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A Study on the Machinability Characteristics of Superalloys Inconel-718 during High-Speed Milling

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Abstract - *The greater challenge to manufacturing engineers is to the machining of complex shapes on Nickel-based superalloy Inconel 718 due to its physical and mechanical properties, i.e., high resistance, toughness, hardness, strength to weight ratio, and chemical property react with tool materials, creep resistance and low thermal conductivity. The Nickel-based superalloys are mainly used for turbine parts as well as high-temperature elements, although these whole properties are necessary to design requirements. The ball end milling machining process is generally used for machining complex shapes three-dimensional sculptured surfaces with definite curvature, and It's a greater challenge due to high temperature and stresses generated during the machining of Inconel 718. This paper presents a detailed experimental investigation of the effect of deflection and machining parameters on the quality of surface integrity in ball-end milling of cantilever-shaped thin plates of Inconel 718. A distinct variation is observed in the measured values of deflection of the workpiece, surface roughness, surface damage, and microhardness in different regions, i.e., fixed end, mid part, and the free end of machined surface and subsurface.*

Keywords - *Superalloys, Milling, Deflection, Surface Integrity*

I. INTRODUCTION

Nickel-based superalloys such as Inconel 718 are always used in marine, aero engines, nuclear power plants, and chemical refinery parts manufacturing like a disc, blades, andrings application due to their superior properties at high temperatures [1-2]. It is difficult to produce a final product from these materials, as they are difficult to machine and poor machinability. However, it can be seen that the material has high specific shear strength and poor thermal properties. It results in the form of frequent and severe tool wear deterioration in part quality, excessive consumption of energy, escalated machining cost, and environmental footprint. To three-dimensional machine shapes like molds, dies, and thin-walled components in aviation, the ball end milling emerged as an efficient process because of its ability to maintain good mechanical strength at elevated temperatures in the recent past. However, the ball-end milling process is a very complex process because of the intermittent nature of the operation and continuous variations of chip dimensions during machining. Many past research and innovations have been done to enhance the machinability of these alloys using appropriate cutting tools etc., [3]. The paragraph below highlights the major findings of these researchers on ball-end milling of Inconel 718. The selection of appropriate cutting tools plays a major important role where their geometries, materials, and treatments are important factors. Coatings and surface texturing of cutting tools have been found very effective in the machinability of various superalloys [4-8].

The detailed review of the existing literature, machining of nickel-based superalloys, the effect of cutter orientation, and flexibility of workpiece on workpiece deflection and surface quality have been addressed independently in the above-discussed studies. However, the effect of workpiece deflection could not be neglected in the case of thin and flexible parts, and hence it is necessary to control the effect of workpiece deflection to achieve higher machined surface integrity.

II. MATERIALS AND METHOD

A. Experimental theme and design

The experimental theme is designed to fulfill the research objectives by including good surface integrity in the machined workpiece. In view of this, as response variables are considered for machined surface are surface roughness, microhardness,and deflection of the workpiece to be studied. Further, the surface and subsurface alterations were quantitatively analyzed to understand the surface topography and microstructural variations. Taguchi L16 standard orthogonal array was used to design the experiments. Besides literature findings, the tool manufacturers catalog [9] was used for selecting cutting conditions see Table 1. The depth of cut is constant for all the experiments as 1 mm.

Table 1. Control factors for an experiment

Machining parameters	Level -1	Level-2
Speed (rpm)	2000	4000
Feed (mm/tooth)	0.05	0.10
Tool path position	Vertical	Horizontal
Workpiece orientation (angle)	15 (degree)	45 (degree)
Workpiece thickness (mm)	4	7

Table 2. L16 Taguchi orthogonal array assigned machining conditions

Exp. Run	Speed	Feed	Workpiece orientation	Workpiece thickness	Tool path
1	2000	0.05	15	4	Vert.
2	2000	0.05	15	7	Hori.
3	2000	0.10	15	7	Vert.
4	2000	0.10	15	4	Hori.
5	2000	0.05	45	4	Vert.
6	2000	0.05	45	7	Hori.
7	2000	0.10	45	7	Vert.
8	2000	0.10	45	4	Hori.
9	4000	0.05	15	7	Vert.
10	4000	0.05	15	4	Hori.
11	4000	0.10	15	4	Vert.
12	4000	0.10	15	7	Hori.
13	4000	0.05	45	7	Vert.
14	4000	0.05	45	4	Hori.
15	4000	0.10	45	4	Vert.
16	4000	0.10	45	7	Hori.

B. Workpiece preparation and experimental setup

The experiments were performed on a rectangular Inconel 718 specimen of dimension 75mm X25mm length with two different thicknesses. The chemical composition of the workpiece is 51.3% Ni, 20.14% Fe, 18.17% Cr, 4.8% Nb, 3.25% Mo, and balance C. Ball end mill cutter of solid carbide Ti-Al-N coated, 10mm diameter, 100 rake angle, and 300 helix angle with two cutting flutes was used for the experiments (Figure 1). A HASS CNC milling machine was used to perform the experiments in dry environments, and sixteen experiments were performed at various machining conditions as per the Taguchi L16 orthogonal array. [10] see Table 2. Each experiment was replicated once.

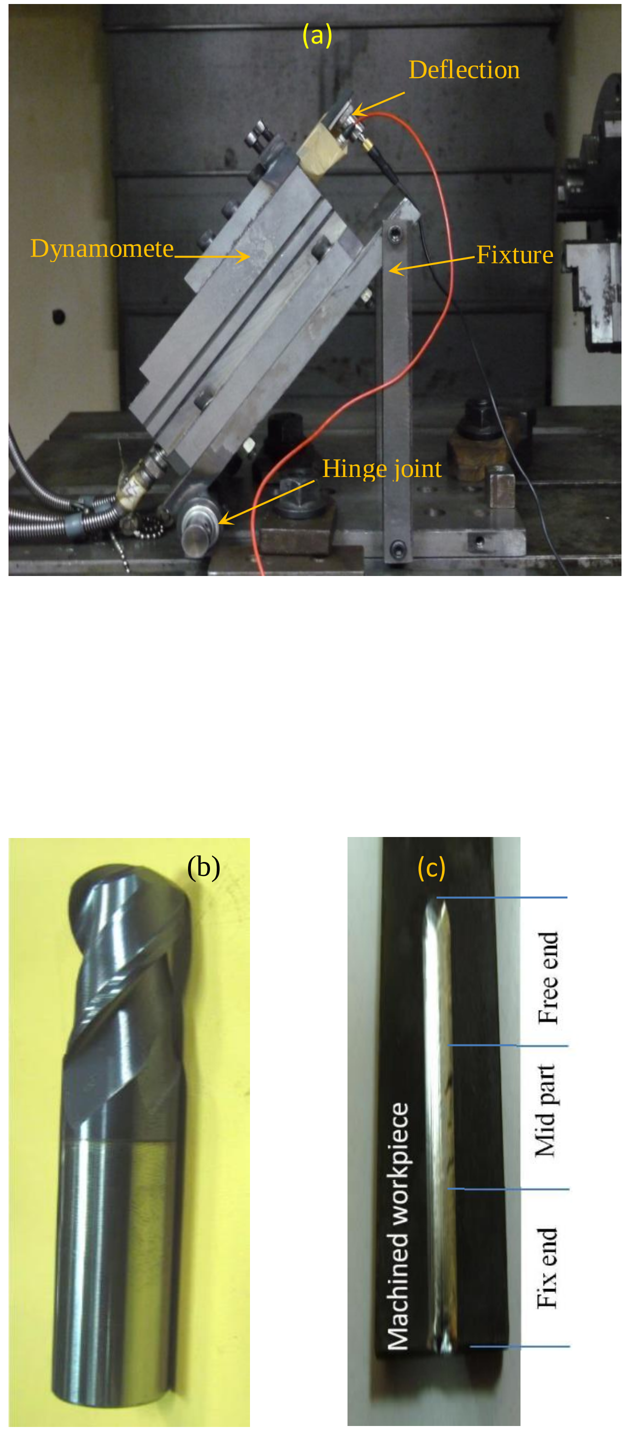


Figure 1. (a) Close up view of Experimental setup (b) Ball end mill tool and (c) Machined workpiece

The machining operation performed was a slot milling along the length on the inclined cantilever type workpiece of various thicknesses. Ball end milling was carried out along two different cutting tool paths, horizontal outward direction and vertically upward direction with 15^0 and 45^0 inclinations

(Figure 2). A deflection sensor was mounted at the free end of the cantilever workpiece specimen. It was connected to deflection measuring software through an amplifier. After the machining of each workpiece, specimens were cut into three parts across the machined surface of size 15mm, 15mm, and 10mm using a precision saw for measurements of surface roughness, surface alteration, and microhardness. The surface roughness of the machined surface was measured using a portable surface roughness tester (Make– Mitutoyo, Model –SJ301). The workpiece segments for the measurement of microhardness were hot mounted using bakelite powder and polished carefully to obtain scratch-free surfaces; for this purpose, initially, a manual polishing using coarse, fine with waterproof SiC sequence of polishing papers was used. Further, these specimens were cloth polished with Al2O3 powder and water using the polishing machine for a fine mirror-like surface.

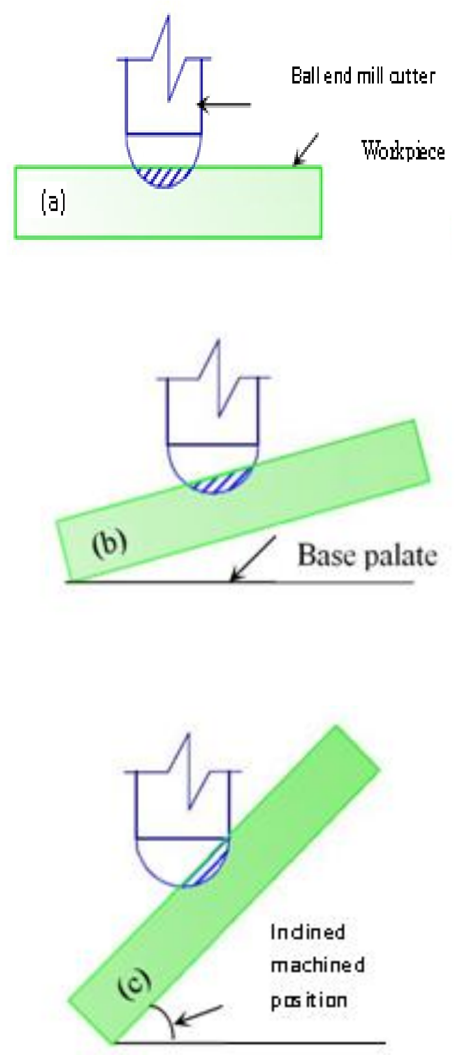


Figure 2. Schematic showing the workpiece inclination (a) 0^0 Inclination (b) 15^0 inclination and (c) 45^0inclination

Microhardness was measured on the transvers section of the machined surfaces at a different depth ranging up to 300um from the respective sample edge. The surface microhardness was measured by the Vickers indenter at a load of 100gm- a force for 10 seconds, using a square base pyramid on Vickers hardness tester (Shimadzu-MV2). A bakelite fixture was used to fix the mount on the table to ensure accurate measurement. Microhardness measurements were taken at different points at the same level; an average of three measurements was considered as final subsurface microhardness.

III. RESULTS AND DISCUSSION

Experimental results were analyzed in terms of understanding the deformation characteristics of the deflected machined surface and subsurface. Initially, the effect of machining parameters on the surface integrity is discussed as a function of workpiece deflection, surface roughness, microhardness, and surface alterations.

A. Statistical Analysis of Workpiece Deflection

Table 3 present the analysis of variance (ANOVA) of the workpiece deflection recorded during machining of a thin plate of Inconel 718. It is observed that the control factors speed, feed, and interaction between feed and tool path significantly influenced the response. i.e., workpiece deflection at 95 percent statistical confidence interval. As the p-value of these factors is less than 0.05, these magnitudes are considered statistically significant.

Table 3. ANOVA of Workpiece deflection

Machining parameters	Sum of square	DF	Adj MS	F-Value	P-Value
*Speed (rpm)	0.015129	1	0.01512	5.166224	0.0491
*Feed (mm/tooth)	0.041209	1	0.04120	14.07198	0.0045
Tool path position	0.008649	1	0.00864	2.953445	0.1198
*Workpiece orientation (angle)	0.001444	1	0.00144	0.493095	0.5003
Workpiece thickness (mm)	0.013924	1	0.01392	4.754743	0.0571
*Feed X Tool path	0.036864	1	0.03686	12.58825	0.0062
Residual	0.026356	25	0.00292		
Total	0.143575	31			
Standard Deviation = 5.4, R-Square = 81 * a statistically significant factor					

The effect of control factors on the resultant workpiece deflection was explained using main effect plots and is depicted in Figure 3 (a-e).

Effect of speed:

The main effects plots in figure 3(a) show that the deflection of the machined plate was 0.45 mm at 2000 rpm, and it increases to 0.51 beyond 2000 rpm. As the speed increases, the material removal rate also increases. The higher magnitudes of cutting forces are experienced during machining. Hence, a significant increase in the workpiece deflection was observed at high-speed machining.

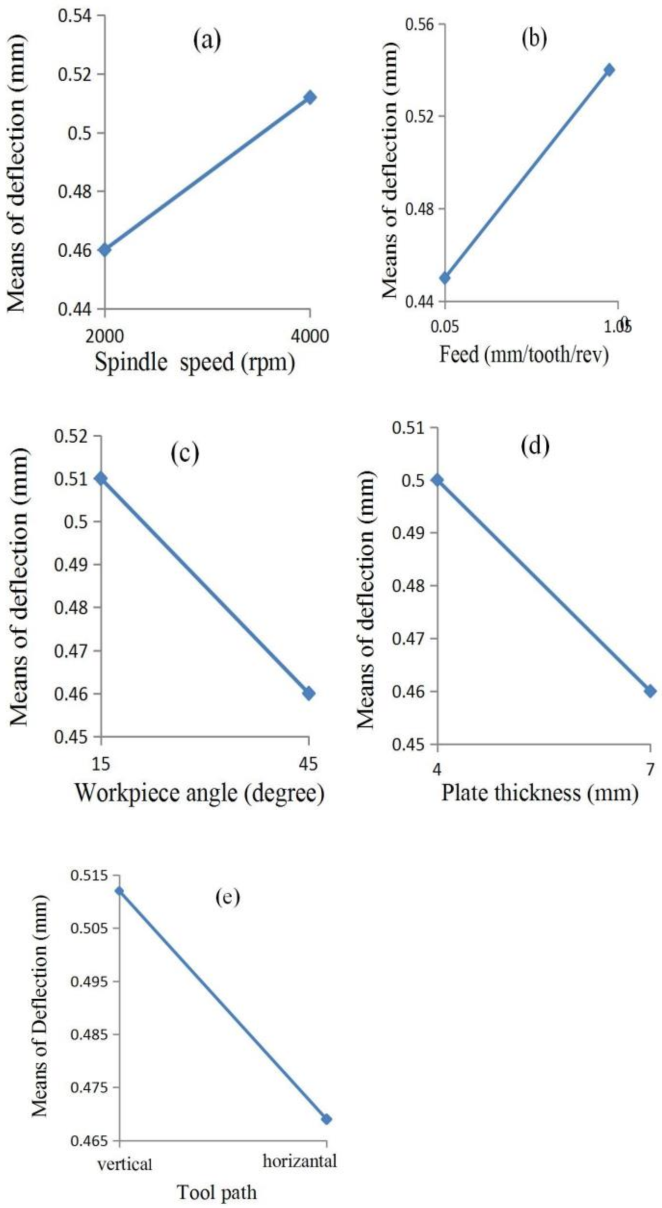


Figure 3. (a-e) Main effects plot of workpiece deflection

Effect of Feed:

The main effects plots Figure3 (b) show that as the feed increases, the magnitude of deflection also increases significantly. An increase in the feed causes an increase in the deflection because of the increase in the cross-sectional area of cutting. This causes an increase in the resultant force, which dominated the inclined workpiece in the downward direction.

Effect of Workpiece orientation and plate thickness:

It is found that the lowest deflection occurs when the workpiece orientation angle is small (see Figure 3 c). The workpiece thickness does not show a significant effect on the workpiece deflection (see ANOVA in Table 3). As the workpiece thickness increases, the deflection of the machined surface decreases causes an increase in the rigidity of the workpiece, which in turns the moment of inertia and thereby facilitates smooth machining with a low deflection (see Figure 3 d).

Effect of Tool path:

The effect of tool path resultant of workpiece deflection on the machined surface shows in Figure 3(e). It is found that the tool path is statistically non-significant, but its p-value is very closer to a significant value of 0.05. While the ball end mill travels in the vertically upward direction, the machined workpiece deflection is observed 0.51 mm. on the other hand, when the ball end mill travels in the horizontal outward direction, the deflection of the machined workpiece is 0.46 mm. it is found that when the workpiece inclination and vertically upward direction, result into a higher chip load per tooth thereby increasing the thrust experienced by the ball nose end mill cutter. However, a comparatively lower chip load is observed during horizontal outward tool travels. Therefore, 45^0 inclined workpieces along with horizontally outward tool orientation become a good condition for the minimum deflection of the machined workpiece.

Effect of interaction of feed and toolpath:

The effect of interaction between feed and tool path on the deflection of the machined workpiece is presented using a contour plot in Figure 4. It's found that the interaction of feed and tool path hasa significant impact on the deflection of the workpiece (see, ANOVA). At 0.05 mm/tooth/rev of feed and horizontal tool path, deflection is less than 0.49mm. However, with an increase in the feed to 0.1mm/tooth/rev with the vertical toolpath orientation, the maximum deflection of the machined workpiece of 0.6 mm is observed.

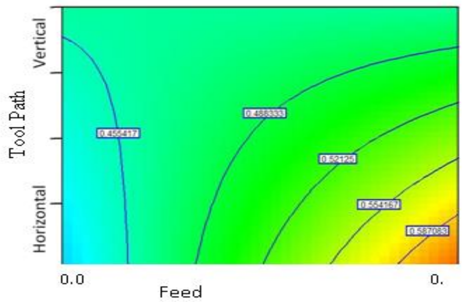


Figure 4. Contour plot of the interaction of feed and tool path on workpiece deflection

B. Quantitative analysis of surface roughness

The surface topography is analyzed quantitatively in terms of arithmetic average surface roughness (*R*a) on machined part on fixed end, mid part, and a free end. The effect of variation in machining conditions on the surface roughness at different locations on the workpiece is presented in Figure 5. It is observed that the mechanics of ball-end milling of the inclined workpiece has a significant influence on the machined surface roughness (*R*a) in various cutting zones. The plot shows that three different values of surface roughness at the fixed end, mid part, and free end of the workpiece. It is observed that the values of surface roughness at the mid part are relatively lower than at the fixed end and free ends. It is further noticed that the surface roughness of the inclined machined workpiece is higher at the free end.

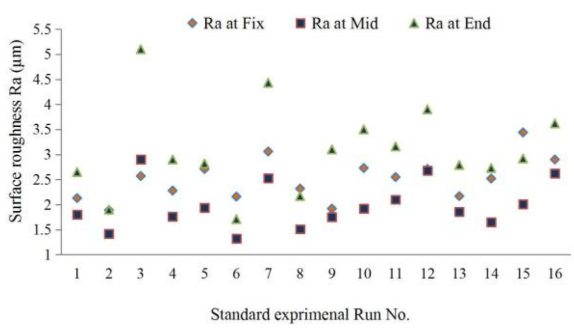


Figure 5. Comparison of surface roughness at various machining condition at fix end, mid part,and the free end

In the statistical analysis of surface roughness, the machining conditions speed, feed, workpiece thickness, tool path, the interaction between speed and tool path, and between feed and workpiece thickness significantly influence at 95% statistical confidence level (see table 4).

Table 4. ANOVA for surface roughness at the mid part

Control factors	Seq SS	DF	Adj MS	F-value	p-value
*Speed (rpm)	0.177174	1	0.177174	15.51241	0.0034
*Feed (mm/tooth)	0.910192	1	0.910192	79.69175	0.0001
Workpiece inclination (degree)	0.051984	1	0.051984	4.551451	0.0617
*workpiece thickness (mm)	0.380961	1	0.380961	33.35494	0.0003
* Tool path	0.211508	1	0.211508	18.51855	0.0020
*Speed × Tool path	0.960008	1	0.960008	84.05336	0.0001
Speed ×Workpiece thickness	0.008647	1	0.008647	2.93446	0.1218
Feed × Workpiece thickness	0.001756	1	0.001756	0.492183	0.5102
Residual	0.102793	23	0.011421		
Total	2.794619	31			
Standard Deviation = 11, R- Squared= 96 *statistically significant factor					

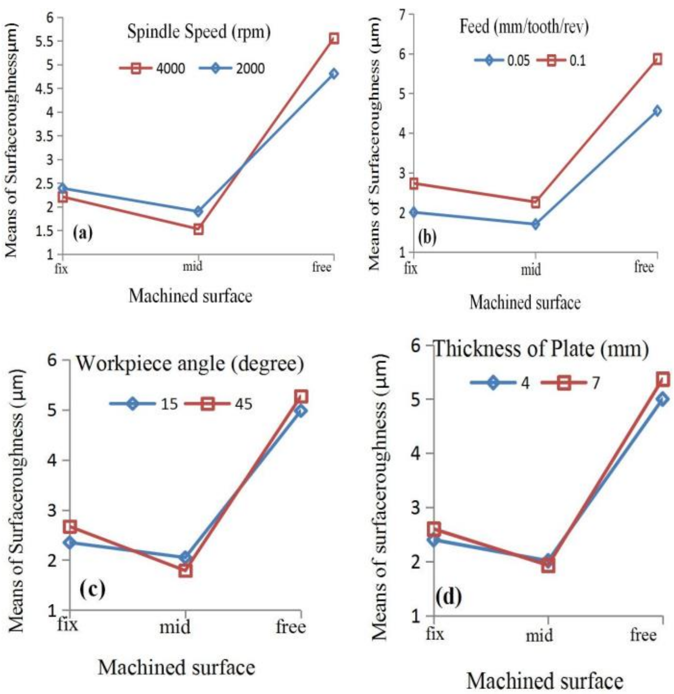
Table 5. Summarized ANOVA for Surface roughness

Control factor	*Ra* at Fixed end	*Ra* at mid part	*Ra* at free end
	F- and p- value	F- and p- value	F- and p- value
Speed (rpm)	✓	✓	×
Feed (mm/tooth)	✓	✓	✓
Workpiece inclination (degree)	✓	×	×
Workpiece thickness (mm)	×	✓	✓
Tool path	✓	✓	✓
Speed × Tool path	✓	×	×
Speed ×Workpiece thickness	✓	✓	×
Feed × Workpiece thickness	×	×	✓
✓ …Significant and × … Non-significant			

The summarized ANOVA of surface roughness is presented in Table 5. It is observed that the surface roughness at the mid part is most significantly influenced by input machining parameters. Itis also observed that at the fixed end side of the workpiece, the machined surface, the width, and depth of cut are higher as per the set parameter values, which generates higher forces, and consequently, higher surface roughness is observed in the fixed end of the machined workpiece. As the ball end moves to the middle part, the width and depth of cut are reduced, which causes a reduction in the cutting forces, and hence the surface roughness decreases. This can be attributed to the minimum deflection of the workpiece and the cutting tool contact with the workpiece prevailing during machining. The tool contact area at the fixed end of the workpiece is more as compared to the middle and free end side of the machined workpiece. This causes plastic deformation at their locations and consequently increases the surface roughness. Further, when the ball end mill travels to the free end, it causes vibrations and chatter that lead to an increase in roughness. The effect of machining parameters on the surface roughness of the machined surface is described using main effect plots in Figure 6 (a-e).

The main effect plot shows that in Figure 6 (a), as the cutting speed increases, the surface roughness also increases at the fixed and middle parts on the machined surfaces. The cutting speed also shows a statistically significant influence on the surface roughness at these locations. As compared to the fixed and middle parts, the values of surface roughness are higher at the free end of the machined workpiece. This can be attributed to the increased deflection of the machined workpieces leading to a higher chatter effect.

In the case of the influence of feed on surface roughness (see Figure 6 b), it is observed that the feed increases from 0.05mm/tooth/rev to 0.01 mm/tooth/rev, the surface roughness at the fixed, middle, and free end part of the machined workpiece also increases. At the feed of 0.01mm/tooth/rev, the highest mean roughness of 5.87 µm was recorded on the end side of the machined part. However, the lowest surface roughness of 1.7 µm was noted at the middle part of the machined workpiece at the feed of 0.5mm/tooth/rev.



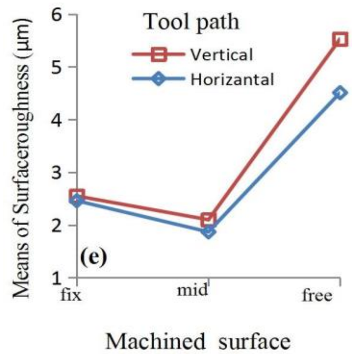


Figure 6. (a-e) Main effects plot for surface roughness

The effect of workpiece angle on the surface roughness is shown in figure 6 (c). It appears to be more prominent on the fixed side of the machined workpiece. However, a large deflection in the middle and free end side of the machined surface leads to a higher value of surface roughness. However, the surface roughness reduces at the middle part of the workpiece. There seem to be a drastic increase in the surface roughness at the free end of the workpiece on account of large deflection and resulting chatter at the machined surface.

In plot 6 (d) found that the thickness of the workpiece significantly influences the surface roughness at the middle part and free end side of the machine surface. This can be attributed to the fact that a higher force magnitude is required for the deflection. Further, the increase in rigidity of thick workpiece less deflection at middle part and end side of the workpiece was found. The minimum surface roughness of 1.99 µm is observed at the middle part, and the maximum surface roughness of 5.37 µm is observed at the free end of the machined workpiece for the 7 mm thick workpiece.

The tool path has a significant influence on the surface roughness at the fixed, middle, and the free endof the machined workpiece. The minimum surface roughness of 1.87 µm at the middle part and maximum surface roughness of 4.51µm is at the free end of the machined workpiece. Further, it is noted that in machining with horizontal tool path orientation, the forces and deflection are less as compared with the vertical tool path. It is that results in a higher chip load per tooth and thereby increases the thrust.

C. Analysis of Subsurface deformation:

The workpiece surface layers undergo plastic deformation due to thermal and mechanical loads imposed during machining. Fig. 7 shows microhardness was measured across the machined surface at 20µm, 40µm, 100 µm, 150µm, 200µm, and 3000µm beneath the machined surfaces.

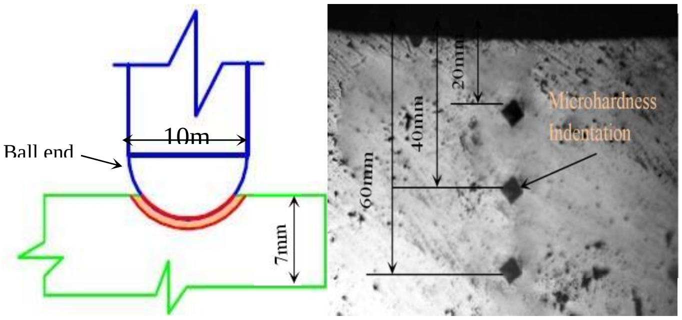


Figure 7. schematic and machined surface image with microhardness indentation

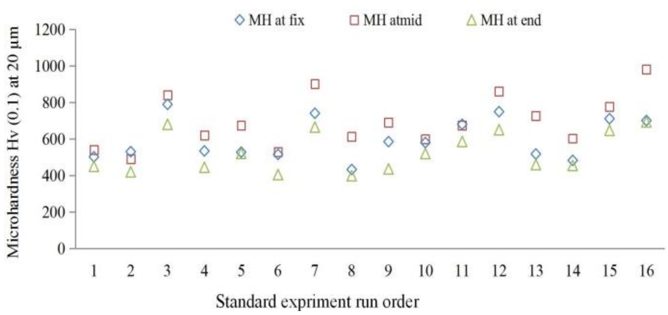


Figure 8. Experimental values of microhardness in ball-end milling at 20µm beneath machinedsurface

The microhardness values at the middle part of the machined workpiece are higher than that of the fixed end and free end of the machined surface. As the ball end mill cutter moves towards the middle part, the workpiece begins to deflect, but at the same time, the machined workpiece opposes the deflection. Therefore, the magnitude of microhardness at the middle part is slightly higher.

IV. CONCLUSION

The experiments were performed to determine the effects of process parameters on the machined beneath the surface of cantilever thin Inconel 718 by using a ball end mill. The following conclusions are drawn.

- ✓ It is observed that the process parameters have a statistically significant effect on the machined surface and subsurface of Inconel 718.
- ✓ It is found that horizontal tool path condition is the most suitable for all considering aspects of the machined surface.
- ✓ The surface roughness values at the middle portion of the machined surface are lower than those at the fixed and free ends.
- ✓ The microhardness values variation is observed up to 60µm beneath the machined surface.

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