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# Effects of Cutting Parameters on Surface Roughness During High-speed Turning of Ti-6Al-4V Alloy

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**Abstract:** Surface roughness constitutes one of the most critical constraints for the selection of machine tools and cutting parameters in metal cutting operations. In this study, the steepest descent method was used to study the effects of cutting parameters (cutting speed, feed rate and depth of cut) on surface roughness of machined Ti-6Al-4V alloy workpiece at high-speed conditions. Machining trials were conducted at different cutting conditions using uncoated carbide inserts with ISO designation CNMG 120412 under conventional coolant supply, while a stylus type instrument was used to measure the centre-line average surface roughness (*Ra*). The results revealed that, surface roughness was more sensitive to variation in feed rate followed by cutting speed and depth of cut. The study is of importance to machinist in the selection of appropriate combinations of machining parameters for high-speed turning of Ti-6Al-4V alloy workpiece.

**Key words:** High-speed turning; Ti-6Al-4V alloy; Surface roughness; Modelling



## INTRODUCTION

Ti-6Al-4V alloy is one of the commonly used commercial grades of titanium alloys in aerospace and power industries. In recent years, Ti-6Al-4V alloy is increasingly finding more applications in many engineering fields because of its exceptional properties at elevated temperatures. However, these properties also make it a difficult-to-machine material. Accordingly, the need for economic machining of this alloy has increased tremendously. The need for harder, stronger, tougher, stiffer, more corrosion or oxidation and heat resistant materials has led to an increase in the development and applications of super-alloys such as titanium and nickel base alloys in the aerospace, automobile, chemical and medical industries. About 70% by weight of titanium-based alloys are used in the aero-space industry [1]. Ti-6Al-4V alloy was specifically developed for applications demanding exceptional mechanical and chemical properties at elevated temperatures. Ti-6Al-4V alloy is particularly known to exhibit high strength to density ratios and good corrosion resistance properties. Its ability to retain its mechanical properties such as hardness, strength, toughness at elevated temperature makes it a difficult-to-machine material. The low machinability of Ti-6Al-4V alloy coupled with the high temperature generated at the cutting edge results in rapid tool wear and consequently, the deterioration in surface roughness of the machined components [2].

Surface roughness is known to play an important role in many areas and is a factor of great importance in the evaluation of dimensional accuracy of the machined components [3]. Surface roughness of a machined component could affect several of the component's functional properties such as frictional, wearing, light reflection, heat transfer, tribological, coating, and fatigue resistance [4]. Although many factors affect the surface conditions of a machined component, cutting parameters such as cutting speed, feed rate and depth of cut are known to have significant influence on the surface roughness for a given machine tool and workpiece set-up [5]. Hence, surface roughness constitutes one of the most critical constraints for the selection of machine tools and cutting parameters in process planning [5].

Surface roughness as affected by the cutting conditions has been investigated by engineers and researchers for many years based on different methods [6]. A number of meshless procedures based on Finite Element Method (FEM) have been proposed. These include the smoothed particle hydrodynamics method [7], the diffuse element method [8], wavelet Galerkin method [9], the element-free Galerkin method [6,10], the reproducing kernel particle method (RKPM) [11], the meshless local Petrov–Galerkin method [12], the natural element method [13], the partition of unity method [14] and the hp-cloud methods [15,16]. The method of factorial

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design has been intensively used in the planning of experiments in order to reduce the number of trials and also identify the individual influence of the parameters [17-19]. The steepest descent method [20] has been applied for the analysis of multi-variant systems to investigate the main and interactive effects of the variables.

In the present study, the steepest descent method was used to study the effects of cutting parameters (cutting speed, feed rate and depth of cut) on surface roughness of machined Ti-6Al-4V alloy workpiece at high-speed conditions. The study is of importance to machinist in the selection of appropriate combinations of machining parameters for high-speed turning of Ti-6Al-4V alloy workpiece.

**2. Experimental Procedures:** A computer numerically controlled (CNC) lathe with a speed range from 18 to 1800 rpm was used for the machining trials. The lathe was driven by an 11 kW stepless motor which provided a torque of 1411Nm. Ti-6Al-4V alloy bars, with 200 mm outer diameter and 300 mm long, with chemical composition 5.50-6.75% Al, 3.50-4.50% V, 0.30% Fe, 0.14-0.23% O, 0.08% C, 0.01% H, 0.03% N, 50ppm Y and balance Ti, were used as workpiece for the machining trials, The mechanical and other relevant properties of the workpiece material are: Tensile strength 900-1160 MPa, 0.2% proof stress 830 MPa, elongation 8%, density 4.50 g.cm$^{-3}$, melting point 1650 °C, thermal conductivity 6.6 W.m$^{-1}$.K$^{-1}$ and Vickers HV hardness 341-363. The microstructure of the workpiece material is shown in Figure 1.

The cutting tools used for the machining trials were uncoated K10 grade carbide inserts with ISO designation CNMG 120412, with nominal chemical composition (by weight): 93.8% WC, 0.2% (Ta, Nb)C and 6% Co. The mechanical and other properties of the inserts are: Vickers HV Hardness 1760, density 14.95 g.cm$^{-3}$ and substrate grain size1.0 mm.

Tool holder with ISO designation MSLNR 252512 was used to hold the insert and the following cutting geometry were employed during the trials: approach angle 40°, side rake angle 0°, clearance angle 6$^0$ and back rake angle -5$^0$. A general purpose coolant containing alkaline salts of the fatty acid (Tri-(2-Hydroxyethyl)-Hexahydrotriazine) with concentration of 6% by weight was used during the machining trials. The coolant was applied at normal convectional flow at a rate of 2.7 l/min. Prior to the machining trials about 6 mm thickness of the top surface of the workpiece was removed in order to eliminate any skin defect that can adversely affect the machining result. The following cutting conditions typical of finish turning of titanium-based alloys in the manufacturing industry were employed in this investigation:

- Cutting speed (m/min): 100, 110, 120.
- Feed rate (mm/rev): 0.10, 0.15, 0.20.
- Depth of cut (mm): 0.5, 1.0, 1.5

A total of twenty-seven ($3^3$ = 27) machining trials were conducted for different possible combinations of the three factors (cutting speed, feed rate, and depth of cut) at three different levels (low, medium and high). Each trial was conducted with new inserts. The centre-line average surface roughness ($R_a$), which is mostly used in industries, was used in this study. After each machining trial, the roughness of machined surface was measured at three different points with a stylus type instrument and electron scanning microscope was used for physical inspection of the machined surface.

The values of the factors were normalised to range from -1 to +1 by using eqn. (1) in order to facilitate direct comparison and visualisation of the effect of the individual control variable on the surface roughness.

$$X_n = 2\left\{ X-\bar{X} \big/ X_{max} - X_{min} \right\} \qquad (1)$$

where $X_n$ is the normalised value of the factor; $X$ is the actual experimental value of the factor concerned;

$\bar{X}$ is the mean of all the experimental values for the factor concerned; $X_{max}$ and $X_{min}$ are the maximum and minimum values of the factor concerned.

The factors investigated in this study and their levels are shown in Table 1. The effect of each factor on the surface roughness was determined by applying the steepest descent method.

## RESULTS AND DISCUSSION

The combinations of the factors at their different levels and the corresponding measured values of the surface roughness generated after the machining operations are given in Table 2. Electron scanned micrographs (ESM) of typical surface profiles generated after different machining operations are shown in Figures 2(a-e). The effect of feed rate on the variation in surface roughness at constant cutting speed (v = 100 m/min) and depth of cut (d = 0.5 mm) are shown in Figure 2(a-b). It can be seen in Figures 2 (a-b), that increase in feed rate from 0.15 to 0.2 mm/rev increased the surface roughness from 0.05 to 0.68 µm. The presence of feed marks was also observed on the surface with increase in feed rate. Surface roughness variation due to changes in cutting speed at constant feed rate (f = 0.15 mm/rev) and depth of cut (d = 0.5 mm) are shown in Figures 2(c-d). Increase in cutting speed from 110 to 120 m/min led to corresponding decrease in surface roughness from 0.57 to 0.50 µm, while increase in depth of cut from 0.5 to 1.5 mm in Figures 2(e-f) showed no measurable different on the surface roughness.

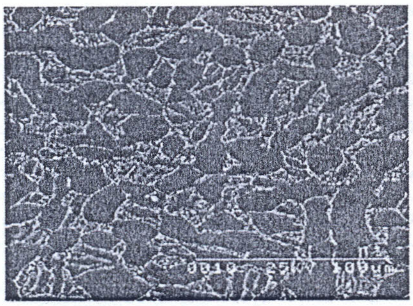


**Fig. 1:** Microstructure of Ti-6Al-4V alloy workpiece (x 500).

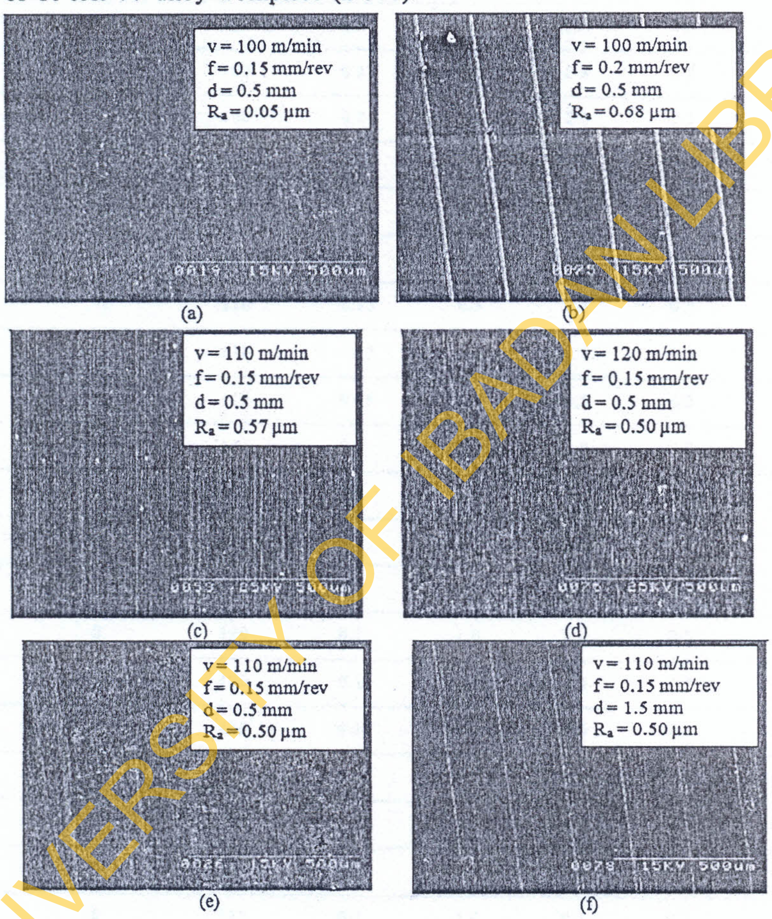



**Fig. 2:** Typical surface roughness generated after different machining conditions.

**Table 1:** Factors and their levels

| S/N | Parameter | Notation | Unit | Levels | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Original values | | | Normalised values | | |
| | | | | Low | Medium | High | Low | Medium | High |
| 1 | Cutting speed | v | m/min | 100 | 110 | 120 | -1 | 0 | +1 |
| 2 | Feed rate | f | mm/rev | 0.10 | 0.15 | 0.20 | -1 | 0 | +1 |
| 3 | Depth of cut | d | mm | 0.5 | 1.0 | 1.5 | -1 | 0 | +1 |

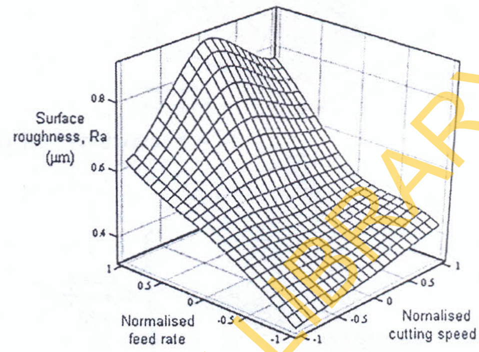
**Table 2:** Factor combinations and measured surface roughness

| Exp. No. | Normalised value | | | Original value | | | Surface roughness (µm) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *v* | *f* | *d* | *v* | *f* | *d* | Rep1 | Rep2 | Rep3 | Mean |
| 1 | -1 | -1 | -1 | 100 | 0.1 | 0.5 | 0.3 | 0.3 | 0.4 | 0.33 |
| 2 | -1 | -1 | 0 | 100 | 0.1 | 1.0 | 0.3 | 0.3 | 0.3 | 0.30 |
| 3 | -1 | -1 | +1 | 100 | 0.1 | 1.5 | 0.4 | 0.5 | 0.5 | 0.47 |
| 4 | -1 | 0 | -1 | 100 | 0.15 | 0.5 | 0.5 | 0.5 | 0.5 | 0.50 |
| 5 | -1 | 0 | 0 | 100 | 0.15 | 1.0 | 0.5 | 0.5 | 0.6 | 0.53 |
| 6 | -1 | 0 | +1 | 100 | 0.15 | 1.5 | 0.5 | 0.6 | 0.5 | 0.53 |
| 7 | -1 | +1 | -1 | 100 | 0.2 | 0.5 | 0.6 | 0.6 | 0.7 | 0.63 |
| 8 | -1 | +1 | 0 | 100 | 0.2 | 1.0 | 0.8 | 0.8 | 0.7 | 0.77 |
| 9 | -1 | +1 | +1 | 100 | 0.2 | 1.5 | 0.6 | 0.5 | 0.5 | 0.53 |
| 10 | 0 | -1 | -1 | 110 | 0.1 | 0.5 | 0.3 | 0.4 | 0.4 | 0.37 |
| 11 | 0 | -1 | 0 | 110 | 0.1 | 1.0 | 0.5 | 0.5 | 0.4 | 0.47 |
| 12 | 0 | -1 | +1 | 110 | 0.1 | 1.5 | 0.5 | 0.6 | 0.6 | 0.57 |
| 13 | 0 | 0 | -1 | 110 | 0.15 | 0.5 | 0.5 | 0.5 | 0.5 | 0.50 |
| 14 | 0 | 0 | 0 | 110 | 0.15 | 1.0 | 0.5 | 0.5 | 0.5 | 0.50 |
| 15 | 0 | 0 | +1 | 110 | 0.15 | 1.5 | 0.5 | 0.5 | 0.5 | 0.50 |
| 16 | 0 | +1 | -1 | 110 | 0.2 | 0.5 | 0.9 | 0.9 | 0.9 | 0.90 |
| 17 | 0 | +1 | 0 | 110 | 0.2 | 1.0 | 0.5 | 0.6 | 0.6 | 0.57 |
| 18 | 0 | +1 | +1 | 110 | 0.2 | 1.5 | 0.5 | 0.5 | 0.6 | 0.53 |
| 19 | +1 | -1 | -1 | 120 | 0.1 | 0.5 | 0.4 | 0.4 | 0.5 | 0.43 |
| 20 | +1 | -1 | 0 | 120 | 0.1 | 1.0 | 0.4 | 0.3 | 0.4 | 0.37 |
| 21 | +1 | -1 | +1 | 120 | 0.1 | 1.5 | 0.4 | 0.5 | 0.5 | 0.47 |
| 22 | +1 | 0 | -1 | 120 | 0.15 | 0.5 | 0.5 | 0.5 | 0.5 | 0.50 |
| 23 | +1 | 0 | 0 | 120 | 0.15 | 1.0 | 0.4 | 0.4 | 0.5 | 0.43 |
| 24 | +1 | 0 | +1 | 120 | 0.15 | 1.5 | 0.6 | 0.6 | 0.5 | 0.57 |
| 25 | +1 | +1 | -1 | 120 | 0.2 | 0.5 | 0.8 | 0.8 | 0.7 | 0.77 |
| 26 | +1 | +1 | 0 | 120 | 0.2 | 1.0 | 0.5 | 0.5 | 0.5 | 0.50 |
| 27 | +1 | +1 | +1 | 120 | 0.2 | 1.5 | 0.9 | 0.9 | 0.9 | 0.90 |

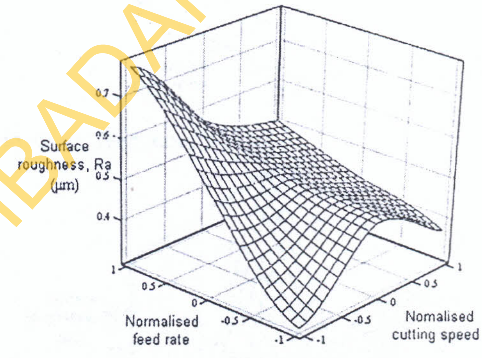
The variation in surface roughness with respect to changes in both cutting speed and feed rate over the range -1 to +1 (normalised values) for low (-1), medium (0) and high (+1) normalised values of depth of cut are shown in Figures 3(a-c), respectively. At low depth of cut (-1) as shown in Figure 3a, the highest surface roughness (0.90 µm) was observed at medium cutting speed (0) and high feed rate (+1), while the lowest value (0.33 µm) was observed at low cutting speed and feed rate (-1 for both variables). The effect of each variable on the surface roughness was determined by applying the steepest descent method [20]. If either of the variables (cutting speed or feed rate) is fixed at constant value that lead to the lowest surface roughness (-1 for both variables). The highest increase in surface roughness (0.30 µm) was observed by varying the feed rate from -1 to +1, while a corresponding increase in the cutting speed resulted in smaller increase in surface roughness (0.11 μm).

Thus, the surface roughness of the machined workpiece was observed to be more sensitive to variations in the feed rate than the changes in the cutting speed. At medium depth of cut (0) in Figure 3b, the highest surface roughness (0.77 μm) was observed at low cutting speed (-1) and high feed rate (+1), while the minimum (0.33 μm) occurred at low cutting speed and feed rate (-1 for both variables). Under later cutting conditions, a high increase in surface roughness (0.40 μm) took place by changing the feed rate from -1 to +1, while small increase in surface roughness (0.07 μm) was observed by varying the cutting speed over the same range (-1 to +1). Hence, the effect of feed rate was significantly higher than cutting speed on surface roughness variations at medium depth of cut. Similarly, for high (+1) depth of cut condition (Figure 3c), higher increase in surface roughness (0.06 μm) was observed by varying the feed rate over the range (-1 to +1), while keeping the cutting speed constant at low value (-1). The analysis showed that, for the entire cutting conditions investigated, the effect of feed rate on surface roughness was consistently higher than cutting speed.
The effects of feed rate and depth of cut over the range -1 to +1 (normalised values) on surface roughness variation for low (-1), medium (0) and high (+1) normalised values of cutting speed are shown are shown in Figures 4(a-c), respectively. The variation in surface roughness with respect to changes in feed rate and depth of cut at low (-1) cutting speed is shown in Figure 4(a). In Figure 4(a), the highest surface roughness (0.77 μm) was obtained at high (+1) feed rate and medium (0) depth of cut, while the lowest (0.30 μm) was obtained at low (-1) feed rate and medium (0) depth of cut. Keeping the feed rate constant at its low level (-1), which led to the lowest surface roughness and varying the depth of cut over the range of -1 to +1 resulted in 0.14 μm increase in the surface roughness, while corresponding higher increase of 0.47 μm was observed when the depth of cut was kept constant at its medium value (0), which led to the lowest surface roughness and the feed rate was varied over the same range.

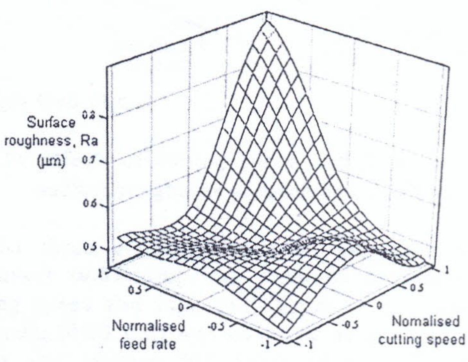
At medium (0) and high (+) levels of cutting speed as shown in Figures 4(b) and 4(c), increase of 0.20 and 0.04 μm in surface roughness were observed when the feed rate was kept constant at levels, that led to the lowest surface roughness and the depth of cut was varied over the range -1 to +1 respectively. Corresponding increase of 0.53 and 0.13 μm were observed when the depth of cut was kept constant at levels, that led to the lowest surface roughness and the feed rate was varied over the same range respectively. Therefore, it follows that the surface roughness was more sensitive to changes in feed rate than depth of cut. Similar to these observations, predominant effect of feed rate over cutting speed and depth of cut on surface roughness has also been reported by [3,21].




a) low depth of cut, d = -1

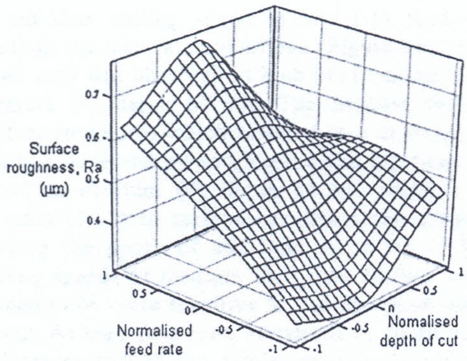



b) medium depth of cut, d = 0

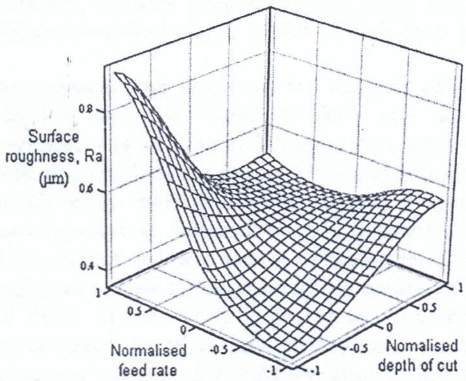



c) high depth of cut, d = +1

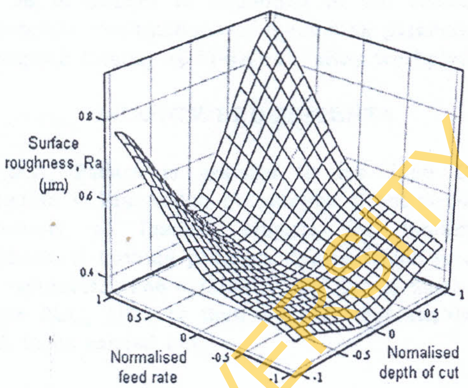
**Fig. 3:** Effects of cutting speed and feed rate on surface roughness of machined Ti-6Al-4V alloy




a) low cutting speed, v = -1



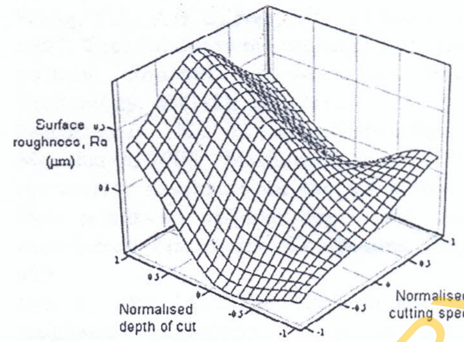

b) medium cutting speed, v = 0



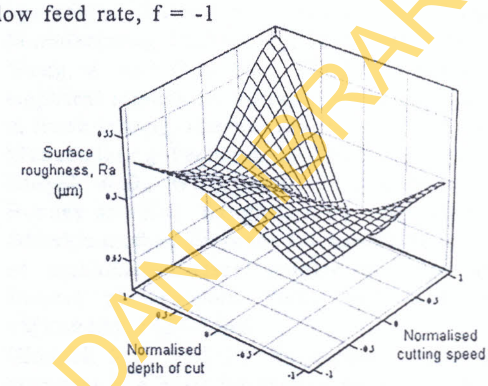

c) high cutting speed, v = +1

**Fig. 4:** Effects of feed rate and depth of cut on surface roughness of machined Ti-6Al-4V alloy.

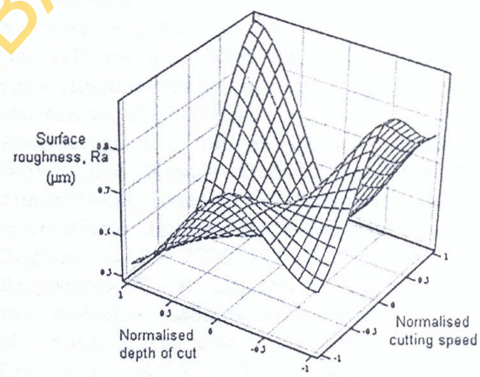
The effects of variations in cutting speed and depth of cut over the range -1 to +1 (normalised values) on surface roughness for low (-1), medium (0) and high (+1) normalised values of feed rates are shown in Figures 5(a-c), respectively. Figure 5a shows the effects of cutting speed and depth of cut at low feed rate (-1).




a) low feed rate, f = -1




b) medium feed rate, f = 0




c) high feed rate, f = +1

**Fig. 5:** Effects of cutting speed and depth of cut on surface roughness of machined Ti-6Al-4V alloy

At these cutting conditions, maximum surface roughness (0.57 μm) was observed at medium (0) cutting speed and high (+1) depth of cut, while the minimum (0.30 μm) was observed at low (-1) cutting speed and medium (0) depth of cut. The highest increase in surface roughness (0.14 μm) was observed corresponding increase in the cutting speed resulted in smaller increase in surface roughness (0.07 μm). Thus, indicating that the surface roughness of the machined workpiece was more sensitive to variation in the depth of cut than cutting speed at low (-1) feed rate. At medium (0) feed rate conditions (Figure 5b), minimum (0.43 μm) was observed at high (+1) cutting speed and medium (0) depth of cut. The highest variation in surface roughness which resulted in a decrease of 0.10 μm was observed by varying the cutting speed from -1 to +1 at medium (0) depth of cut, while a smaller increase (0.07) in surface roughness was observed by varying the depth of cut from -1 to +1 at high (+) cutting speed. At medium feed rate, surface roughness tended to be more sensitive to cutting speed than depth of cut. At high feed rate, variations in depth of cut led to increase of 0.13 μm, while variation in cutting speed resulted in decrease of 0.27 μm in surface roughness. Therefore, surface roughness was more sensitive to cutting speed than depth of cut at high (+1) feed rate.

**Conclusions:** The results of the analysis of this study indicated that the effect of feed rate on surface roughness was consistently higher than that of cutting speed and depth of cut during high-speed turning of Ti-6Al-4V alloy workpiece. The surface roughness was more sensitive to variation in cutting speed than depth of cut, except at lower values of feed rate. The surface roughness tended to increase with increase in feed rate and depth of cut, while it decreased with increase in cutting speed. Good surface quality can be achieved in high-speed turning of Ti-6Al-4V alloy at low feed rate and depth of cut with high cutting speed. The analysis can be of benefit to machinist in the selection of appropriate combinations of machining parameters for high-speed turning of Ti-6Al-4V alloy workpiece.

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