceleration amplitude of vibration. Guimu et al. [12] have observed an increase in the cutting speed can lower the workpiece deformation. Also, the highest as well as the lowest feed rates result into the conditions leading to unstable machining vibrations. It results into the poor surface finish in milling of thin specimens of titanium (TC4). Landers et al. [13] have found that the optimal feed increases as the width-of-cut and depth-of-cut decrease, resulting in higher surface roughness of the machined surface.

From the above discussions, it is clear that hardly any work has been found in the literature on preheating of Inconel alloy during ball end milling. Hence, further research is still needed for optimal parametric analysis to minimize the surface roughness, and to increase the metal removal rate.

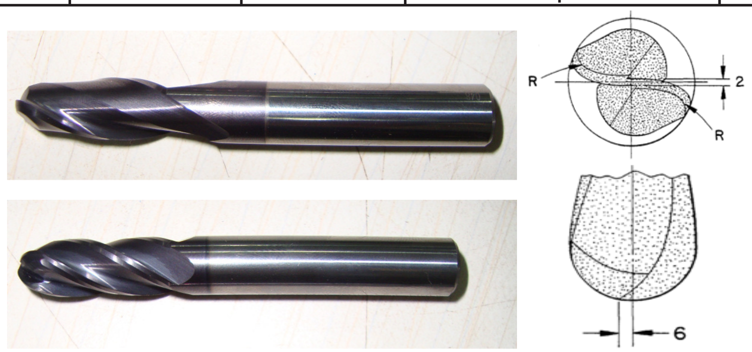
2. Experimental Work

In this experimental investigation, L8 orthogonal array (OA) was chosen since the factor levels are two and there are three interactions [14]. Surface roughness, R_a and material removal rate were chosen as the response variable for optimizing the input parameters in ball nose end milling. Table 1 shows the orthogonal array with coded and the actual values along with the recorded response values. In this study, the experimental plan has four controllable variables namely, spindle speed, feed per tooth, axial depth of cut and number of flutes. The speed is planned to be used in the range of 1000 to 1500 rpm. The feed per tooth and axial depth of cut selected are in the range of 40 to 74 mm/tooth and 0.75 to 1 mm respectively. The variation of number of flutes have effect on the material removal rates and resulting surface finish since the amount of flute space changes as the number of flute changes, and hence, the chip carrying capacity which influence the surface finish. Therefore, two different flutes (two and four) were selected for ball end milling cutter.

Inconel 600 workpiece in a plate form with dimensions 50 mm×33 mm×6 mm was used. The chemical composition of the work material is: Ni 77.00; Cr 14.00; Mn 0.55; Fe 8.00; Cu 0.19; S 0.003; C 0.05; Si 0.20. TiC coated tungsten carbide end mills of 10 mm diameter were selected (See Fig. 1).

Table 1 Observed values of the reposes as per orthogonal array L8

Levels of the factors				Spindle speed (rpm) (Factor 1)	Feed (mm/tooth) (Factor 2)	Depth of Cut (mm) (Factor 3)	Number of flutes (Factor 4)	Observed surface roughness (μm)	MRR found (mm^3/ min)
Factor 1	Factor 2	Factor 3	Factor 4						
1	1	1	1	1000	40	0.75	2	1.09	246
1	1	2	2	1000	40	1.00	4	0.85	234
1	2	1	2	1000	75	0.75	4	1.74	252
1	2	2	1	1000	75	1.00	2	1.58	240
2	1	1	2	1500	40	0.75	4	2.38	405
2	1	2	1	1500	40	1.00	2	1.97	331
2	2	1	1	1500	75	0.75	2	6.56	562
2	2	2	2	1500	75	1.00	4	4.37	502



(a) (b)

Fig. 1 Ball nose end mill geometry (a) photograph and (b) end and side view of the tool

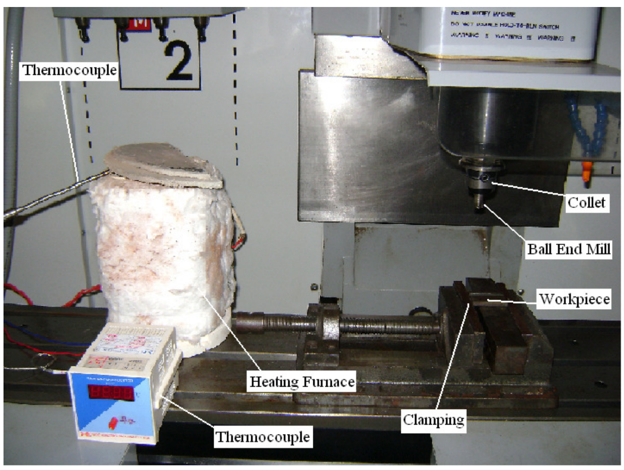


Fig. 2 Experimental setup of ball end milling of preheated Inconel 600

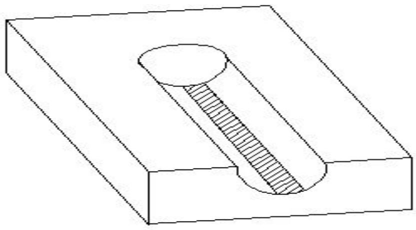


Fig. 3 Measurement of surface roughness Ra

Fig. 2 shows the experimental set up of the preheated ball nose end milling. The slot end milling tests in dry condition were performed on HAAS make CNC milling machine having a maximum spindle speed of 6000 rpm and maximum power of 15 kW. A constant tool overhang of 60 mm was maintained for all tests with measured tool runouts not more than 8 µm. The workpiece was heated in the induction furnace till it attained the temperature of 650°C. As the softening temperature of Inconel 600 is up to 900°C, therefore, the Inconel 600 plate was heated near to the softening temperature because the superalloy has excellent creep rupture strength up to 700°C [10]. After the milling operation, surface roughness Ra was measured using a portable tester (Mitutoyo make, model- Surf Test SJ 301) with cut off length of 0.8mm and an evaluation length of 4 mm. Three readings were taken per sample and made average for future analysis. The surface of the groove was cleaned by acetone to remove the oxide layer on the surface before measurement. The central portion of the machined groove was selected for the surface roughness R_a measurement as shown in Fig. 3.

Material removal rate was calculated by the below given formula as :

$$MRR = w\ d\ v \qquad (1)$$

where, w = width of cut (mm), d = depth of cut (mm), v = feed rate (mm/min)

The experimental results of surface roughness and MRR were further transformed into a signal to noise ratio (S/N). Higher the better for the MRR and lower the better quality characteristics for the surface roughness were selected for obtaining machining performance. The lower the better quality characteristic can be expressed as—

(2)

and higher the better quality characteristics for MRR should be taken as—

$$\eta = -10 \log \frac{1}{m} \sum_{i=1}^{m} \frac{1}{MRR_i^2} \qquad (3)$$

where, m is the number of tests, and SR is the value of surface roughness for the ith test.

3. Analysis of Surface Roughness and MRR

3.1 Analysis of Variance (ANOVA)

Table 2 shows the results of ANOVA for surface roughness and material removal rate (MRR). As far as the surface roughness is concerned, the parameters, feed rate and number of flute, are statistically significant at 95% confidence level (Table 2). In the case of material removal rate (MRR), it is observed that the parameters, spindle speed and depth of cut, are statistically significant at 95% confidence level. Among the interactions, the interaction between spindle speed and depth of cut shows statistical significance at 95% confidence level as can be seen from their values which are less than 0.05.

3.2 Analysis of Parameter Effects on Surface Roughness and MRR

3.2.1 Surface Roughness

Effect of Spindle Speed : It is observed from the main effects plot that the better quality surface is produced when the spindle speed is 1500 rpm. However, the surface finish degrades when the spindle speed reduced to 1000 rpm. As the cutting speed increases, the cutting temperature also increases leading to softening of the cutting tool. Once cutting tool cannot withstand the cutting force, its cutting action becomes that of extrusion (similar to rubbing in grinding). This causes further reduction of surface roughness.

As can be seen from Fig. 4, there is only a small amount of chip flows out of the cutting zone. Most of the chips are pushed to the sides of the slot, and they are stacked piece-wise. The chips welded on both sides of the slot retard chip flow, and cutting temperature will increase because the heat generated cannot be dissipated with the chips. At this moment, the cutting force will increase rapidly. Cutting tool becomes red hot even at 1000 rpm. All chips are welded onto the sides of the slot, and there is no chip disposal. Therefore, the surface generated shows higher surface roughness.

Table 2 Analysis of variance for surface roughness and material removal rate (MRR)

Surface roughness						Material removal rate (MRR)					
Source	DF	SS	MS	F	P	Source	DF	SS	MS	F	P
S	1	0.669	0.669	0.25	0.629	S	1	171008	171008	145.53	0.000
f	1	33.887	33.887	12.82	0.007	f	1	2	2	0.00	0.968
A_a	1	0.108	0.108	0.04	0.845	A_a	1	35051	35051	29.83	0.001
NF	1	18.531	18.531	7.01	0.029	NF	1	294	294	0.25	0.630
S × f	1	0.551	0.551	0.21	0.660	S × f	1	1514	1514	1.29	0.289
S × A_a	1	13.651	13.651	5.16	0.053	S × A_a	1	7009	7009	5.96	0.040
S × A_a	1	1.191	1.191	0.45	0.521	S × A_a	1	5527	5527	4.70	0.062
Error	8	21.149	2.644			Error	8	9400	1175		
Total	15	89.737				Total	15	229805			

S : Spindle speed; f : Feedrate; A_a : Depth of cut ; NF : Number of flutes ;
DF : Degree's of freedom;
SS : Sum of square ; MS : Mean Square ; F : F ratio ; P : P value

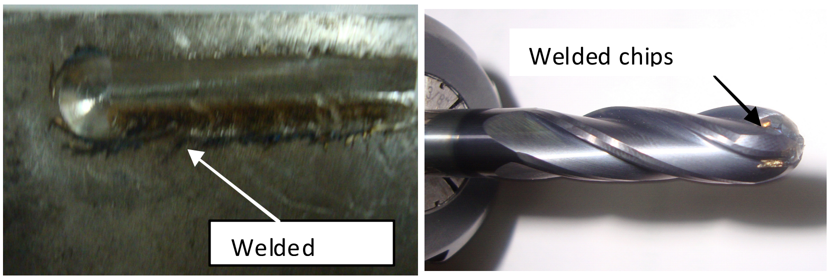


Fig. 4 Surface image of the groove machined and a BUE attached to the ball end mill

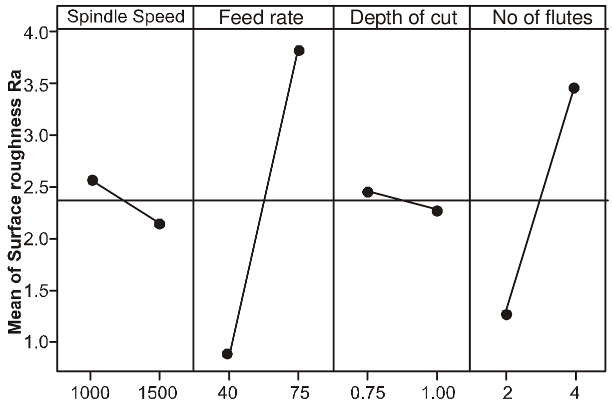
Effect of the feed rate : It is observed from the main effects plots that when the feed rate increases from 40 mm/min to 75 mm/min there is significant increase in the surface roughness. In this case, the increase in the surface roughness is drastic as compared to that in the case of spindle speed. This trend of increase in the surface roughness with an increase in the feed rate could be because of increased work hardening behaviour due to higher deformation. There is an increase in the amount of γ' and γ'' precipitates when Inconel 600 alloy is deformed. This leads to difficult movement of dislocations, and it is the main reason of work hardening [15].

Effect of depth of cut : It is seen from the main effects plots that the depth of cut has marginal effect on the variation in surface roughness. It is observed that the surface roughness is relatively high when the depth of cut is at lower level at 0.75 mm. However, an increase in the depth of cut to 1 mm causes slight reduction in surface roughness. This reduction in surface roughness might be due to the following reason. During entry, the cutter encounters minimum chip thickness. This approximated rubbing at the beginning of the cut results into an excessively work hardened layer in the workpiece, and hence, the material is pushed instead of cut.

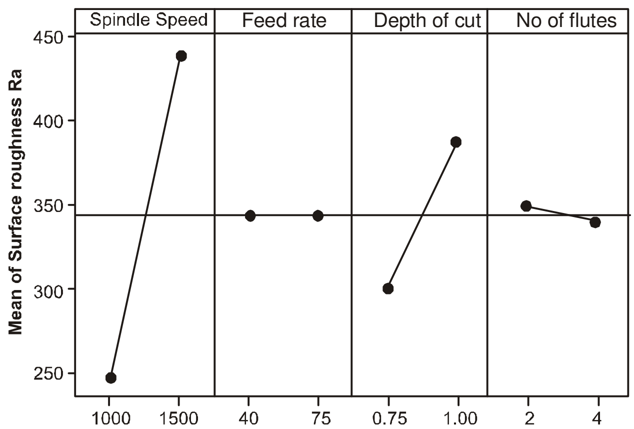
Effect of number of flutes : It is found that the number of flutes provided on the ball end mill cutter has considerable effect on the variation in surface roughness. It is observed that the surface roughness is low when a two fluted ball nose end mill is used during machining (see Fig.5). But as the number of flutes on the ball end mill cutter increases to four correspondingly surface roughness also increases by a significant value due to welding of chip particles to the cutting edges of flutes which causes more attrition wear of the cutter.

3.2.2 Material Removal Rate (MRR)

In the case of MRR, an increase in the spindle speed from 1000 rpm to 1500 rpm leads to increase in the volume of material undergoing deformation and MRR increases. Similar observations were also found when the depth of cut increases from 0.75 mm to 1 mm. It is observed that the number of flutes provided on the ball end mill cutter has an effect on the variation in material removal rate. It is found that the material removal rate is high when a two fluted ball nose end mill is used during machining. But when the ball end mill with four flutes was used, the material removal rate decreases. This decrease in the material removal rate due to increase in number of flutes can be attributed to the welding/adhesion of chip particles appearing like built up edges on the cutter edges leading to notching, and hence, the material removal rate reduces owing to tool wear.



(a)



(b)

Fig. 5 Main effect plots for surface roughness R_a and MRR

4. Conclusions

The experimental investigation yielded the following conclusions:

- It is found that when the higher spindle speed (1500 rpm), higher depth of cut (1 mm) and lower feed speed (40 m/min) were set with two fluted ball end mill, the lower surface roughness results.
- On the other hand, the higher MRR is obtained for the higher spindle speed (1500 rpm), higher depth of cut (1 mm) and higher feed speed (75 m/min) with the similar ball end mill. This shows that the feed speed has dominating effect in influencing the MRR.

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