Surface Roughness of Stainless Steel by Micro-Milling for Biomedical Applications

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ABSTRACT

Biomedical industry is one of the fastest growing industries nowadays. A lot of improvement and development has been done in order to maintain the usage for biomedical industry. Stainless steel is one of the material that usually been used in this industry but still need to be improved so that every weaknesses can be taken out. Stainless steel also can be processed by milling operation. By milling operation, it will affect the surface roughness of the material.

It is important for a material especially for material in biomedical industry to have the optimum value of surface roughness so that it will meet the requirement that is needed by the body. To obtain the optimum surface roughness, we need to find the optimum feed rate, spindle feed and also depth of cut. From the optimum value of all those three variables, and the value that is obtained can be used as the reference for future works.

INTRODUCTION

Background

The usage of Stainless steel in various machining related application has been growing progressively in the last two decades. In the manufacturing industries, there are a lot of machining processes that are applied nowadays, such as broaching, sawing, filing, and also milling. Milling is one of the most versatile machining processes in which a rotational cutter removes material while traveling along various axes with respect to the work piece. It covers a wide variety of different operations and machines, on scales from small individual parts to large, heavy-duty gang milling operations. It is one of the most commonly used processes in industry and machine shops today for machining parts with precise sizes and shapes. Milling has more variations in machine types, tooling, and workpiece movement than any other machining method.

One of the main properties that must be considered in milling operations is the surface roughness. This is because the surface roughness is directly affected by the milling process. For this project it is desirable to get the surface roughness to the lowest possible value. To achieve the optimum surface roughness, it required specific parameter from various variable such as depth of cut, feed rate, cutting speed and spindle speed. (Mathew A. Kuttolamadom, 2010)

Problem Statement

In machining process, milling or micro milling is the main machining operation that has been used in this industry. All machining process will affect the surface on the machined part. One of the most important aspects that need to be considered is the surface roughness of the machined parts. The surface roughness would be high if the machine is not operated at the best feed rate and at the best cutting speed. The optimum the surface roughness would be better as we need to use it for biomedical usage and it is well known that biomedical industry is the industry that really concerned about the accuracy.

Objective

a) To study the effect of different spindle speed of micro milling on the surface roughness of stainless steel.
b) To study the effect of different feed rate of micro milling on the surface roughness of stainless steel.
c) To achieve the optimum cutting parameter for the best surface roughness. The cutting parameters that will be used as variable is the cutting speed and also feed rate.

LITERATURE REVIEW

Milling concept

To handle metal material such as stainless steel, it requires machining process such as drilling; milling welding etc. this project will be focused on the milling process.. The most important interactions, that effect surface roughness of machined surfaces, are between the cutting feed and depth of cut, and between cutting feed and spindle speed. Surface Roughness is affected negatively if the applied force is increased. Surface roughness at the same feed rate becomes higher when a small nose radius is used. (Amit Joshi, 2012)

Milling parameter of the cutting speed V, in peripheral milling is surface speed of cutter

$$V = \pi \text{DN}$$

Where D is the cutting parameter and N is the rotational speed of the cutter (Figure 1)

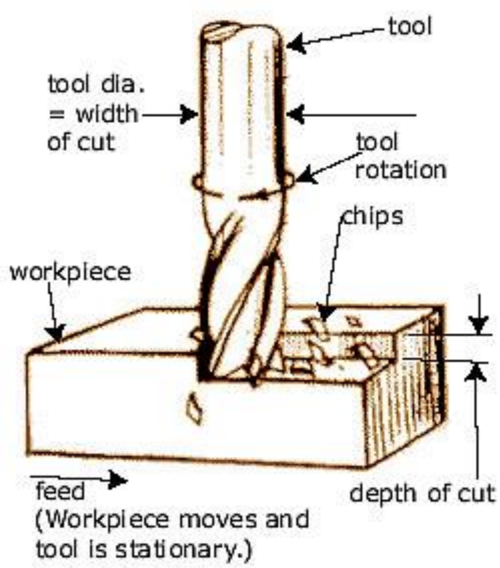

Figure 1 Cutting Parameter

$$t_c = 2f\sqrt{\frac{d}{D}}$$

f is the feed per tooth of the cutter – that is, the distance the workpiece travels per tooth of the cutter in mm/tooth and *d* is the depth of cut. As t_c becomes larger, the force on the cutter tooth increases.

Feed per tooth is determined from the equation

$$f = \frac{v}{Nn}$$

Where v the linear speed (feed rate) of the work is piece and n is the number of teeth on the cutter periphery. The dimensional accuracy of this equation can be checked by using appropriate units for the individual terms; for instance,

(mm/tooth) = (m/min)(10^3mm/m)/(rev/min)(number of teeth/rev)

The cutting time *t* is given by the equation

$$t = \frac{l + l_c}{v}$$

Where *l* is the length of the workpiece and l_c is the horizontal extent of the cutter's first contact with the workpiece. Based on the assumption that $l_c \ll l$ the material –removal rate (MRR) is

$$MRR = \frac{lwd}{t} = wdv,$$

Where w is the width of the cut , which in slab milling is the same as the width of the workpiece.

(Serope Kalpakjian, 2010)

Peripheral Milling parameter and formulas

N	Rotational speed of the cutter, rpm
F	Feed, mm/tooth
D	Cutter diameter
n	Number of teeth on cutter
v	Linear speed of cutter
V	Surface speed of cutter m/min DN
f	Feed per tooth , mm/tooth v/Nn
l	Length of cut, mm
t	Cutting time , s or min $(l = l_c)/v$, where l_c = extent of the cutter's first contact with the workpiece
MRR	$\frac{mm^3}{min}$ wdv, where w is the width of cut
Torque	N.m $F_c D/2$
Power	kW (Torque)(ω)where$\omega = 2\pi N$ radians/min

Table 1 Formulas and Parameters

Micro Milling

The function of the micro milling scale will be different from the conventional scale. In conventional scale milling, the feed per tooth in usually much larger than the cutting edge radius of the tool, but the feed per tooth in micro milling is often comparable to or even less than the cutting edge radius. “The small size of micro milling cutters makes them very weak and results in a small stiffness.” (Chang-Ju Kim, 2002)So it is better to find the cutting tool that is strong as the metal that will be use will be very small.

(Zdebski, 2012)Majority of tools used in recently published research for micro milling have cutting diameters in a range of 0.3 mm to 1 mm

1	Experimental Analysis of Chip Formation in Micro Milling. (Chang-Ju Kim, 2002)	• 2F emd-mill (635µm) • Brass 360 • Depth of cut 0.254 mm • Spindle speed 80000 rpm • Cutting speed 159600 mm/min • Feed/tooth 0.188 µm to 6 µm.
2	Optimization of cutting parameters in micro end milling. (Operations under dry cutting conditions using genetic algorithms) (Sonti Sreeram A Senthil Kumar, 2006)	• Unknown material • Tool Diameter 2F (1mm-2mm) • Range of depth of cut 0.25-2(mm) • Spindle speed 10000-20000(rpm) • Feed rate 50-200(mm/min)
3	Multi-category micro-milling tool wear monitoring with continuous hidden Markov models (Kunpeng Zhu, 2009)	• Copper and Steel • Tool Diameter (0.5mm-0.8mm) • Depth of cut 0.03-0.15(mm) • Spindle speed 18000-20000(rpm) • Cutting speed 80-180(mm/min)

	International Journal of Machine Tools & Manufacture Mechanistic model for prediction of cutting forces in micro end-milling and experimental comparison (Y.V. Srinivasa, 2013)	• the cutter is a two fluted solid carbide micro end-mill of 0.5 mm diameter, having 1.5 mm • Spindle Speed 20000-40000RPM • Depth of cut 0.1mm-0.2mm

Table 2 References for cutting parameter

Stainless steel

In biomedical industry, it divided into some division, and each division have their own implant. The example of implants that used in cardiovascular division stent and artificial valve. Types of metal used such as 316L SS, CoCrMo, and Ti Ti6A14V

316L type of stainless steel is still the most used alloy in all implant ranging from cardiovascular to otorhinology. (Hendra Hermawan, 2011)

Division	Example of implants	Type of metal
Cardiovascular	Stent Artificial valve	316L SS, CoCrMo: Ti Ti6A14V
Orthopedic	Bone Fixation (plate , screw, pin) Artificial join	316L SS; Ti; Ti6Al4V CoCrMo; Ti6Al4V; Ti6Al7Nb
Dentistry	Orthodontic wire Filling	316L SS; CoCrMo; TiNi; TiMo AgSn(Cu) amalgam, Au
Craniofacial	Plate and screw	316L SS; CoCrMo; Ti; Ti6Al4V
Otorhinology	Artificial eardrum	316L

Table 3. Implants division and tupe of metals used (Hendra Hermawan, 2011)

.

Metal	Main Alloying Decomposition	Mechanical Properties			
		YS (MPa)	UTS (MPa)	YM (GPA)	Max Elongation
Stainless steel: 316L type (ASTM, 2003)	Fe; 16-18.5Cr; 10-14Ni; 2-3Mo; <2Mn; <1Si; <0.003C	**190**	**490**	**193**	**40**

Table 4 316L Properties (Hendra Hermawan, 2011)

*under annealed condition except for WE43 which was solution heat-treated and artificially aged (T6).
YS = yield strength, UTS = ultimate tensile strength, YM = Young's modulus.

Besides, Austenitic 316L stainless steels have a range of favorable mechanical properties, also have good corrosion resistance, high strength under elevated temperatures, excellent ductility, and good weldability also that 316L SS alloy has good ductility under low strain rate and high temperature loading conditions. (Woei-Shyan Lee, 2011)

Surface Roughness

Optimization of feed rate is valuable in terms of providing high precision and efficient machining. The surface roughness is particularly sensitive to the feed rate and the run out errors of the inserts in a face-milling operation. This paper analyzes the effects of the insert run out errors and the variation of the feed rate on the surface roughness and the dimensional accuracy in a face-milling operation using a surface roughness model. The validity of the developed model was proven through cutting experiments, and the model was used to predict the machined surface roughness from the information of the insert run outs and the cutting parameters. From the estimated surface roughness value, the optimal feed rate that gave a maximum material removal rate under the given surface roughness constraint could be selected by a bisection method.

A theoretical arithmetic expression was proposed for average surface roughness as follows (Whitehouse, 1994):

$$R_a \approx 0.032 \frac{f^2}{R}$$

Where f is the feed rate and R is the tool nose radius.

An exponential empirical model for surface roughness as a function of cutting speed (V), feed (f) and depth of cut (d) was suggested (X.D. Fang, 1997)as follows:

$$Ra=C_0V_{c1}f_{c2}d_{c3}$$

Where Ra is the surface roughness, C0 is a constant, and c_1, c_2 and c_3 are indexes which describe the empirical model.

The following empirical expression for surface roughness in turning was proposed (Hong Xiang, 2002)They used a diamond cutting tool and the workpiece material was aluminum alloy, where R is the surface roughness, Vc is the cutting speed, f is the feed rate and Dc is the depth of cut.

The current research studies the mechanism of chip formation in micro-milling and reveals some ‘important information about how the tool interacts with the workpiece material. This type of fundamental study contributes to a comprehensive understanding of the micro-milling process that will allow engineers to develop improved tools and processes.. In addition, the marks made by the tools on the machined surface of the workpiece are analyzed. The information gained from these experiments has led to a better qualitative understanding of how chips are formed. (Chang-Ju Kim, 2002)

In term biomedical application, surface roughness an implant has significant effect on the process on healing. The surface roughness of the implant will determine its ultimate ability to integrate into the surrounding tissue. In an article, five important effects have been attributed to increase of implant surface roughness. First is increase in surface area of the implant adjacent to the bone, second is improved cells attachment to the implant surface, third, increased bone present at the implant surface, fourth, increased biomechanical interaction of the implant with bone, and lastly promoted inflammation of the peri-implant mucosa if the rough surface is located in a transmucosal area (Cooper, 2000).

However, in another finding it is showed that implant with mother surface has a better removal torque and better percentage of bone in contact (Ellingsen, Johansson, Wenneberg, & Holmen, 2004). In this experiment three test and three control implants, with different surface roughness, were placed in rabbit tibia and left to heal for one to three month.

Besides that, in another researched it is found that the cell grown on a rougher surface is significantly lower that smoothest surface (Kieswetter, Z.Schwartz, Dean, & Boyan, 1996). Besides that tissue grown on a smooth surface had a well spread and flattened morphology. Different level of roughness will have different rate of cell growing on it. The faster the rate of cell growing, the faster is the healing process. It is also concluded in this article that the implanted device interfaces with a variety of tissues such as epithelial, connective tissues, and bone. By understanding the implant surface characteristics which are optimal for each one of these tissues, investigators will be able to design better implants by customizing specific regions of the implant for each tissue type.

Based from (Manop Vorasri, 2011) results shows that the surface roughness and the surface finish influenced by depth of cut, cutting speed and feed rate. The results also showed that the lower feed rate would be cause of better surface quality. Higher cutting speed would cause better surface quality, lower feed rate be increase the better surface roughness.

METHODOLOGY

Project Flow

This project will involve a lot of machining works which will be conducted in the machining labs.

In order to the machining works appropriately, a proper planning need to be done and a project flow need to be developed.

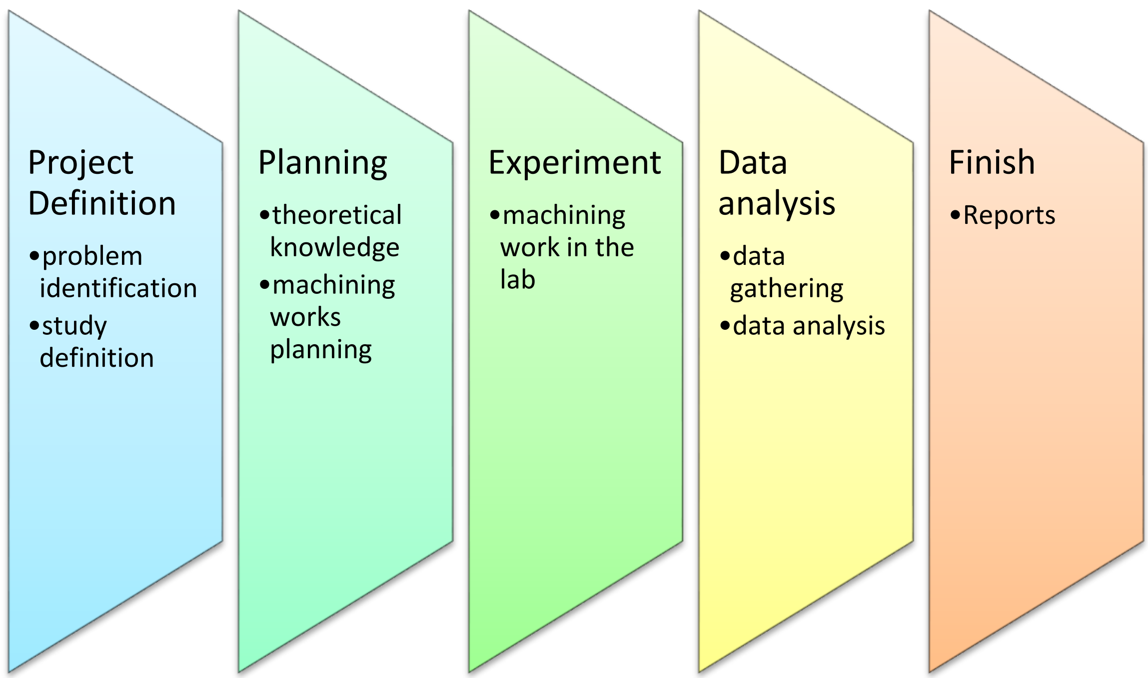

Figure 2 Project Flow

Table 5: Project Flow

The project will be started with the problem identification, followed by the definition of the study. That includes the study of background, its objectives, scope and the relevancy of the topic.

The next step is the planning. Its required theoretical knowledge for the projects and the knowledge will be gathered from suitable sources to enhance the integrity of the study and also the relevancy of the projects. If not, this project may not be strong and not valid. Since the research is mainly about machining, the reference also will be related with machining especially in machining. The range of the variable will be wide so that it will be easier to find the best cutting variable.

There are a lot of parameters that can affect milling quality such as:

i. Feed rate
ii. Spindle speed
iii. Cutting tool size
iv. Type of material
v. Type of cutting tool
vi. Vibration of machine

However based on the literature review, previous researchers found out feed rate and spindle speed are two most important keys in determining surface roughness of a drilled hole. These two parameters then are selected to be tested in this research.

The tool's diameter is keep as a constant variable. From here also we start to decide the variable which is in this project the variable would be the

a) Cutting speed (manipulated variable)
   The range of the cutting speed will be at 3000RPM-15000RPM
b) Feed rate (manipulated variable)
   Feed rate will be at (50-250) mm/min
c) Depth of cut (constant variable)
   Depth of cut will be at 0.2mm
d) Diameter of the cutting tools.
   The diameter will be 1mm

On the execution step, this project continued with the experiment work which is the machining work and follows the entire variable that has been decided before. And after the machining, the result will be observed by 3 steps which are

a) Surface roughness testing
b) Scanning electron microscope
c) Optical microscope

Results obtained from the experiment will be collected and analyzed using the mathematical model developed earlier. Relationship between parameters that are varied with regard to the depth of cutting, cutting speed and also feed rate will be observed. From the result we manage to get the best value to the cut the material.

Procedure

4.2.1 Preparation of Material and tool

a) Cutting tools (1mm)
b) CNC Milling Machine
c) (Specimen) Stainless Steel
d) Profilometer
e) Scanning electron microscope
f) Optical microscope

4.2.2 Experiment

The experiment started with making the milling process on the stainless steel by using CNC milling machine. It has different feed rate and cutting speed but with same depth of cut. The parameter that have decided.

- Material: Stainless Steel 316L
- Mill Bit: 1mm 2 Flute
- Feed Range: 50mm/min- 300mm/min
- Spindle Speed Range: 3000RPM- 15000RPM
- Depth of Cut: 0.2mm
- Milling length: 38mm
- Surface Roughness length: 2cm
- Machine: MAZAK VARIAXIS 630-5X
- Surface Roughness Tester: Profilometer

Figure 3 CNC Milling Machine

Micro-milling Operating Procedure

i. Work piece is produced by cutting magnesium alloy is cut into the desirable size and thickness.
ii. The surface of the work piece is cleaned from any dirt and grease.
iii. Set the milling machine with the selected parameters.
iv. Position the work piece into the milling machine.
v. Start milling on the work piece stating with smallest cutting speed and label the work.
vi. Repeat step i to v for different selection of parameters.

N (RPM)	Feed Speed (mm/min)	Coordinate
3000	50	X: 7.1cm Y: -4.8 cm
	100	
	150	
	200	
	250	
5000	50	
	100	
	150	
	200	
	250	
10000	50	
	100	
	150	
	200	
	250	
15000	50	
	100	
	150	
	200	
	250	

Table 6 table example

For this project, the parameters will arrange randomly to avoid the drift effect.

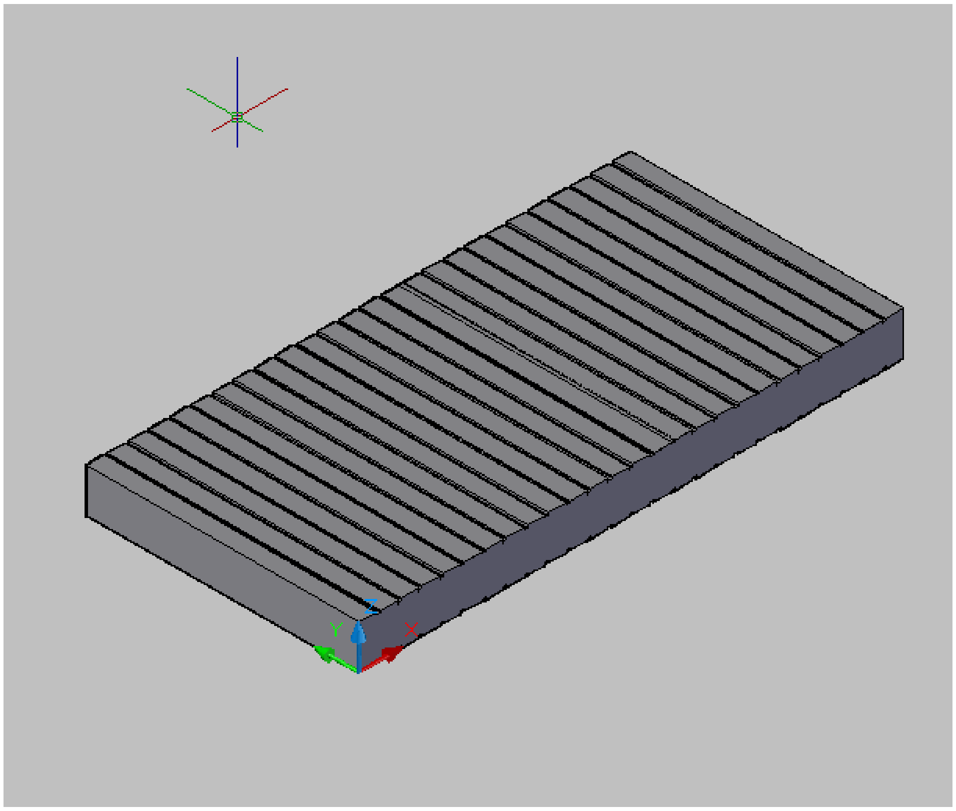

Figure 4 Cutting Design

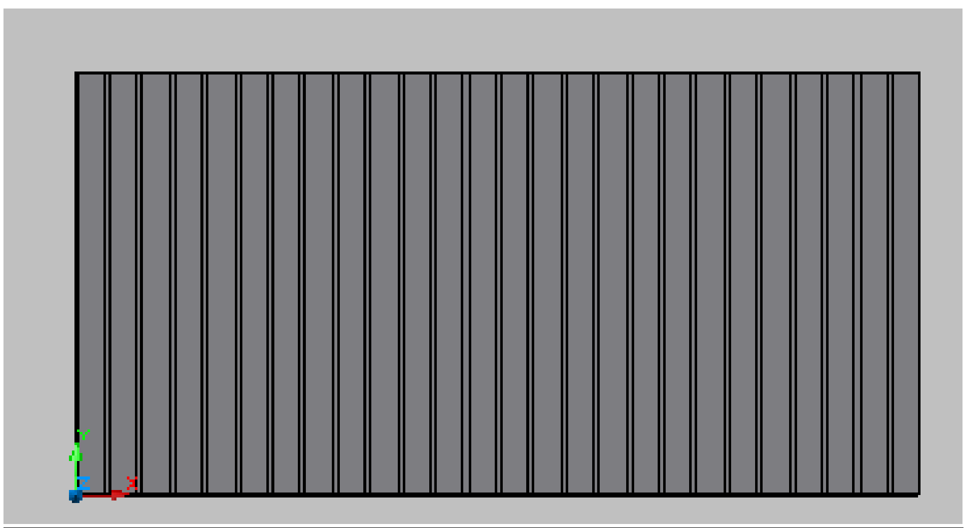

Figure 5 Cutting Design, Top View

4.2.3 Data Gathering and Analysis

Surface roughness of the milled part can be measured using surface roughness profilometer testing equipment. Profilometer would give the average roughness of the inspected surface. Sample with a smooth surface would give a lower reading of average surface roughness compared to rougher surface.

Figure 6 Surface Roughness Tester

Profilometer Standard Operating Procedure

i. Switch on the machine and the computer.
ii. Run the profilometer software
iii. Key in the parameter and select for average roughness
iv. Place the sample at its position and run the machine
v. Save the data and reset for new sample
vi. Repeat step ii to v for all the samples.

Tabulate Result

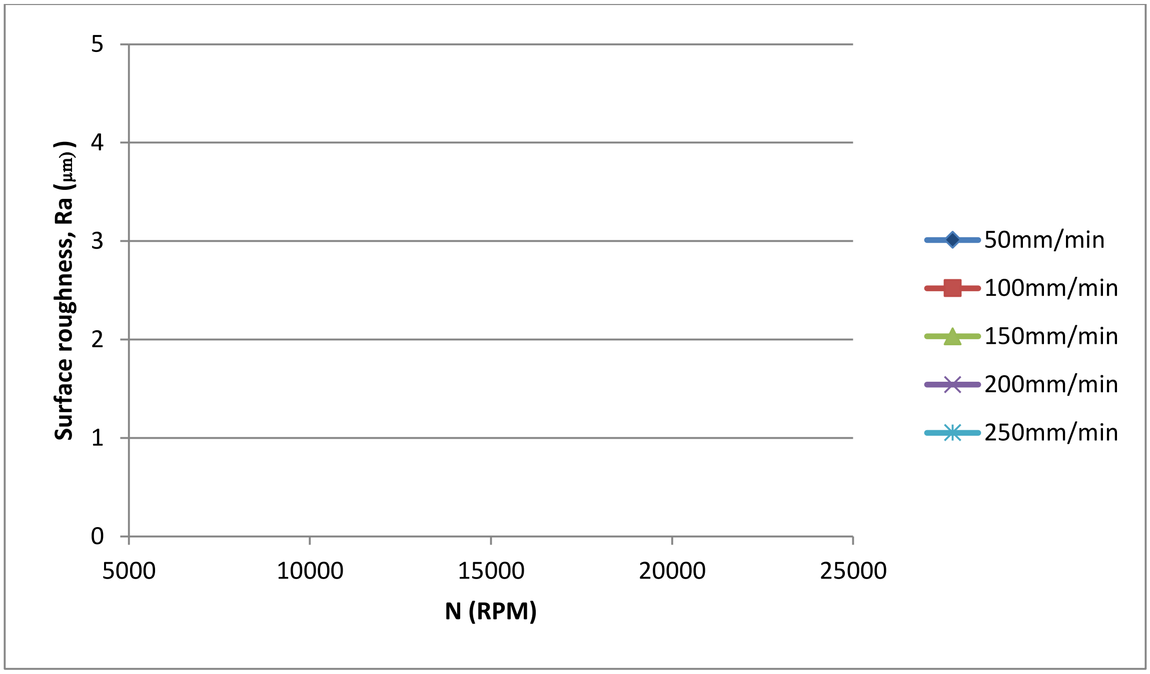

Figure 7 Feed Rate vs. Surface Roughness

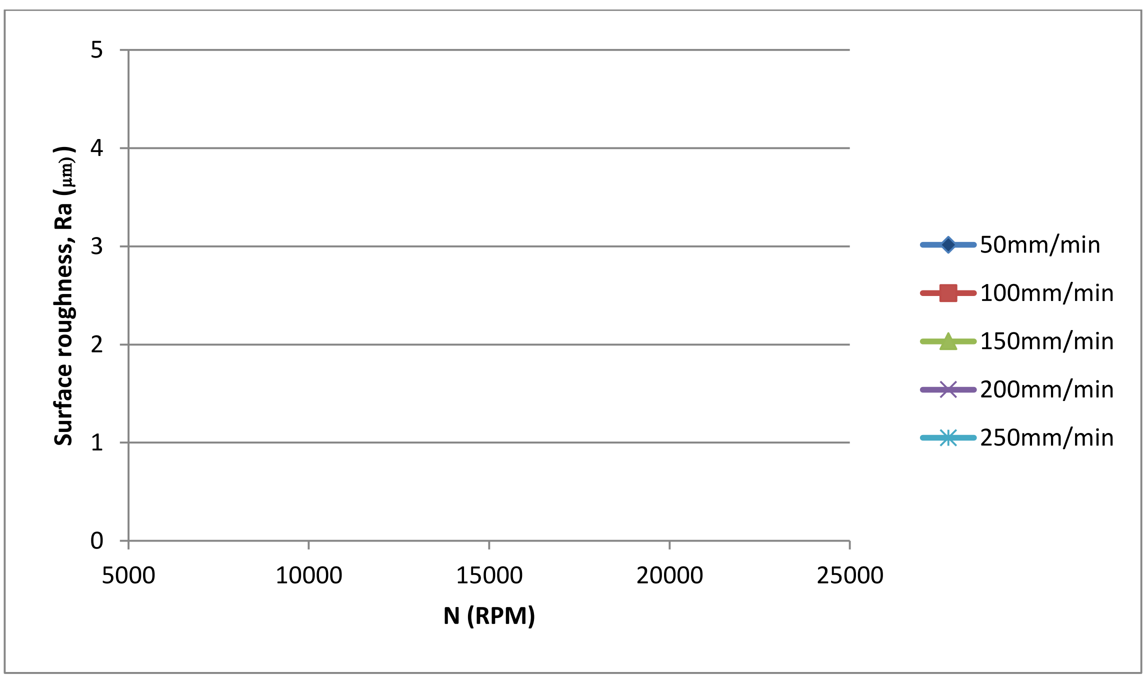

Figure 8 Spindle Speed vs. Surface Roughness

Gantt Chart FYP 1/FYP 2

FYP 1

DETAIL/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
First meeting with coordinator and supervisor															
Preliminary research work															
Submission of Extended Proposal Defense															
Proposal Defense								**Mid-Semester break**							
Project work continues															
Submission of Interim Draft Report															
Submission of Interim Report															

Figure 9 FYP 1 Gantt chart

FYP2

DETAIL/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Preparation for lab															
Milling process															
Surface roughness process								Mid-Semester break							
Data Collection and analysis															
Preparation final report															
SEDEX															
Submission of Final Report															`
Final Presentation															

Figure 10 FYP 2 Gannt chart

Key Milestone

1st June 2013	:	Cutting tool arrived.
11th July 2013	:	Start with Micro-milling Process
15th -16th July 2013	:	Surface Roughness testing
23rd -24th July 2013	:	Optical Microscope Observation
25th – 26th July 2013	:	Preparation of Poster Presentation
2nd August 2013	:	Poster Presentation
28th August 2013	:	Viva (Final Presentation)

RESULTS

3000RPM

Feed Rate(mm/min)	Ra_1(µm)	Ra_2(µm)	Ra_3(µm)	Average Ra (µm)
50	1.154	1.266	0.996	1.138666667
100	0.78	0.678	0.649	0.702333333
150	3.574	3.742	3.738	3.684666667

Table 7 Results: 3000RPM

5000RPM

Feed Rate(mm/min)	Ra_1(µm)	Ra_2(µm)	Ra_3(µm)	Average Ra (µm)
50	0.212	0.202	0.215	0.209666667
100	0.239	0.23	0.232	0.233666667
150	0.476	0.518	0.505	0.499666667
200	0.651	0.612	0.608	0.623666667
250	0.327	0.341	0.318	0.328666667

Table 8 Results 5000RPM

10000RPM

Feed Rate(mm/min)	Ra_1(µm)	Ra_2(µm)	Ra_3(µm)	Average Ra (µm)
50	0.356	0.356	0.362	0.358
100	0.521	0.598	0.593	0.570666667
150	0.611	0.607	0.643	0.620333333
200	1.974	1.819	1.844	1.879
250	0.711	0.532	0.514	0.585666667

Table 9 Results 10000RPM

15000RPM

Feed Rate(mm/min)	Ra_1(µm)	Ra_2(µm)	Ra_3(µm)	Average Ra (µm)
50	0.166	0.129	0.166	0.153666667
100	0.378	0.49	0.318	0.395333333
150	0.624	0.593	0.453	0.556666667
200	0.828	0.733	0.723	0.761333333
250	0.185	0.171	0.171	0.175666667

Table 10 Results 15000RPM

Surface Roughness Vs Feed Rate

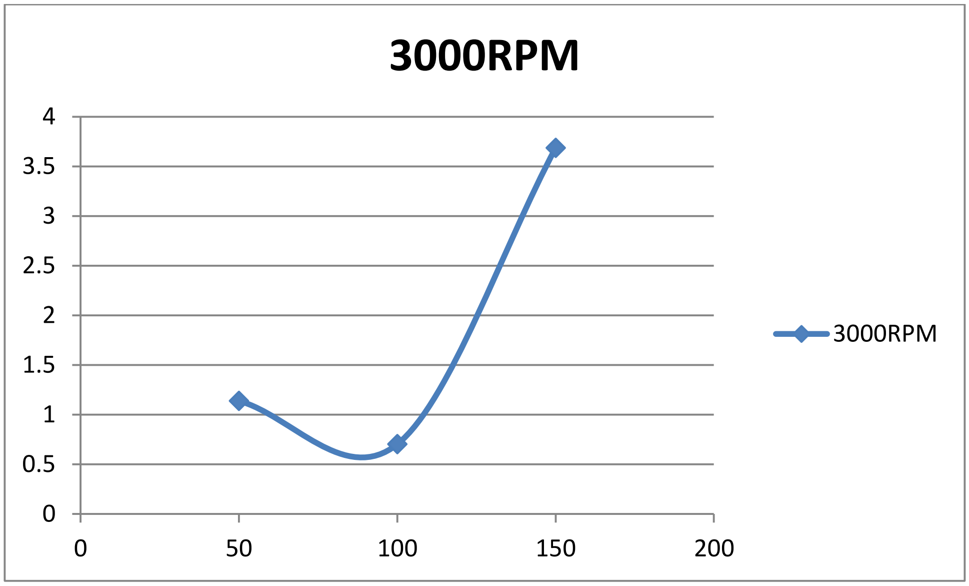

Figure 11 RPM 3000

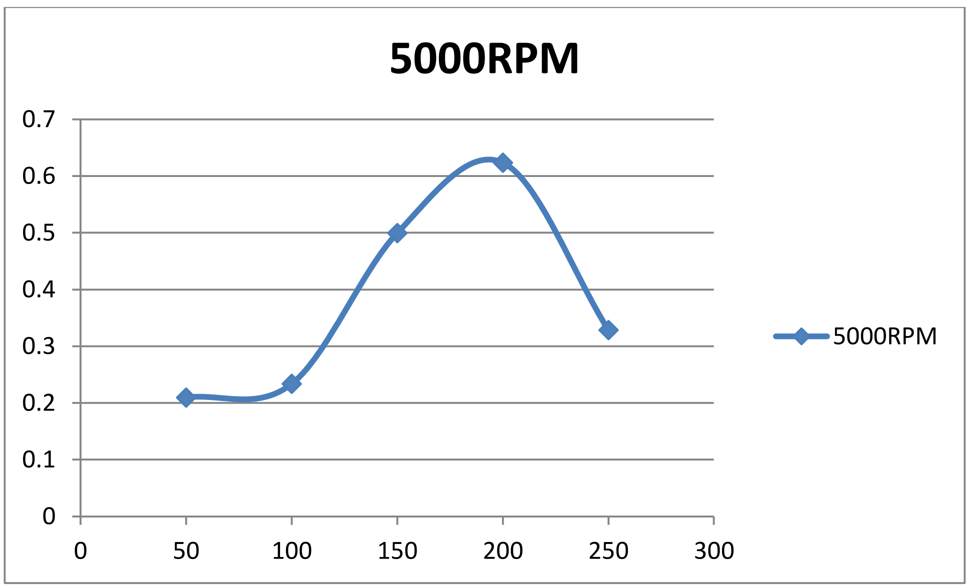

Figure 12 RPM 5000

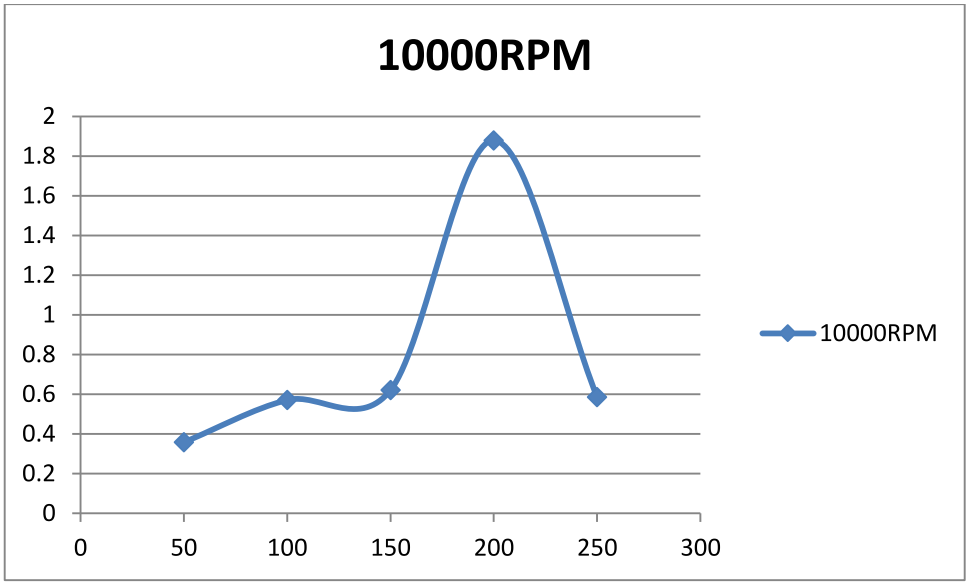

Figure 13 RPM 1000

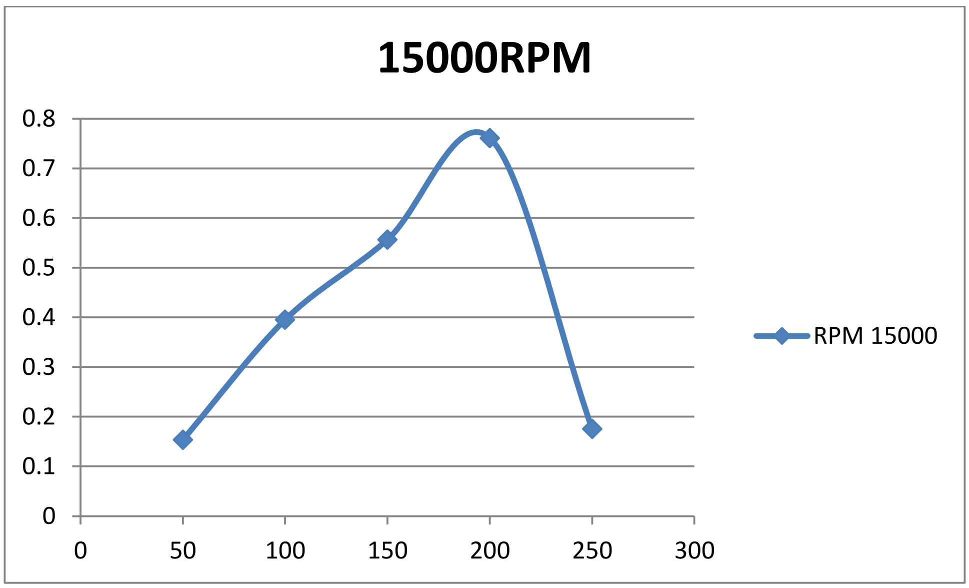

Figure 14 15000

Surface Roughness Vs Spindle Speed

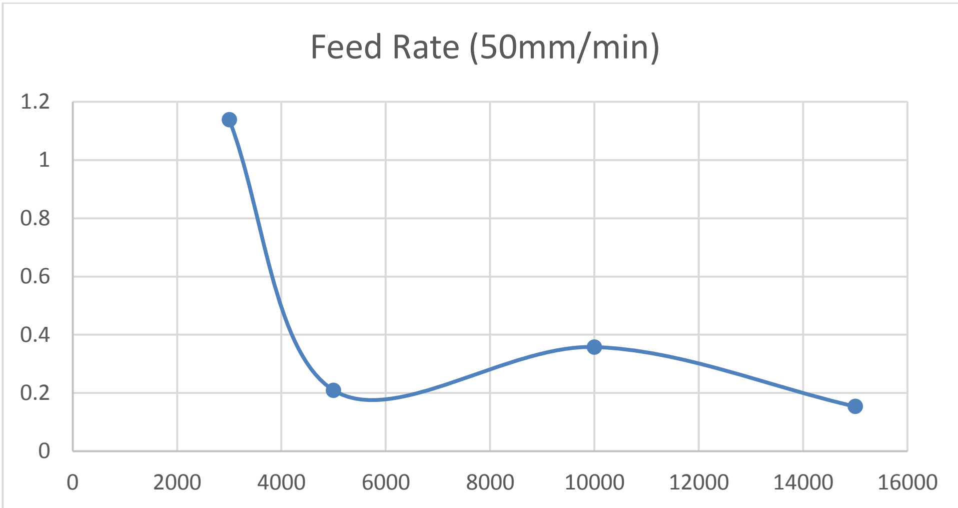

Figure 15 Feed Rate 50mm/min

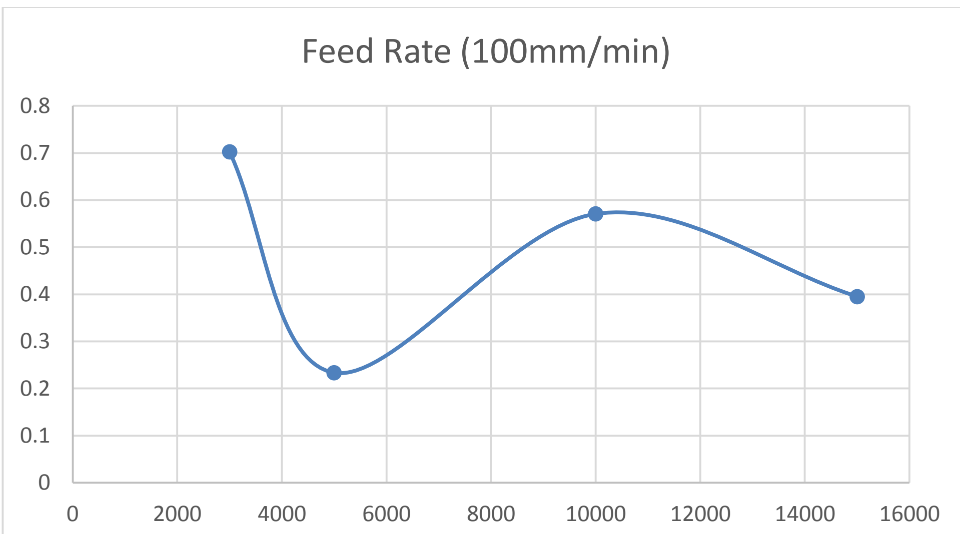

Figure 16 Feed Rate 100mm/min

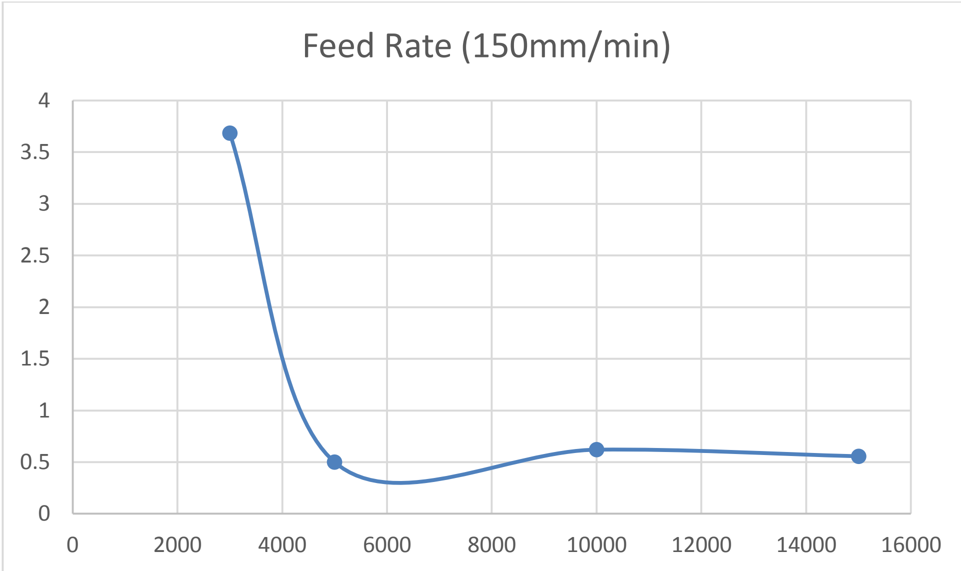

Figure 17 Feed Rate 150mm/min

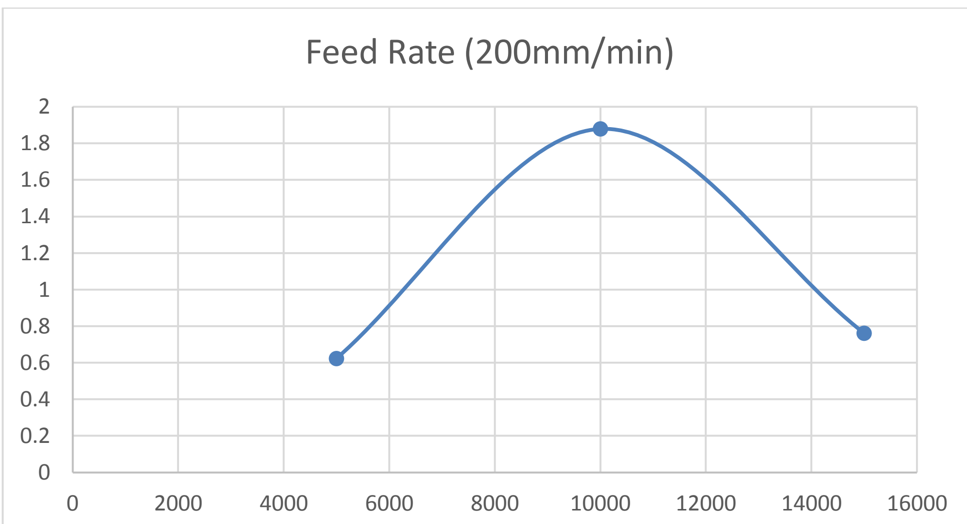

Figure 18 Feed Rate 200mm/min

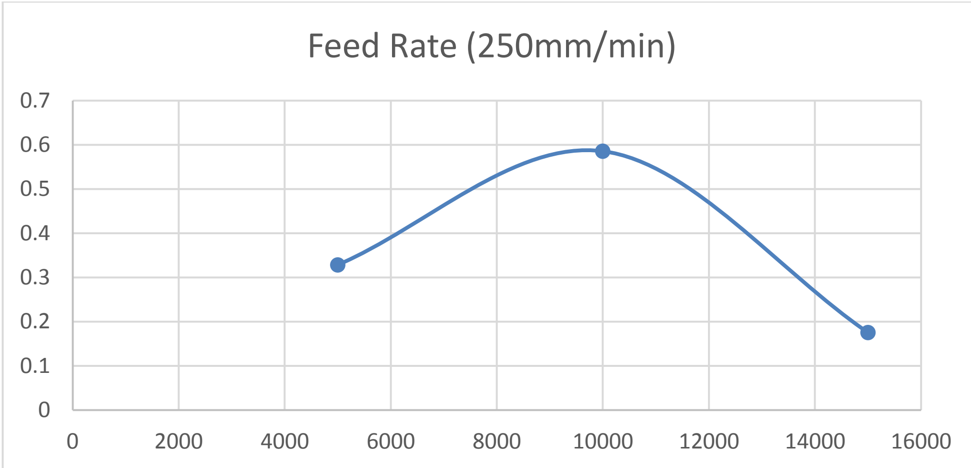

Figure 19 Feed Rate 250mm/min

DISCUSSION

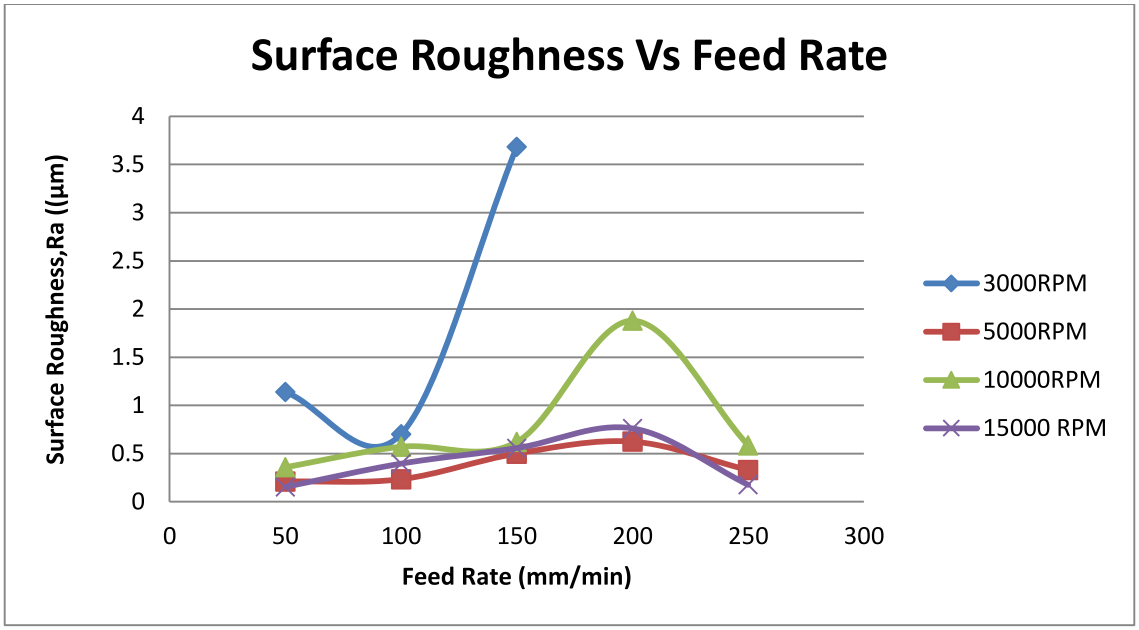

Figure 20 Feed Rate vs. Surface Roughness

From the result, it is showed that the lowest surface roughness that calculated is at the feed rate 50mm/min and 15000RPM spindle speed. Besides, as the feed rate increase, the surface roughness also increase until it reach 200mm/min feed rate because the surface roughness reduce on the 250mm/min. the highest surface roughness that recorded is at 150mm/min with 3000RPM.

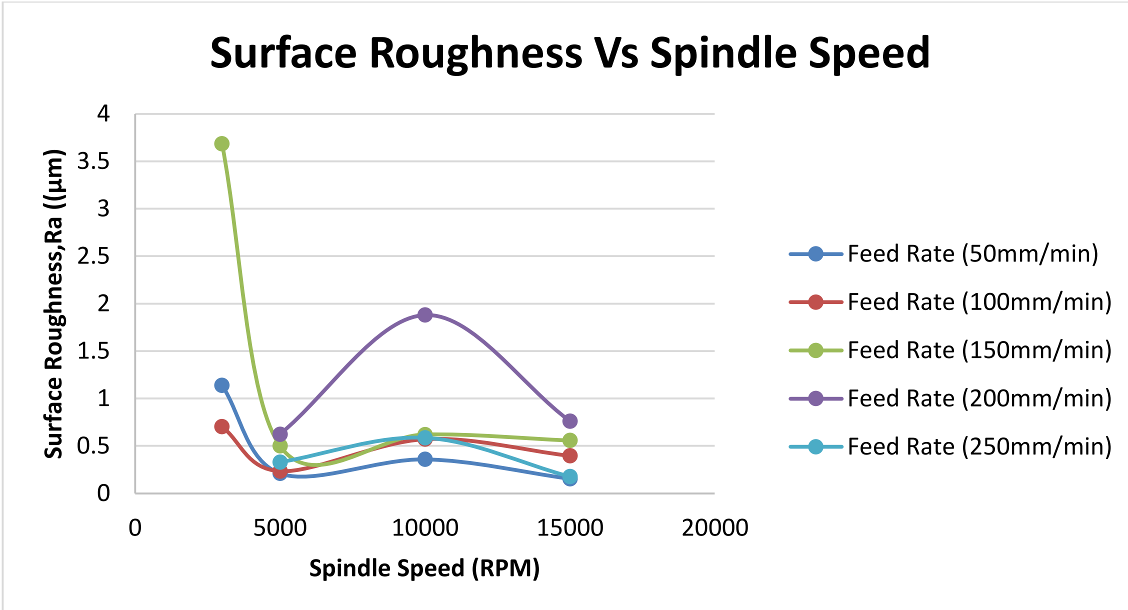

Figure 21 Spindle Speed vs. Surface roughness

Figures show the spindle speed against the surface roughness. The result shows that the lowest surface roughness recorded is at spindle speed 15000RPM and feed rate 50mm/min. the results also shows that the surface roughness increase at 10000RPM.

For spindle speed 3000RPM, results that managed to be obtained only at 50,100 and 150 mm/min while at 200mm/min, the tool broke and when the experiment repeated the results still the same which is the tool break. The tool broke maybe cause by the high feed rate with high spindle speed. The tool cannot stand the high speed cutting.

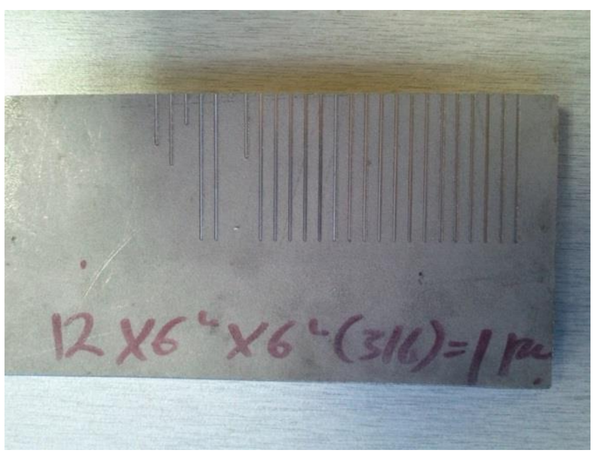

Figure 22 Stainless Steel 316L Sample

Figures 22 showed that there are some machining that not completed because of the tool broken. The milling should completed 2cm length. The tool broken is mainly because of the high feed rate with low spindle speed.

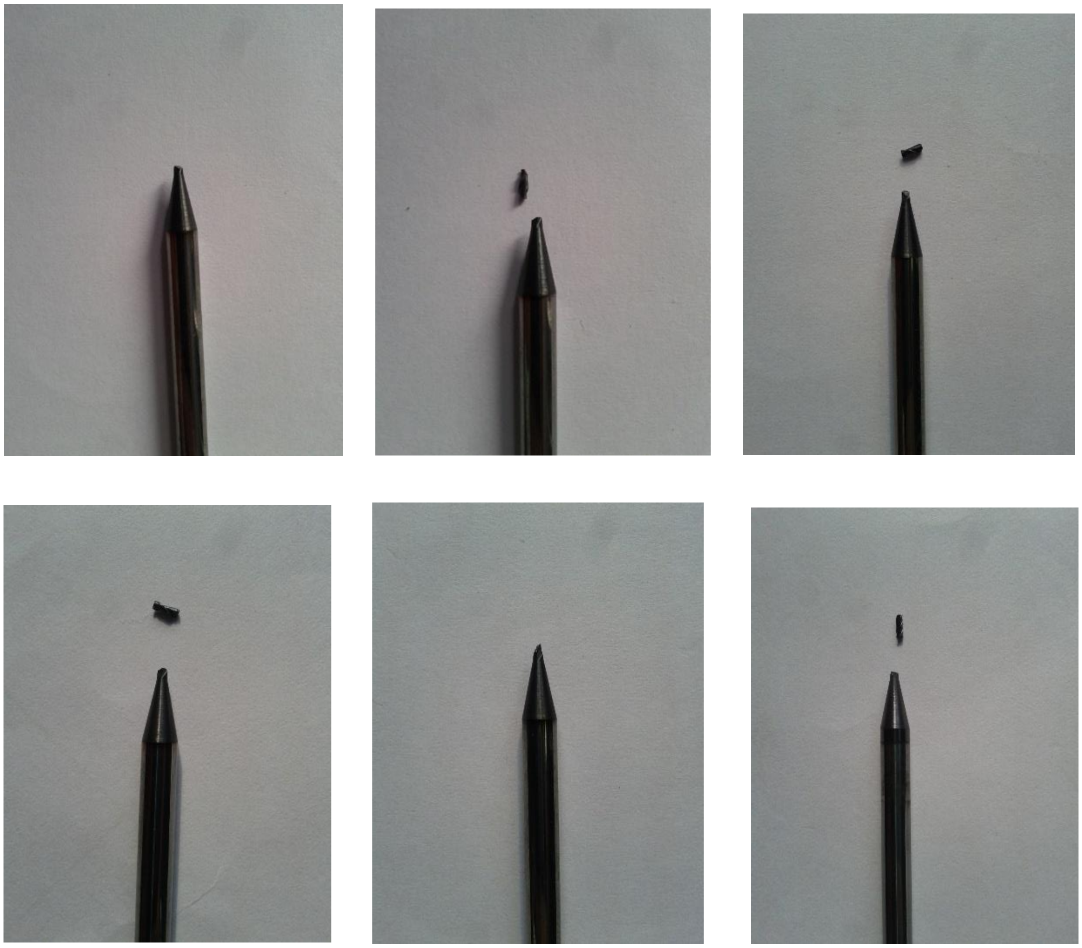

Figure 23 cutting tool used

Figures shows that the tool that broke after certain experiment. There were some causes that make the tool broken. One of them is the high value of feed rate with high value of spindle speed.

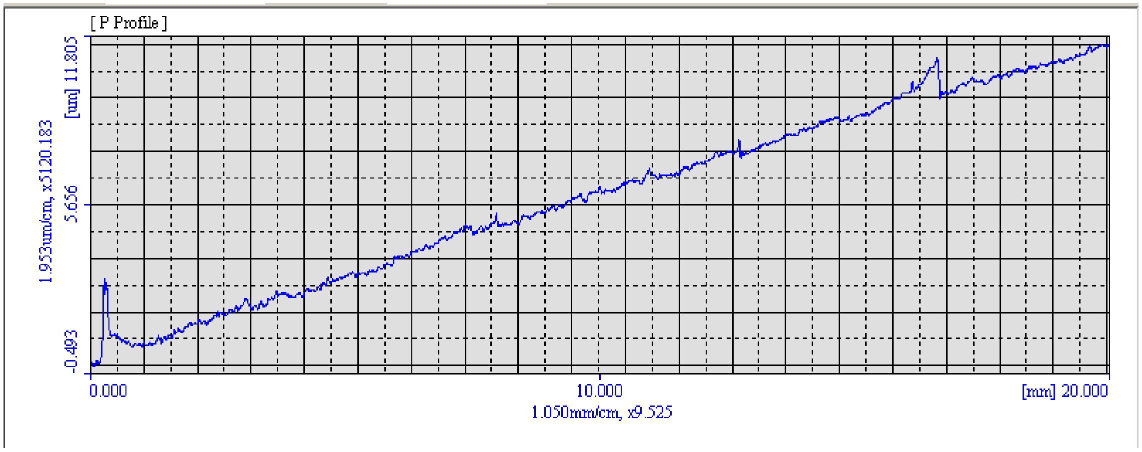

Figure 24 lowest surface roughness recorded

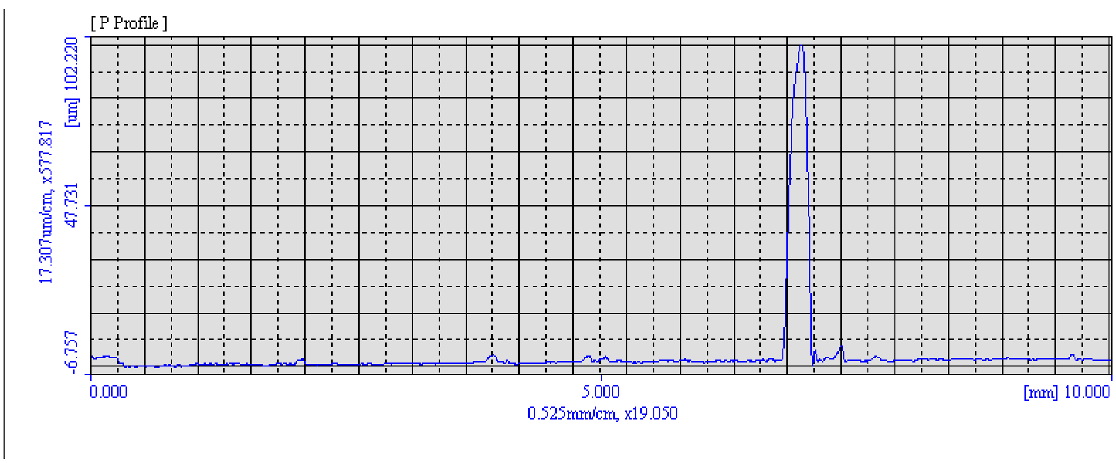

Figure 25 highest surface roughness recorded

CONCLUSION

Based on the result, we can conclude that the best parameter to find the lowest surface roughness would be at feed rate 50mm/min and spindle speed of 15000RPM. And it's also following the theory that the lower the feed rate, the lower the surface roughness.

From the results also it shows that there were some parameters or values that need to be avoided. The surface roughness of the material become high when it reach 10000RPM for spindle speed and also at the feed rate 200mm/min. which means that it is preferable for to use other parameters beside this two to get the lower surface roughness. It could be the milling process on 10000PM and 200mm/min was dealing with chatter. Chatter is a resonant phenomenon where the machine or workpiece vibrate. It can become quite violent and generate a distinctive loud noise.

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APPENDICES