Chatter characterization of Micro-milled Surfaces in Ti6AL4V using Focus Variation Microscopy

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Abstract

This article presents surface topography analysis performed on Ti6Al4V via micro-milling process. Whenever there is a physical contact between two hard materials vibrations are inevitable. Chatter has a variety of effects on the machined surface with different parameters such as cutting speed, feed rate, axial and radial depths of cut. It impacts the stability of the machining process. Properties like fatigue and friction (contact or air drag) are heavily affected by surface defects.

Out of the many methods used for chatter detection, focus variation microscopy (FVM), which is an optical method, is the most reliable because it is not limited by bandwidth or natural frequency of tool. It also does not have issues of placing sensors during the machining such as displacement sensor, dynamometer. It is an offline, contactless method in which we are passively measuring the tool chatter without actually interfering in the machining process.

Images of the machined surface are captured using FVM and these images are then processed to get machined surface topography, which gives an idea about the amount of chatter (amplitude of variation, surface features).

Parameters such as natural frequency of the tool and workpiece (if thin or supported by thin walls) can be obtained. This can be used to predict machining conditions to minimise chatter and as a secondary objective, optimise machining time and cost.

Keywords: Surface topography, Ti6Al4V, Focus Variation Microscopy, Micro-milling

Contents

1 Introduction

1.1 Need and Background

The objective of this study is to estimate chatter by measuring surface undulations in a micro milling process for different spindle speeds, feeds, depths of cut.The apparatus used in conducting the experiment are the High speed micro milling machine, Digital Microscope,milling tool 3mm (diameter),micromill tool 100 μm (diameter), block of Ti6Al4V of size 60 mm x 40 mm x 0.4 mm, Computer (with softwares drivemaster, Dinocapture for setting tool zero position using a digital microscope). Computer with MATLAB, MS Excel softwares for performing analyses.

Why Ti6Al4V?

Ti6Al4V is the most widely used of Titanium. Ti-6Al-4V is a titanium alloy featuring high strength, low weight ratio and good corrosion resistance. It is used in applications where low density and good corrosion resistance is necessary such as e.g. aerospace industry and biomechanical applications such as implants and prostheses.

Why Micromilling?

Milling process with very small cutting dimensions is often called micro milling. The typical tool diameters are around 100 microns(roughly the diameter of single human hair strand).

In recent times, micro products and components are demanded for industrial applications including electronics, optics, aerospace, medicine, biotechnology etc. Its capability to manufacture a wide range of workpiece materials and complex three-dimensional geometries makes it one of the best candidates to produce the micro parts.

This process is used for machining which requires small cutting dimensions and to get surface finishes with high accuracies and low surface roughnesses.

1.2 Methodology

We started with analyzing probable workpiece materials. After choosing Ti6Al4V the objective of finding was materialized. Process parameters were decided and passive method of Focus variation Microscopy was chosen for measurements. Experiments were performed high speed micro milling center which was already developed at Machine tools Laboratory, IIT Bombay. The too center was designed to negate influence of other external factors which may otherwise affect the machining process . The Mathematical analysis of the data obtained from Alicona Microscope was done using MATLAB.

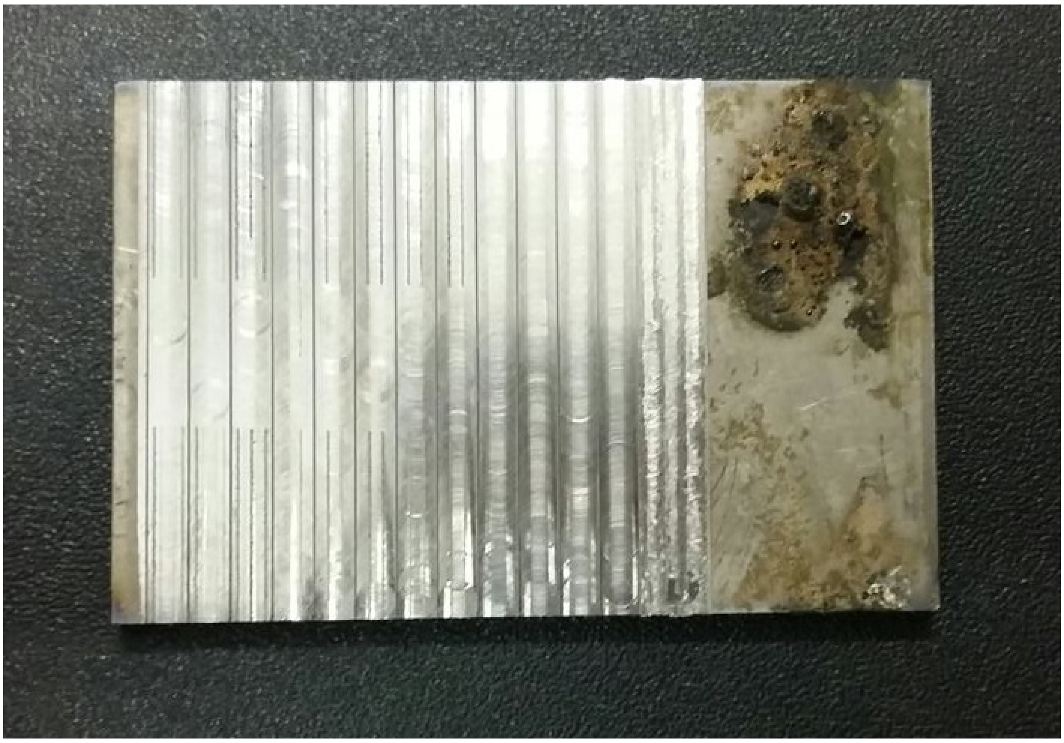


Figure 1: Workpiece

2 Literature Review

During machining, tool vibrates to and fro from the desired location, in an unambiguous direction relative to the workpiece. This introduces a pattern on the workpiece surface. It is extremely critical in high speed micro milling (spindle speeds >100,000 rpm) where the limited tool stiffness and small fluctuations in the cutting forces may cause dynamic instability. Here in this project we use spindle speeds less than 100,000 rpm because the machine's physical limit is that value.

Various techniques have already been devised and experimented with, for chatter identification in the machining. A few such methods, and corresponding drawbacks are listed below:

- Force Dynamometer: Used as sensors for chatter detection. This method fails in high speed micromilling. Given the high rotational speed of the tool, interaction time gets reduced drastically, causing frequencies to peak at around 10kHz. This data cannot be captured, given the limited bandwidth of the dynamometer used.

- Displacement Sensor Measurements: Laser is used to take readings of displacement of tool during machining process. Placement of laser and noise are two important issues with this measurement.

- Offline method of measuring surface topography using optical methods and scribe based instruments is a lot easier and can be done at a later time after actual machining.

2.1 Focus Variation Microscopy

Focus-Variation combines the small depth of focus of an optical system with vertical scanning to provide topographical and color information from the variation of focus. The main component of the system is a precision optic containing various lens systems that can be equipped with different objectives, allowing measurements with different resolution.

The algorithm works as follows: At first images with difference focus are captured. This is done by moving the sample or the optics in relation to each other. Then for each position the focus over each plane is calculated the plane with the best focus is used to get a sharp image. The corresponding depth gives the depth at the selected position.

2.2 Characterization

Average Power Spectral Density(APSD) is a common term used in signal processing for measuring strength of signal at any frequency. Spatial Frequency is a parameter which describes the waviness which has a maximum value of 1/(Sampling frequency). Units are 1/mm or 1/μm. In this experiment the sampling is done at an interval of 0.4369μm.
In this experiment we use Variation of Range, Standard Deviation, Number of Oscillations for this purpose.

Limits observed for various parameters are as follows.
(i) Spindle speed range$\leq$ 100000 rpm
(ii) Depth of cut $\leq$ 100 microns (else tool may fail)
(iii) Feed - 1-10 microns/flute

Typical parameter values		
Spindle speed range (RPM):	Depth of Cut (μm)	Feed (μm/flute)
20000	10	1.5
40000	20	3
60000	30	4.5
80000	40	6

Typical parameter valu1es			
Sample number	Spindle speed range (RPM):	Depth of Cut (μm)	Feed (μm/flute)
1	20000	10	1.5
2	20000	10	3
3	20000	10	4.5
4	20000	10	6
5	20000	20	1.5
6	20000	30	1.5
7	20000	40	1.5
7	40000	10	1.5
8	40000	10	3
9	40000	10	4.5
10	40000	20	1.5
11	40000	30	1.5
12	60000	10	1.5
13	60000	10	3
14	60000	20	1.5
15	80000	10	1.5

Machining was done and readings were taken for the above sets of data. The Reading for the *7* row had been abandoned due to tool failure at that depth of cut.

3 Procedure

3.1 Setting up the apparatus

Switch on dehumidifier and wait till the reading on the display shows 5oC. Switch on compressor. Open valve of the dehumidifier after the reading reaches 5oC. Select fixture based on the workpiece. Check tool securing locks on machine and alter them accordingly before and after the experiment. Switch on PC and the softwares mentioned in the introduction for starting the tool. As given in the next steps.

1. Open A3200 CNC software on desktop
2. Mount the tool on the tool-holder
3. Use tool opener to open/lock the tool-holder
4. Mount workpiece on the fixture (should be snug tight)
5. Open drivemaster software on desktop
6. Go to Extras ->drive setup tool; F8 to reset, then F5 ->F6 ->F7
7. Open DinoCapture software, which displays the microscope view
8. Use this to set the tool to zero position (just in contact with with the workpiece)
9. Start Machining accordingly as shown below.

3.2 Machining Process

1. *Facing*- (3mm diameter)
   The surface of the workpiece is machined once, with an end-mill tool. The surface now has lesser aberrations and hence, is easier to work on, given that the micro-milling tool's depth of cut is very minute (10μm).
2. *Milling*-(100μm diameter)
   The workpiece is machined at the mentioned depths of cut and corresponding spindle RPMs, for 1.5cm into the workpiece from either edges. In every 3cm gap, 2 different input configurations are set and the machining is done. The final workpiece, ready for analysis looks as workpiece image.

3.3 Codes used for milling

- G-code for facing the job: (G92 for setting zero)
  INCREMENTAL
  REPEAT 6
  LINEAR Y45 F5
  LINEAR X3 F5
  LINEAR Y-45 F5
  LINEAR X3 F5
  END REPEAT
  END PROGRAM

- Code for the micro milling experiment :(for feed=1mm/s)

```
INCREMENTAL
LINEAR Y15 F1
LINEAR Z-1 F1
LINEAR Y26 F10
LINEAR Z1 F1
LINEAR Y-15 F1
LINEAR Z-1 F1
LINEAR Y-26 F10
LINEAR Z1 F1
END PROGRAM
```

3.4 Cleaning the Workpiece

After machining (Surfacing + Micromilling). Workpiece is cleaned in an acetone bath using an ultrasonic cleaning machine to remove any impurities in the cuts else the particles may interfere during the imaging process and if any particles are present they will give erroneous primary depth of cut values at the location being imaged.

3.5 Imaging

Device used: *Alicona (Infinite Focus)* at 20x magnification

The images of the machined surface are taken using ''Alicona©" focus variation microscope. The concept of focus variation is due to the fact that "Z upper" & "Z lower" are two distance parameters which are above and below the exact focus distance of desired location on workpiece.Zooming should be done at 20X. Press 'Start Measurement' option. Now a separate window opens. Here best fit line is set (in one of the options present on the right side panel). After this line is drawn on the cut surface (pressing SHIFT key and mouse pointer clicks). After processing another window (table) is generated with various parameters such as x,y, z characteristic length etc.

The machined surface is examined using the 20x objective lens, along the various lines on the workpiece where the milling operation is done. The workpiece is placed on the mechanical stage and the configuration is aligned such that the machined cut to be analyzed is viewed at the centre of the screen, using 2.5x zoom on the software. Then, using the 20x zoom, the machined cut is focussed on the screen. The cut is then analyzed for any unwanted aberrations Lower and an upper

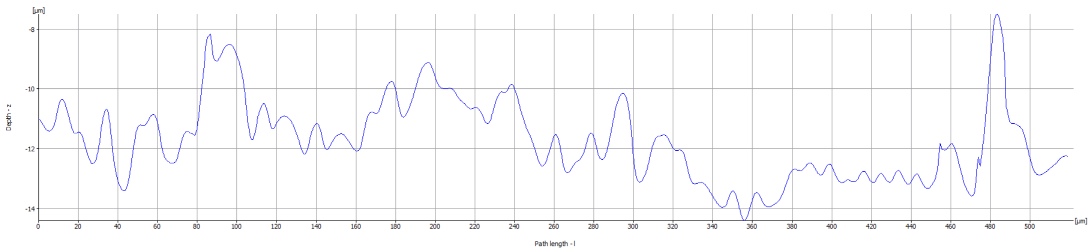


Figure 2: Primary Depth vs length

foci are set by zooming in and out desired amounts respectively, so that the entire surface profile appears in the 3D surface metrology. The three coordinate axes X, Y and Z are auto-set in the interface. A vertical line is selected along the machined cut, along which the values of depths of cut and path length are tabulated and plotted.

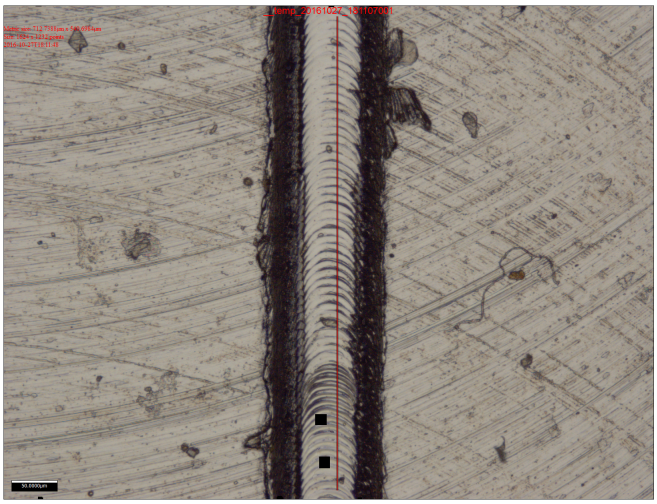


Figure 3: 2D rendering of cut surface with values of depth known along red line

The process is repeated 6 times for a every set of process parameters. Corresponding tables, images, and depth of cut diagrams are simultaneously saved, for further analysis.Furhter another set of readings are taken on the non-milled region of the workpiece, to be used as base values, while accounting for aberrations in the machining process for “Z- Referencing of Tool ” step.

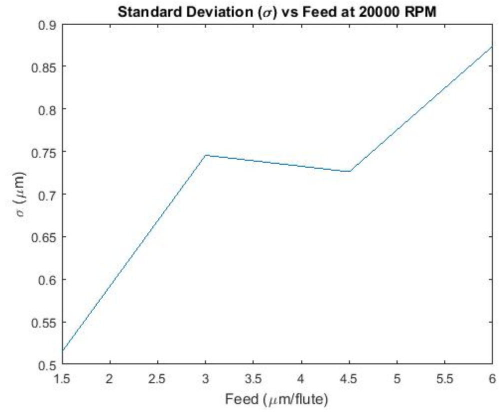


Figure 4: SD vs F at 20000

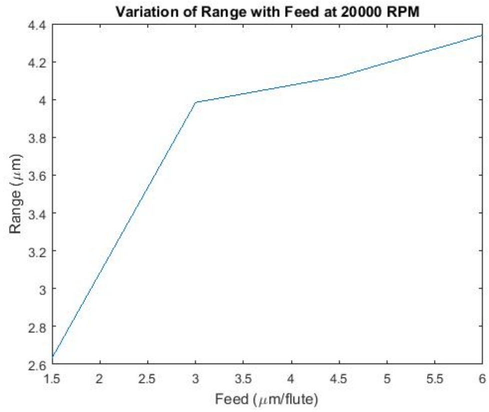


Figure 5: R vs F at 20000

4 Results and Discussion

Important parameters are length (y distance from origin along the cut) and depth of cut at each data point.

We have used 3 statistical parameters to determine the stability of the process with respect to feed, rotational speed and depth of cut. They are:

1. Standard Deviation

2. Range (difference between maximum depth and minimum depth)

3. Number of oscillations (over a length of 450 μm)

A number of experiments have been performed (as mentioned in the previous section), and hence, our conclusions are pretty robust considering that they have been averaged over so many experiments.

The variations of these statistical parameters with the experimental parameters (feed, rpm, and depth of cut) have been obtained and conclusions have been made. Following are the plots for the variations: SD - Standrad Deviation
C - No of oscillations
N - RPM
F - Feed
R - Range
d - depth of cut

From these graphs (Fig 4 to Fig 19), we made the following observations:

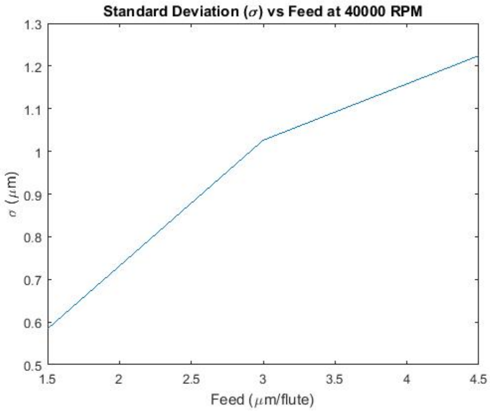


Figure 6: SD vs F at 40000

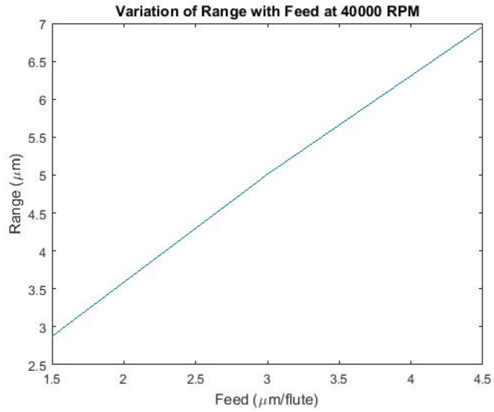


Figure 7: R vs F at 40000

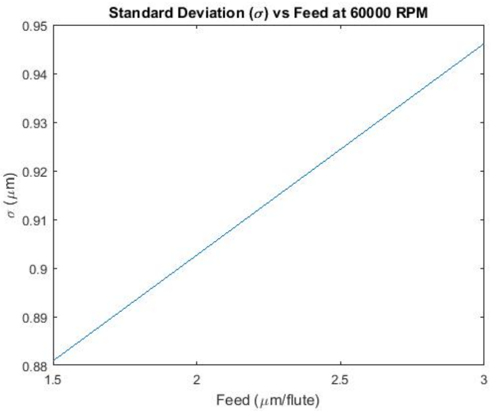


Figure 8: SD vs F at 60000

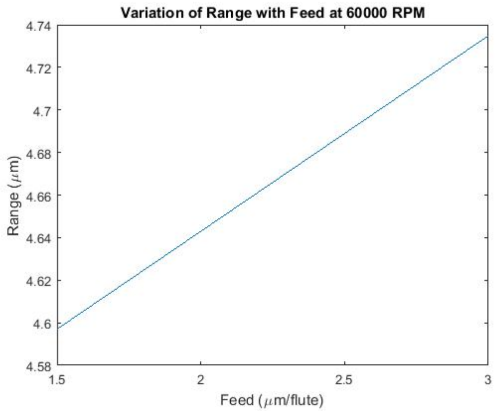


Figure 9: R vs F at 60000

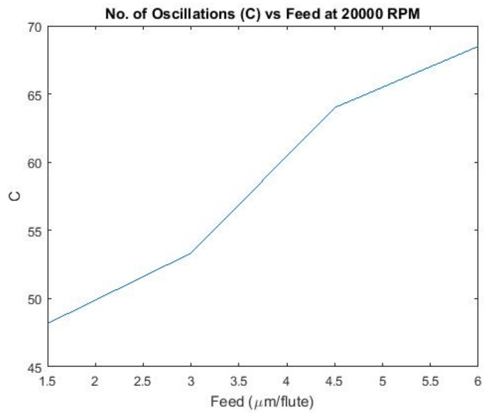


Figure 10: C vs F at 20000

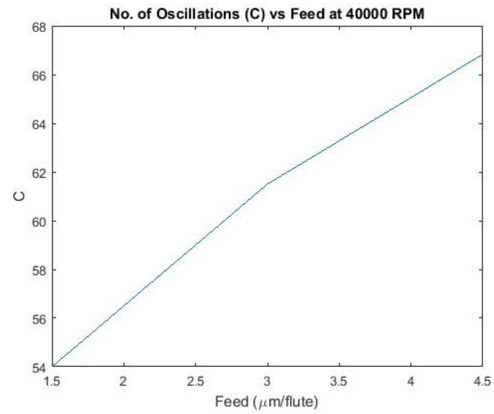


Figure 11: C vs F at 40000

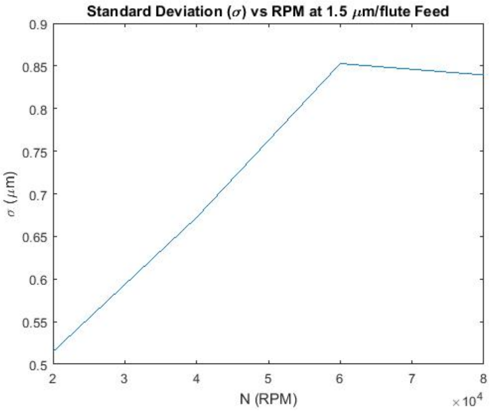


Figure 12: SD vs N at 1.5 F

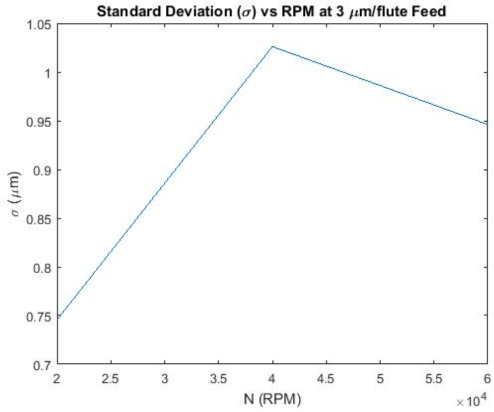


Figure 13: SD vs N at 3 F

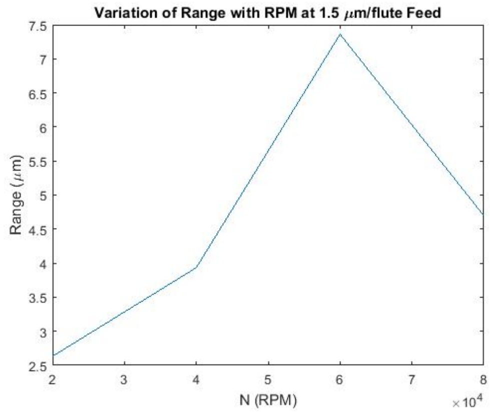


Figure 14: R vs N at 1.5 F

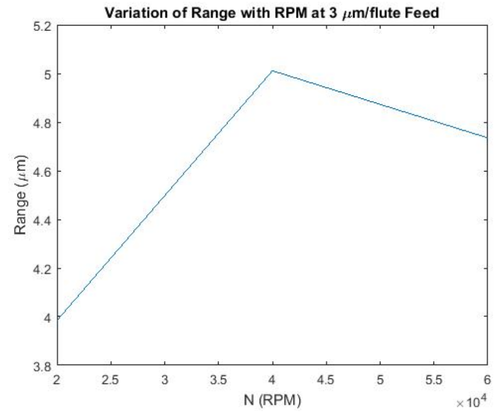


Figure 15: R vs N at 3 F

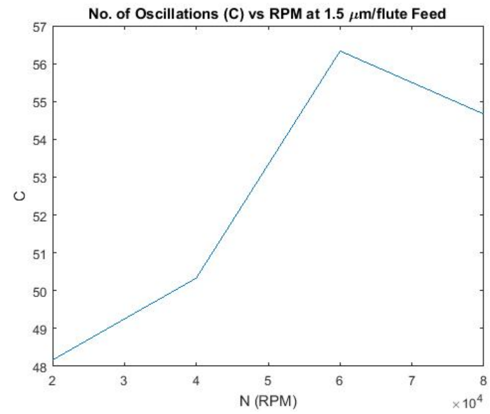


Figure 16: C vs N at 1.5 F

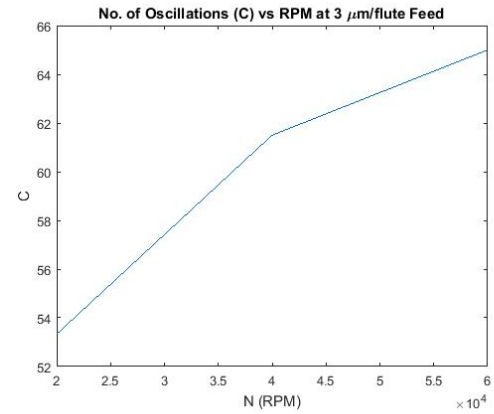
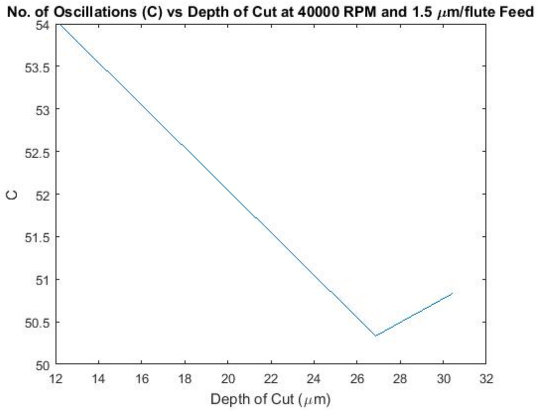


Figure 17: C vs N at 3 F



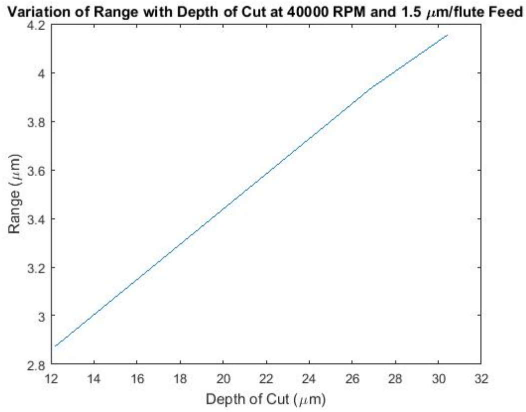


Figure 18: SD vs d at 40000RPM, 1.5 F Figure 19: R vs d at 40000RPM, 1.5 F

1. With increasing feed, keeping the RPM and depth of cut constant,
   (a) The standard deviation increased.
   (b) The range of oscillations increased.
   (c) The number of oscillations increased.
2. With increasing RPM, keeping the feed and depth of cut constant,
   (a) The standard deviation increased till a particular RPM and then decreased.
   (b) The range of oscillations increased till a particular RPM and then decreased.
   (c) The number of oscillations more or less increased.
3. With increasing depth of cut, keeping the feed and RPM constant,
   (a) The standard deviation increased.
   (b) The range of oscillations increased.
   (c) The number of oscillations decreased did not change much with depth of cut.

From these observations, we have made the following conclusions:

- Increasing the feed always led to increase in vibrations (inferred from the increase in standard deviation, range and number of oscillations), and hence more undulations on the surface leading to poor surface finish.

- Increasing the Spindle Rotation speed leads to increase in vibrations till a particular critical RPM. After this, the vibrations actually decreased. So probably, very high RPM's can lead to a better surface finish. This can be explained by stability lobes.
- Increasing the depth of cut led to a consistent increase in vibrations. As a matter of fact, after a particular depth of cut, the tool simply broke. So it is best to do machining in steps of low depths, if time is not a constraint.

The final conclusion is: If the machining time is to be reduced, then the best way to do it is by increasing the spindle rotation speed, keeping the feed and depth of cut in a stable range. This will increase the feed rate (feed x RPM x (no. of flutes)) to effectively reduce the overall machining time.

5 Conclusions and Future Work

5.1 Conclusion

Potential outcomes of project We have performed micro milling of Ti6Al4V, a reasonably hard and versatile material. Stability Lobe diagrams is a comprehensive set of charts for determining stable cutting parameters for workpiece. It is useful for industries where individual measurements for roughness at different process parameters are infeasible. Vibration elimination is possible by changing process parameters, Tuned Dampers, holding the workpiece tightly, using stiffer supports, and active control of the tool movement.

5.2 Future Work

Open issues for further investigation. We assumed in this analysis that machined surface is perfectly is perfectly smooth. We did not take into account the effect of undulations previously present on the surface. Regenerative chatter comes into play at low frequencies(<1000 Hz)

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