

## Surface Integrity Study of Ti-Alloy using Optimal Cutting Speed

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Received: 27 May 2022  
Accepted: 08 July 2022  
Published: 20 July 2022  
Publisher: Deer Hill Publications  
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### ABSTRACT

Ti-alloy represents a significant metal portion of aircraft structural and engine components for high reliability. Surface integrity is one of the most relevant parameters used for evaluating the quality of finish machined surfaces. The residual stress and surface alteration with each layer and depth of work hardening by machining Ti-alloy are critical due to safety and sustainability concerns. Residual stresses, white layers well microstructural alterations can be figured out to improve surface qualities of end products. Many parameters such as cutting speed, feed rate, depth of cut affect the machined surface quality particularly surface finish. This article provides details of lathe turning for investigation of surface roughness for varying cutting parameters. An attempt has been made to search for best ranges of cutting regimes that could produce best surface roughness for machining Ti-6Al-4V alloy using uncoated cutting tool. Taylor-Hobson device is used to measure the surface roughness on the machined workpieces. In this project three series of experiments were carried out and a total of 16 steps of operations in each series are performed for determining the surface roughness. Real life experimental investigation has allowed to express the results in graphical form (using tabulated data) that has suggested best ranges of cutting regimes (parameters) for obtaining the best ranges of surface roughness for machining Ti-6Al-4V using uncoated carbide tool. The work has indicated to investigate the science of bulk flow, particularly the plastic deformation, for difficult to machine materials, at a much higher temperature. Behaviour of cutting tool materials for high speed cutting is another issue to develop.

**Keywords:** Ti-alloy, machining, surface roughness, surface integrity

### 1 Introduction

Lathe turning is the most widely used metal removal process where material properties, turning parameters, tool wear, dynamic systems interact in a complex way and eventually affect the surface integrity. In this work an attempt has been made to investigate the effect of cutting parameters on surface roughness and eventually surface integrity of  $\alpha$ - $\beta$  titanium alloy Ti-6Al-4V. Titanium alloys are used in various industrial applications specially in aviation and automotive industries because of their high strength-to-weight ratio, excellent corrosion resistance and high strength at higher application temperature. However, titanium alloy (Ti-6Al-4V) has been recognised, by many researches, as a difficult to cut material due to its low thermal conductivity, high toughness and strength properties, high chemical reactivity with cutting tool material and high hardness. These cause unusual temperature rise in cutting zone (Umasekar et al., 2006), faster tool failure, poor surface roughness and higher level of sublayer residual stresses (Ezugwu and Wang, 1997). As such optimizing cutting parameters for individual alloy using particular cutting tool for better surface roughness and surface integrity remains as a challenge in academia and industries (Mazid et al., 2019). Lathe turning parameters have been optimized for different grades of titanium alloy by analyzing various methods such as surface roughness (Akkus and Yaka, 2021; Umasekar et al., 2017), vibration signal (Anil et al., 2016), lubrication method (Revenkar et al., 2014), cutting tool temperature (Vinayagamoorthy and Xavior, 2014) and in addition, sublayer stresses that remains in a body which is stationary at equilibrium condition after removal of external load is residual stress (Withers & Bhadeshia, 2001). This stress involves numerous sub-surface and superficial characteristics inclusive of plastic deformation, metallurgical changes, crack formation and surface roughness. Residual stress is induced on the microstructure layers due to mismatching in the thermal expansion coefficient of the deposited layers (non-uniform), plastic deformation, interstitial impurities and deposition process as shown in the Figure 1.

The term surface integrity deals with the different mechanical properties such as residual stress and hardness, metallurgical states, and topological parameters (Jawahir et al., 2009). The importance of surface integrity in the field of engineering including biomedical applications is very high. According to Machado and Wallbank (1990) in

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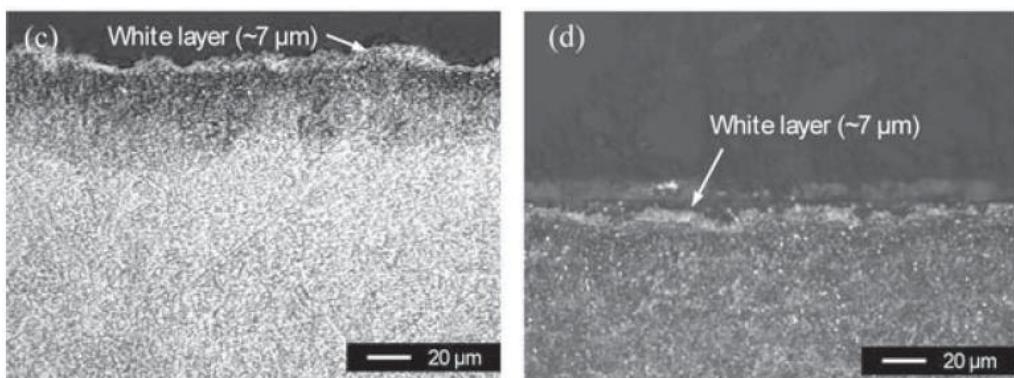
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the process of the surface integrity, the issues related to the alloy are a surface drag, micro-crack, feed marks, surface tear, deforms and debris. Due to plastic deformation, in the machining process, the primary issue related is white layer formation (Fig. 1) and plastic deformation. The hardening of the subsurface is seen in the Ti alloy which is due to the thermal and mechanical loads. The calculation of the residual stress for the surface integrity can be achieved using different method whereas no quality of work is performed for the Ti-alloy. Whereas, the finite element based way for the modelling or simulation process is the best approach because of its computational power and advance numerical solutions.

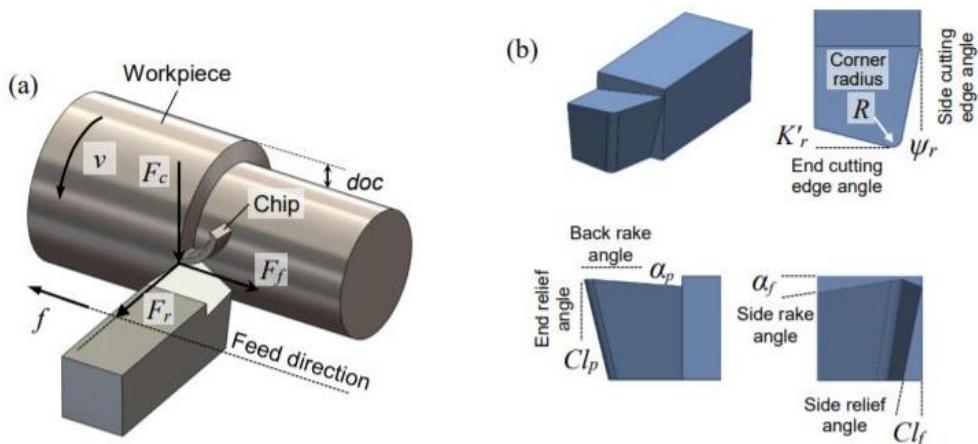
For the residual stress assessment in Ti-alloy, the most important is the machining process parameters since residual stress is evident in the machining process. The machining has been performed using the lathe turning. For the cutting speed ( $v$ ) optimization, with different speed and machining fluid-applied, turning operation is completed with measurement of the surface roughness at each step.

Afterwards, the plot of average surface roughness against individual cutting regimes helps to visualize the best surface roughness zone in graph. Likewise, feed rate ( $f$ ) optimization helps to determine surface quality. The study by Guo et al. (2009) illustrated that the stress evident in the solid body that exists remaining when external loading is removed from the body is known as residual stress. This residual stress has a different effect on the machining phenomenon such as deformation, static strength, dynamic strength, chemical resistance and magnetism. The residual stress that is obtained from the hard turning and the grinding is different such as for the fresh tool ware hook-shaped residual stress is evident for the hard turning. In contrast, grinding produces a significant amount of residual surface stress only. Similarly, using the worn tools, in the white layer (thermal), there is a considerable amount of tensile stress with more profound and compressive nature is seen for hard turning.

Oblique cutting (Fig. 2) conditions are described throughout by the cutting parameter combination of the depth of cut  $d$ , cutting speed  $v$ , feed rate  $f$  and tool corner/nose radius  $r$ . The cutting process is parallel to the direction of motion to remove the unwanted material from a workpiece. The chip flow angle is defined as direction of the chip flow velocity is at an angle normal to the cutting edge of the tool.



**Figure 1:** Surface integrity and microscopic view (Jawahir et al., 2009)



**Figure 2:** Oblique cutting process (a) process schematic, (b) tool geometry

## 2 Research Scope

The project concentrates on the research for the economic and sustainable manufacturing processes development for Ti-alloys based on the  $v$ ,  $f$ , and  $d$  parameters of machining in respect of surface integrity. The current piece of work targets the followings:

- Determining the optimum set of cutting parameters, for uncoated carbide tools, that can provide sufficient enough surface roughness. Thus to increase cutting tool life with less wear.
- To provide sustainable procedure for manufacturing industries to make the Ti-alloy parts easier and low cost.

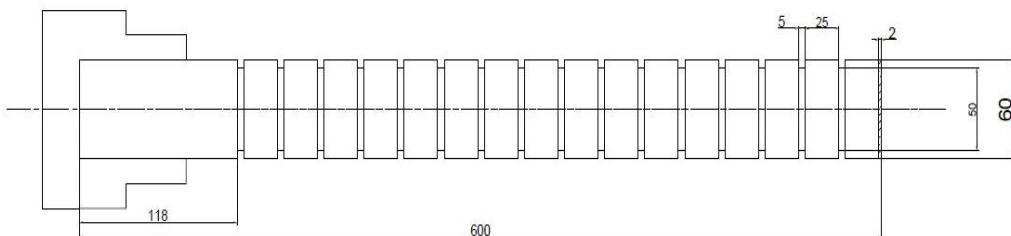
### 3 Experiments

The machine operation is performed with variation in speed ( $v$ ), feed ( $f$ ), and depth of cut ( $d$ ) using a conventional lathe to produce three sets of samples using uncoated carbide tool. During the process, the tool may damage and needs to replace. Using surtronic roughness machine, the roughness of the surface is measured for each sample.

#### 3.1 Sample Workpiece and Cutting Tool

Ti-alloys are recognised as difficult to machine materials which is highly problematic for manufacturing industries. The solution to this problem is made by using hybrid cutting tools. They come with diamond, ceramics and CBN. The tool used to machine the Ti-alloy samples is uncoated carbide tools. The tool geometry parameters are lead angle 97°, rack angle 7° and the nose radius 0.8 mm. These values may differ while operating to get the right  $v$ ,  $f$ ,  $d$  parameters.

Roughing, facing, turning, finishing and chamfering is done by the triangular tool. The Ti-alloy Ti-6Al-4V (sample workpiece drawing is shown below in Fig. 3 (Ahsan et al 2016) with length 600 mm and diameter 60 mm. It is a cylindrical shaft. Fig. 3 depicts the drawing of the sample-workpiece which explains its dimensions. The workpiece is divided into 16 different parts (samples) with equal size of 5 mm grooving in between.



**Figure 3:** Sample workpiece specimen (Ahsan et al.)

#### 3.2 Sample Preparation Procedures

The workpiece specimen (Fig. 3) is clamped in 3-jaw chuck of an available conventional chucks. It is series of machining operation with variable machining parameters. In this real life experiment 16 steps of machining operations, 16 steps of turning with various  $v$ ,  $f$ ,  $d$  cutting parameters. Experimental data tables can be obtained, on request, from the contact authour.

During the process of turning cutting speed ( $v$ ) varied within the range of 15 m/min to 120 m/min throughout the process of turning. This is known as step turning and is performed under eight steps taking the depth of cut and cutting speed constant 0.7 mm and 0.2 mm/rev respectively. Tool wear can occur during some time when an increase in the feed rate; at that point, tool bit must be replaced. Sparkling can occur when a tool gets damaged. By using surface roughness measuring device, surface roughness can be known, and the specimen is taken for the inspection under a microscope to examine the surface integrity of the specimen whether it had any surface deformation such as, plastic deformation, cracks and some factors that influence machining operations.

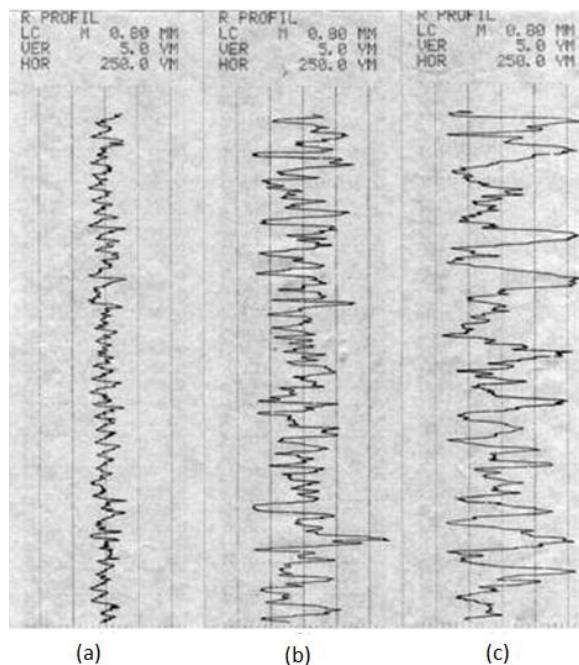
The constant cutting speed with different feed influence of cutting speed on the surface roughness profile the surface roughness increases with decrease in the cutting speed. This fact can be attributed to a technological contribution inherent to the cutting process, which produces high imperfection cutting surface, change in surface finish can be obtained geometrical model. The geometrical model doesn't consider the important influence of cutting speed on surface finish (Monkova and Hloch, 2012).

#### 3.3 Surface Roughness Measurement

There is a device available to measure the roughness of the surface. For measuring the roughness of the surface Surtronic 3+ roughness measuring device (Fig. 4) was used. The roughness of the surface depends on the finishing and the cutting parameters that are associated with the workpiece (Wang et al., 2012). The surface roughness on the workpiece/sample are measured by Talyrond Surtronic for the roughness parameter of the workpiece.



**Figure 4:** Talyrond Surtronic 3+ surface roughness measurement device



**Figure 5:** Surface profile at cutting speed (a) 283 m/min, (b) 141 m/min, and (c) 71 m/min. Depth of cut 0.5 mm, and feed rate 0.10 mm/rev (Davim, 2010)

#### 4 Results and Discussions

A conventional lathe machine was used to produce the samples. Measured data were recorded in tabular forms. The machining operation is carried out for three times in each speed to attain the average surface roughness value. At every speed three surface roughness values were obtained and the average surface roughness is calculated from the three values.

**Cutting speed study:** The measured data (for three series of experimentations) were tabulated and surface roughness graphs were built in respect of individual cutting parameters ( $v$ ,  $f$ ,  $d$ ). The graph in Fig. 6 provides machining data where cutting speed was varied while feed rate and depth of cut were kept constant at the values of feed rate = 0.15 mm/rev and depth of cut = 1.1 mm. The surface roughness measured varies with various cutting speeds. The cutting speed is calculated by using the fundamental formula:

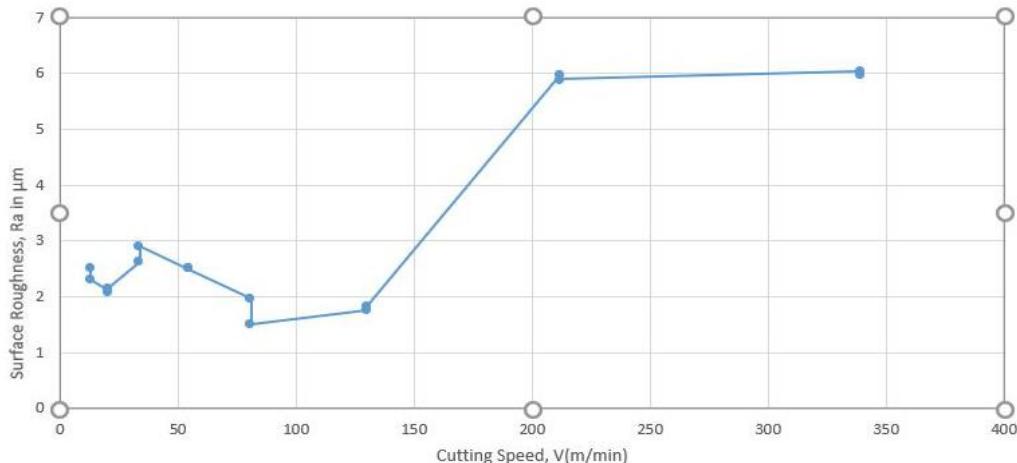
$$v = \frac{\pi \times D \times N}{1000}$$

Where,

$$\pi = 3.14$$

$$D = 60 \text{ mm (as available)}$$

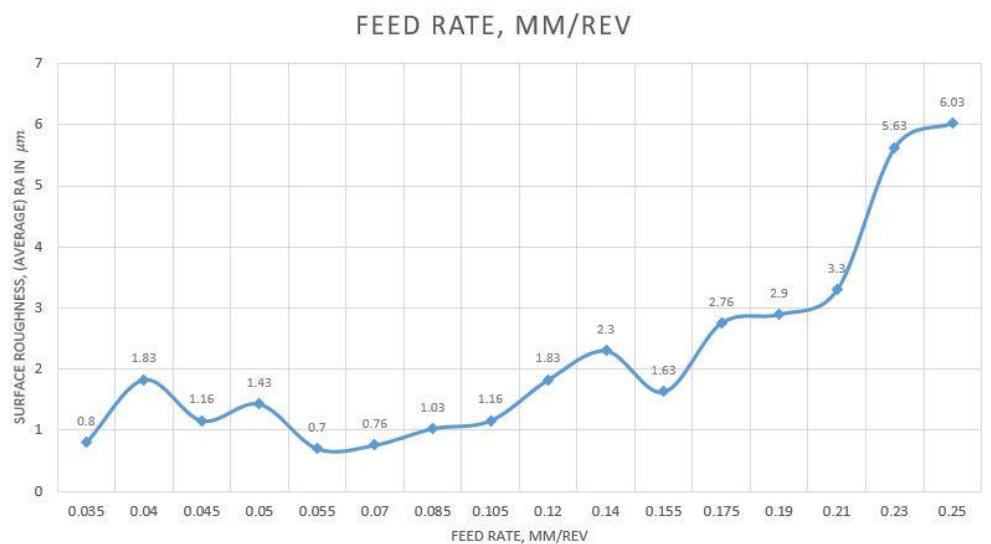
$$N = \text{spindle speed in RPM}$$

**Figure 6:** Cutting speed and  $R_a$  graph ( $v$  and  $f$  kept constant)

The above graph (Fig. 6) describes the machining process for cutting speed optimisation. The graph is plotted between cutting speed (m/rev) and the average surface roughness ( $\mu\text{m}$ ) values from the table and graph the optimum surface roughness value is found at a range of 80 m/min to 140 m/min cutting speed ( $v$ ). These cutting speeds having the possible best surface roughness  $R_a$  value of 1.5– 1.7  $\mu\text{m}$ . When the cutting speed is minimum and maximum the surface roughness values are higher but when the cutting speed is in-between these values (80 – 140 m/min) better surface roughness values are obtained.

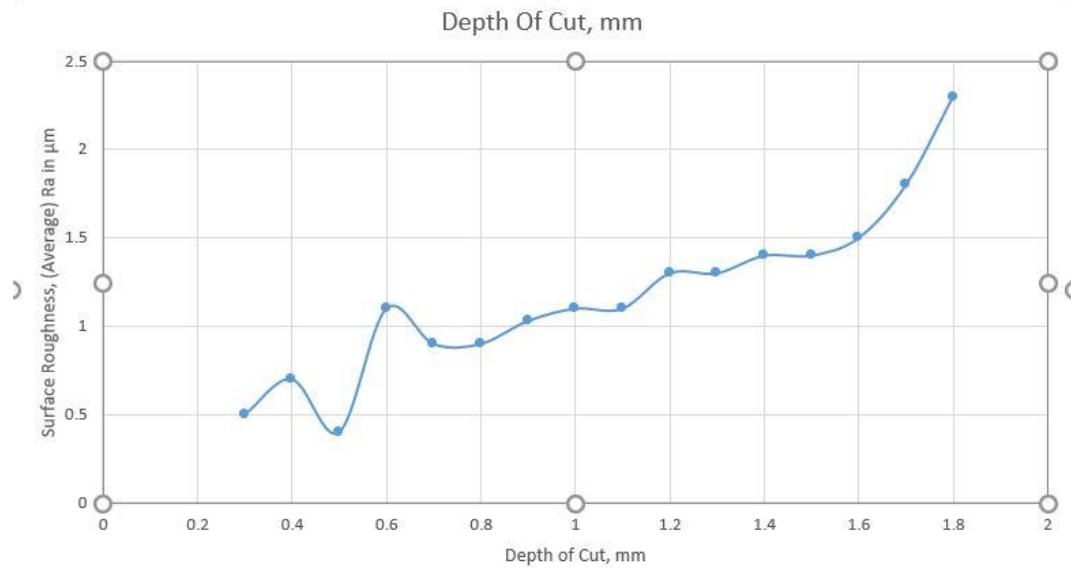
**Feed rate study:** Similarly a second series of experiments were carried out while the feed rate was varied and cutting speed and depth of cut were kept constant. The data obtained were recorded in tabular form in an XL-sheet and the result was presented in graphical form (Fig. 7) of variation of surface roughness irrespective of variable feed rate.

The graph in Fig. 7 was produced using the experimented data describing machining process where the feedrate is turning operation in sixteen different steps of the workpiece from 0.035 mm/rev to 0.25 mm/rev where the cutting speed and depth of cut are kept constant and at each step the surface roughness is measured. Accepted constant cutting speed = 80 m/min and depth of cut = 1.1 mm.

**Figure 7:** Feed rate and  $R_a$  graph ( $v = 80$  m/min,  $d = 1.1$  mm kept constant)

The above graph describes the machining process for feedrate optimisation. The graph was plotted using feedrate (m/rev) and the surface roughness ( $\mu\text{m}$ ). From the table and graph the optimum surface roughness is obtained in between feedrate from 0.055 mm/rev to 0.1 mm/rev. It was found in the graph as the feedrate increases, surface roughness also increases. The surface roughness value is 0.7  $\mu\text{m}$  which is obtained at feedrate 0.05 mm/rev.

**Depth of cut study:** The graph given below in Fig. 8 was built of tabulated data describing the machining process for depth of cut variation, variation from 0.3 mm to 1.8 mm by increasing 0.1 mm for every step up to 1.8 mm, the sixteen different depth of cut were used and relevant surface roughness values were measured using Talysurf Surtronic 3+ machine. In this series of experiments cutting speed and feed rate were kept constant. These values are taken from the previous above two graphs, the constant values were cutting speed = 81 m/min and feedrate = 0.055 mm/rev.



**Figure 8:** Depth of cut and  $R_a$  graph ( $f = 0.055 \text{ mm/rev}$ ,  $v = 80 \text{ m/min}$  kept constant)

The graph given above (Fig. 8) describes the machining process for depth of cut optimization. The graph was plotted using depth of cut (mm) to surface roughness ( $\mu\text{m}$ ). The best surface roughness values are obtained for values of depth of cut within the range of 0.3 mm and 0.5 mm. The surface roughness value at 0.5 mm depth of cut is  $0.4 \mu\text{m}$  as the depth of cut increases the surface roughness value also increases.

## 5 Conclusion and Future Scope

After performing operations on the Ti-alloy (Ti-6Al-4V) using uncoated carbide tool and processing the obtained series of data the following conclusion can be made: Best surface roughness values can be expected while using cutting speed within the range of 80 m/min to about 140 m/min (Fig. 6). Beyond these values starting from 150 m/min upto 210 m/min surface roughness values rapidly increasing from  $0.80 \mu\text{m}$  to  $6 \mu\text{m}$ . Strangely cutting speeds beyond 210 m/min and upto 340 m/min (maximum as we could set in the available lathe) surface roughness remains almost same around  $6 \mu\text{m}$ . This creates a thirst to look for beyond that limit of cutting speed and hence new cutting tool materials that could survive high speed cutting.

Best surface roughness expected to be obtained while using feed rate  $0.052 \text{ mm/rev}$  to  $0.105 \text{ mm/rev}$ . It is evident from the graph (Fig. 7) that the feed rates ranging from  $0.10 \text{ mm/rev}$  and  $0.20 \text{ mm/rev}$  surface roughness increases but reasonably stable and it goes upto maximum  $3 \mu\text{m}$  which is not that bad for many parts. But that value crucially increases (worsens) while using feed rate beyond  $0.20 \text{ mm/rev}$  and surface roughness rapidly increases upto  $7 \mu\text{m}$  which may not be acceptable for many parts made of valuable Ti-alloys. Best surface roughness possible to obtain while using depth of cut within the range of  $0.30 \text{ mm}$  to  $0.50 \text{ mm}$  (Fig. 8). Depth of cut within the range of  $0.60 \text{ mm}$  to  $1.60 \text{ mm}$  higher but reasonably stable values. But once feed rate goes beyond  $1.6$  surface roughness values geometrically increases, suggesting not to use this range of depth of cut.

From conclusion as evident that these are opening eyes for scientist to think about the plastic deformation beyond temperature  $2,000^\circ$  while so far we know a little about plastic deformation only below  $1,000^\circ$  for machining general steel materials. It is essential to look for plastic deformation process in machining hard materials. Searching for chip formation phenomena and behaviour of cutting tools and dynamic systems at a temperature range beyond  $2,000^\circ$  for hard materials or known as difficult to machine materials. Authors sincerely agreed, since this is a pioneering work, in future more accurate experimentations, not only searching for best ranges of machining parameters, but searching for new and tougher cutting tool materials that could survive at high speed cutting. This certainly reduces the machining cost enhancing the sustainability and open up the science of plastic deformation of difficult to machine materials at much higher temperature.

## Acknowledgement:

The authors acknowledge sincere help of Mr Randall Stock and Mr Garry Hoar (retired) of CQU Machine Shop for preparing samples. The work was partially supported by CQU NSRG grant 2019.

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