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JUDUL: **EFFECTS OF TOOL PATH STRATEGIES ON SURFACE ROUGHNESS IN HIGH SPEED MACHINING**

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EFFECTS OF TOOL PATH STRATEGIES ON SURFACE ROUGHNESS IN HIGH SPEED MILLING

ABDUL RASHID BIN MUHAMMAD

Report submitted in partial fulfillment of the requirements for the award of the degree of Bachelor of Manufacturing Engineering.

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JUNE 2012

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Bachelor of Manufacturing Engineering.

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STUDENT'S DECLARATION

I hereby declare that the work in this thesis is my own except for quotation and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Dedicated to my late mother, Nor Rashidah Binti Mat Ali, whose love, support for me, and wishes for my success has encouraged me realize my potential. She lives on in our memories and is the greatest strength of my being. Al-Fatihah.

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ABSTRACT

In this project, two type of tool path strategies have been selected which are helical and back and forth tool path in order to determine the effects of both tool path strategies on surface roughness. The effects of the feed rate, cutting speed, and depth of cut on surface roughness were determined. Taguchi method was employed in order to optimize the machining parameters. The optimum machining parameter combination was determined by using analysis of signal-to-noise (S/N) ratio. The impact of the machining parameters on the surface roughness was determined by the use of analysis of variance (ANOVA). Measurement of surface roughness has indicated that helical has lowest surface roughness compare to back and forth tool path. Results from ANOVA also proved that helical tool path has significant impact on surface roughness. Furthermore, S/N ratio shows that each type of tool path has different combination of optimum machining parameters. From this project, it has been learned that helical tool path is better cutting tool path to be used in machining operation. This project would help engineer and machinist to select the best pocketing tool path for their product.

ABSTRAK

Di dalam projek ini, dua jenis cara laluan pemesinan mata alat telah dipilih iaitu ‘helical’ dan ‘back and forth’ supaya dapat menentukan kesan kedua-dua cara laluan pemotongan ke atas kekasaran permukaan. Kesan kadar suapan, kelajuan pemesinan dan kedalaman pemotongan telah ditentukan. Kaedah Taguchi telah digunapakai untuk mencari parameter pemesinan yang optimal. Parameter pemesinan yang optimal telah di cari menggunakan nisbah ‘signal-to-noise’ (S/N). Impak parameter pemesinan juga telah dikaji menggunakan ‘analysis of variance’ (ANOVA). Pengukuran kekasaran permukaan telah menunjukkan bahawa cara pemotongan ‘helical’ mempunyai nilai kekasaran yang terendah berbanding cara pemotongan ‘back and forth’. Keputusan dari ANOVA juga membuktikan bahawa cara pemotongan ‘helical’ mempunyai kesan yang ketara ke atas kekasaran permukaan. Daripada projek ini, cara pemotongan ‘helical’ adalah terbaik dan sesuai digunakan semasa operasi pemesinan. Kerana ini, projek ini akan membantu jurutera dan pengendali mesin untuk memilih cara pemotongan yang sesuai bagi menghasilkan produk mereka.

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V_c	Cutting speed
a_p	Percentage of the cutter diameter
a_e	Percentage of the cutter diameter
f_z	Feed rate per tooth
R	Roughing
F	Finishing
R_a	Average surface roughness
R_q	Root-mean-square roughness
SN	Signal-to-noise
n	Number of observations
$\bar{y}$	Mean of observed data
s_y^2	Variance of y
y	Observed data
A	Feed rate (mm/min)
B	Cutting speed (rpm)
C	Depth of cut (mm)
C %	Carbon (percentage)
Si %	Silicon (percentage)
Mn %	Manganese (percentage)
Cr %	Chromium (percentage)
Mo %	Molybdenum (percentage)

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION OF THE PROJECT

Generally, this project would give benefit to manufacturing industry especially for tool and die making industry. This is because this project would help manufacturing engineer and machinist to select best pocketing tool path strategy with given optimal machining parameters. The pocketing tool path strategy and machining parameters are defined in Computer Aided Manufacturing (CAM) software such as CATIA and Mastercam in order to produce machining program.

The result from this project would help engineer and machinist to produce machining program which produce best surface finish so that they can reduce time to fabricate the part or product. Usually, they used try and error method to determine best machining parameters where this method consumed much time and cost.

This project is expected to obtain result from the experiments which utilized Taguchi design of experiment. The experiments are based on given machining parameters which consist of three levels. Machining parameters used in the experiments are cutting speed, feed rate and depth of cut. All these parameters are specified into three levels which are low, medium and high.

Then, the value of surface roughness of determined machining parameters are checked to gain the result. The result is then compared with specified pocketing tool path strategy in order to determine best surface roughness and optimal machining parameters.

1.2 BACKGROUND OF THE PROJECT

Nowadays, high speed machining method is applied extensively in manufacturing industry. This is because high speed machining can improve surface quality of the product and also decrease machining cycle time with high efficiency if compare to conventional method. One of its major applications is to produce tool and die for plastic injection moulding. Others applications of high speed machining such as to make components for aeronautical and automotive, biomechanical and medical products and also electrical and electronic devices. The advantages of high speed machining are it is able to produce the product with high efficiency, accuracy and also quality.

Surface roughness is one of important aspect when to determine quality of the product. It is because surface roughness may affect some of properties of the product such as friction, wear, fatigue and others. There are many factors that contributed to surface roughness such as machining parameters, material of the workpiece and cutting tools, lubrication fluids and others. Another application of surface roughness is to check performance of the machine and cutting tool.

Taguchi method design of experiment is a method which used optimization of machining parameters in order to obtain high quality product, efficient process and decrease the manufacturing cost. Compare to other design of experiment method, Taguchi method is much easy to perform and not complex to understand. In this project, this method is used to find optimal machining parameters with good surface roughness which is confirmed by signal-to-noise (S/N) ratio and also analysis of variance (ANOVA).

Commonly, P20 is pre-hardened steel is a material used to produce tool and die making industry such as to make mould components and inserts. Other than that, it is also used to produce tool and die in die casting process. It is a chrome-moly alloy with carbon content of 0.4% and thermal conductivity of P20 is 29.0 w/(m °K).

Many experiments have been made in order to investigate surface roughness in high speed machining. Some of the researches investigate the effect of material or machining parameters on surface roughness while others investigate relation between material of workpiece and surface roughness. It is essential to determine on how to obtain optimal machining parameters and strategy that will help to minimize machining time and cost.

1.3 PROBLEM STATEMENT

Pocketing is a machining operation used to produce pocket whether it is open pocket or close pocket. This machining operation is commonly used in tool and die making industry to produce inserts or tool and die components. Other than that, pocketing also used to produce profiles depend on the geometry of the product.

Normally, pocketing machining operation leaves cutter mark which is depend on the machining parameters and tool diameter. The cutter mark leaved by this machining operation also depends by the selected pocketing tool path strategy defined in CAM software. Usually, there are five types of tool path strategies provided in CAM software such as helical, back and forth, spiral and others.

Because of that, the purpose of this project is to determine the effect of different pocketing tool path strategy on surface roughness of machined surface. This project utilized Taguchi method design of experiment which is designed according to specified machining parameters and levels.

1.4 OBJECTIVES OF THE PROJECT

There are three main objectives of this project which are:

- **To study effect of tool path strategies on surface roughness.**
  The experiments were performed by using specified machining parameters such as feed rate, cutting speed and depth of cut. These parameters used are divided by three levels which are low, medium and high. After the

machining process is done, the surface of the machined surface are checked using surface roughness tester to determine the effect.

- **To analyze data obtain from the experiment.**
  After the experiments were done, data from the experiments were analyzed using signal-to-noise (S/N) ratio and analysis of variance (ANOVA) to determined optimal machining parameters which can produce good surface roughness.

- **To decide which tool path strategy results optimal surface roughness.**
  After the result is analyzed, then the result for tool path is compared with each other to determine which tool path can produce optimal machining parameters.

1.5 SCOPES OF THE PROJECT

The scopes of the project include:

- **Different type of tool path strategy.**
  Selection of two different type of tool path cutting movement in machining parameter defined in CAD/CAM software which are helical and back and forth.

- **Machining parameters.**
  To used three machining parameters which are feed rate, cutting speed and depth of cut in order to determine optimal machining cutting for these parameters.

- **Machining conditions.**
  To use three levels of machining parameters conditions which are low, medium and high.

1.6 REPORT ORGANIZATION

In this project report, it is consists of five main chapters which is to explain specific information according to each chapter. Contents of all the chapters are arranged systematically in order to make this report more understandable and clear.

- **Chapter 1: Introduction**
  In this chapter, information displayed is the background, problem statement, objectives, scopes and others. This chapter is important because it used to introduce the specific problem which is lead to realization of this project.

- **Chapter 2: Literature Review**
  Detail information about this project is written in this chapter. Some of the information is about high speed machining, surface roughness, material used in this project and others.

- **Chapter 3: Methodology**
  Design of experiment is presented in this chapter. It gives details about the experiment that has been carried out so that data can be obtained for analysis process.

- **Chapter 4: Results and Discussions**
  Presented results from the experiment which illustrate in terms of tables and graphs. Also, details about data analysis are given in order to explain how the results are analyzed and compared.

- **Chapter 5: Conclusion and Recommendations**
  Presented conclusion of the project and determine whether the objectives of the project are achieved or not. Then, recommendation for further research also suggested in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 HIGH SPEED MACHINING

2.1.1 Definition

High speed machining (HSM) is the machining process that has many advantages compare to the conventional machining process such as able to produce high quality parts, increase productivity rate and high accuracy. Because of that, this machine is used widely in the industry, for example in tool and die making industry and to make components for aviation industry (Ekanayake and Mathew, 2007).

In 1931, Carl Solomon introduced the first concept of High Speed Machining where in his experiments he found that when cutting speed is increase, the cutting temperature increases up to a maximum value close to the melting point of the material and then the temperature is decreases with further increase in speed. This concept is shown in Figure 2.1 where temperature of the material is decrease when the cutting speed used is higher (Ekanayake and Mathew, 2007 and Pasko et al. 2002).

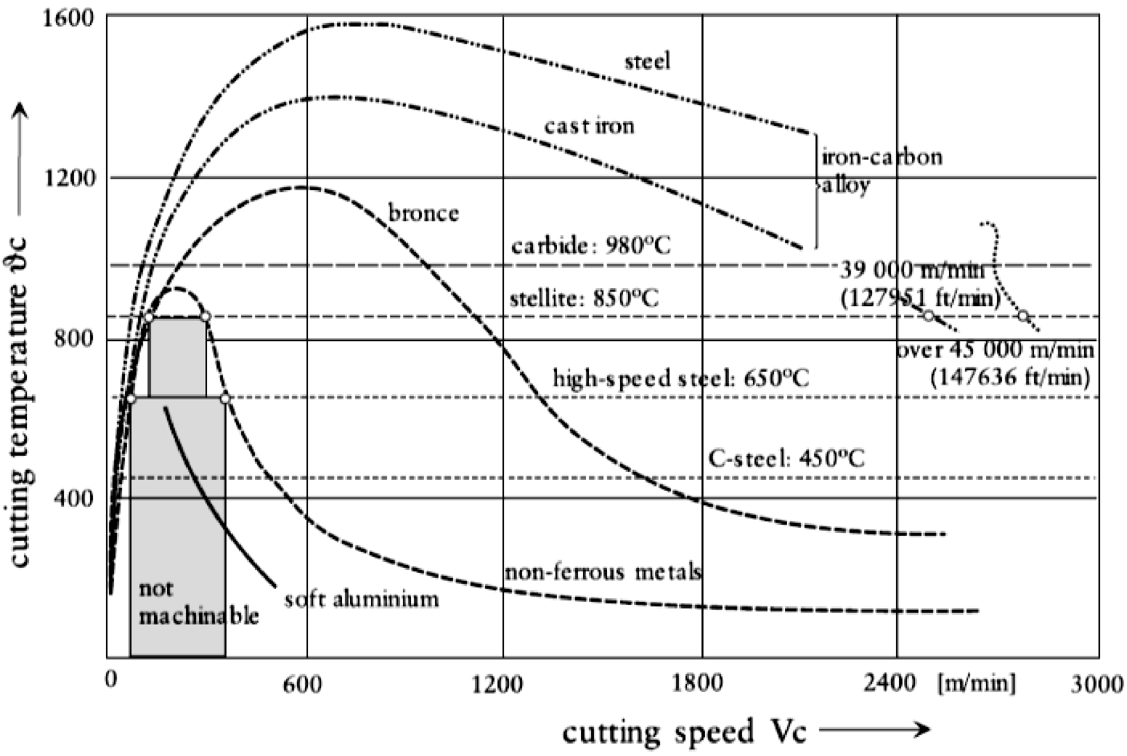

Figure 2.1 Cutting temperature vs. cutting speed

Source: Schulz (1999)

Ekanayake and Mathew (2007) have explained that high speed machining can be defined as a machining process that used higher speeds or higher feed rates while the depth of cut is smaller compare to the conventional machine. Thus, the chip produced by this process is small and the chip formation is much complex.

But Pasko et al. (2002) have stated that high speed machining is not only defined as high cutting speed but also high rotational speed machining, high feed machining and others. Pasko et al also referred this machining process as the operations which are carried out with special methods and equipment.

Schulz and Moriwaki (1992) explained that high speed machining is difficult to be defined because actual cutting speed achieved is influence by some factors such as material of the workpiece, the type of machining operation, cutting tool used in the machining operation and others. Because of that, there are many ways to define high speed machining which depends on some factors. For example in Figure 2.2, it shows that the range of cutting speed changes according to material of the workpiece.

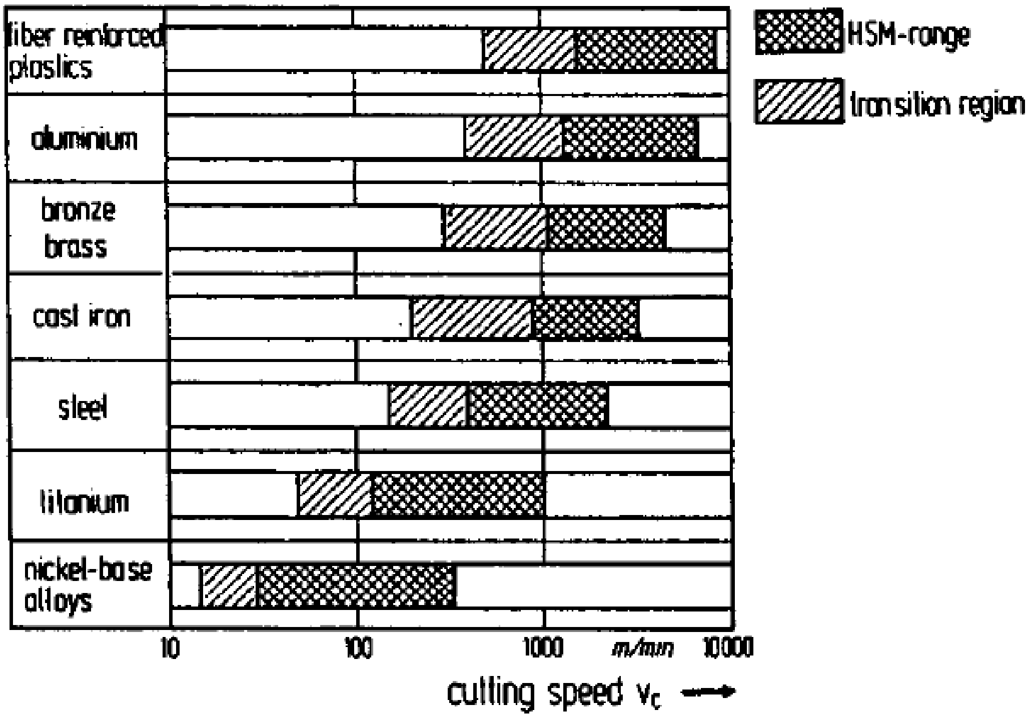

Figure 2.2 HSM cutting speed based on material

Source: Schulz and Moriwaki (1992)

2.1.2 Advantages

It has been known that high speed machining has many advantages compare to conventional machining process. Some of the advantages are this machining process able to produce high quality parts, increase productivity rates and also high accuracy. Other advantages of high speed machining are (Sandvik Coromant, 1999):

- Cutting tool life and durability can be increased.
- Shorten engagement time for the cutting edge.
- Minimum and constant tool deflection.
- Low radial forces on the tool and spindle.
- Low impact on the spindle bearing.

- Longer tools can be used without risk for vibration.
- Reduced cost when the machining process produces low material removal.
- Good surface finish can be achieved and thus minimize manual polishing process.
- Able to machine very thin walls.
- Produce accurate dimension and shape.
- Manual polishing process can be minimized because the machine able to produce good surface finish.

2.1.3 Disadvantages

Although, high speed machining is able to have many advantages in its application, at the same time it is also have some disadvantages. Some of disadvantages of high speed machining including (Sandvik Coromant, 1999):

- Guide ways, ball screws and spindle bearing wear in short of period.
- Expensive and higher maintenance cost.
- Need special knowledge about the process, programming, and interface.
- Skilled human resource with knowledge in high speed machining is hard to find and recruit.
- Longer period of trial and error process.
- Bigger consequences if mistake and errors occurred.
- Necessary to have good work and process planning.
- High precautions are compulsory when operating the machine.

2.1.4 Cutting Tools

There are four important criteria of cutting tools in high speed machining which are cutting alloy, cutting edge geometry, design and the interface between tool and machine spindle (Schulz and Moriwaki, 1992).

- **Cutting alloys**

  It is very important to know wear processes for cutting tools in order to choose right material for the machining operation. Diffusion wear usually occurred in high speed machining which is due to higher cutting temperature caused by higher cutting speed. Other than that, wear by abrasion and wear processes between workpiece and cutting edge also happened in high speed machining. Table 2.1 summarized specified workpice materials and suitable cutting tools for high speed machining processes.

Table 2.1 Suitable cutting tools for specified workpiece material

Workpiece Material	Suitable Cutting Tools
Steel	• Coated and uncoated hard metals. • Cermets. • Ceramics. • Polycrystalline boron nitride (PKB).
Cast iron	• Hard metals. • Cermets. • Silicon nitride. • Cubical boron nitride (CBN). • Polycrystalline boron nitride (PKB).
Special alloys (high alloy steels, titanium and nickel-based alloys)	• Ceramics. • Hard metals. • Cermets. • Carbide. • High-speed steel (HSS).
Light metal alloys	• Polycrystalline diamond (PKD).
Copper alloys	• Hard metals. • Polycrystalline diamond (PKD).
Fiber reinforced plastics	• Carbide.
Graphite	• Polycrystalline diamond (PKD). • Polycrystalline boron nitride (PKB).

Source: Schulz and Moriwaki (1992)

- **Cutting edge geometry**

  Optimization of cutting edge geometry is necessary so that sufficient tool life and low forces can be achieved. Table 2.2 summarized the specified workpiece materials and cutting edge geometry.

Table 2.2 Specified workpiece materials and suitable cutting and draft angle

Workpiece Material	Cutting Angle	Draft Angle
Aluminum wrought alloys	12° to 15°	13° to 15°
Steel	0°	16°
Cast iron	0°	12°
Copper and copper alloys	8°	16°
Fiber reinforced plastics	>20°	15° and 20°

Source: Schulz and Moriwaki (1992)

- **Design of tools**

  Basic designing directives for fast-rotating tools:

  1. Using ductile materials.
  2. Minimize the notch effect which is depends on the necessary chip space.
  3. Minimize the notch effect which is depends on the cutting edge design.
  4. Provide for form-fit connections.
  5. Maintain low masses for all tool components.
  6. Arrange center of mass on small radii.

- **Interface between spindle and tool**

  Interface between spindle and tool and on the clamping system are important because both of these things must be able to operate under difficult condition. The design requirements that need to fulfill are:

  1. Rapid automatic tool change.

2. High performance functions.
3. Highest changing and repeating accuracy.
4. Small balance error.
5. High concentricity.
6. High run-out tolerance and position accuracy.
7. Reduced centrifugal force influenced by small radial dimensions and masses.

2.1.5 Machine Components

Schulz and Moriwaki (1992) explained that the concept of the machine and components must be equipped with sophisticated machine design. Important components of the machine as follow:

- **Machine base**

  To ensure the good dynamic performance this component must be made from polymer concrete because of economical and fabrication aspect.

- **High frequency main spindles**

  This is most essential component in high speed machine. It is created as a motor spindle with an integrated motor. The frequency regulated motor is always situated between the bearings.

- **Carriages**

  In order to ensure this component is lightweight, it is needed to:

  1. Select suitable construction material.
  2. Build by lightweight construction design.
  3. Use finite element analysis to determine optimal geometric dimension.
  4. Determination of the impacts on adjoining machine components.

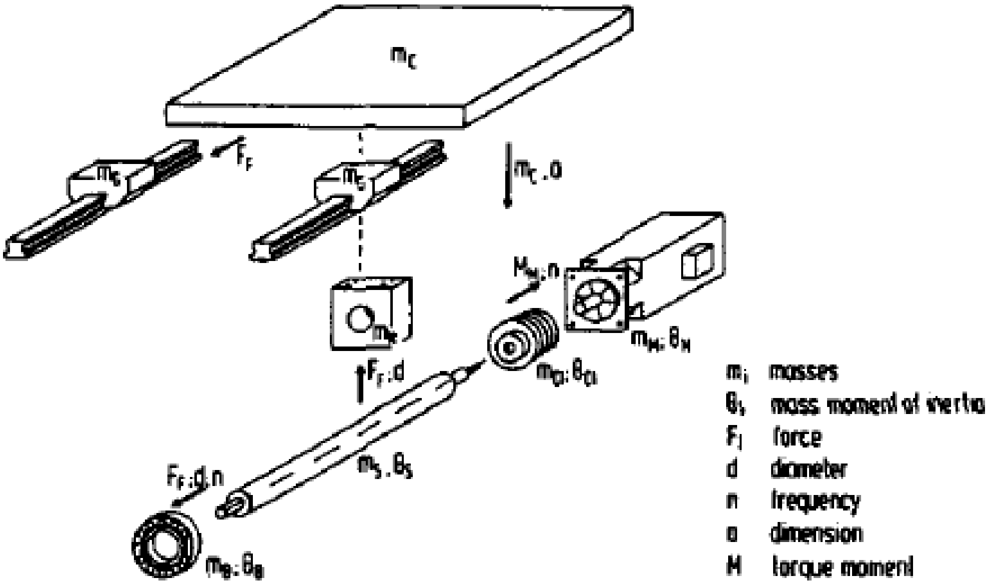

Figure 2.3 Effects of the lightweight construction moving components

Source: Schulz and Moriwaki (1992)

- **Guideways**

  Use antifriction guideways with roller or ball bearings because of high infeed speeds.

- **Feed drives**

  In order to reduce space allocations and increase infeed per spindle rotation it use multiple thread roller drives. This component must have good dynamic characteristics.

- **Controller**

  Use latest CNC controller system which offered large program capacity and high data processing rates.

- **Chip removal and coolant system**

  Chip removal systems must be able to remove high chip production per time unit during machining operation which is assisted by high pressure spray cooling systems.

- **Security devices**
  The cabin wall must be able to absorb the energy of a catapulting part without breaking due to high speed operation.

2.1.6 Applications

Generally, there are many industries that gain benefits in application of high speed machining such as aerospace, automotive, mould and die, electrical and electronic, biomechanical and medical, also other industries (Pasko et al. 2002 and Schulz and Moriwaki, 1992).

This is because the characteristic of high speed machining which can produce products more efficient, accurate, and quality if compare to conventional machining. It is also can reduce manufacturing time and cost because of reduction in machining processes compare to traditional methods.

Table 2.3 briefly describe the characteristic, applications, and examples of high speed machining in manufacturing sector around the world. As seen on Table 2.3, high material removal volume in time is required in aerospace and tool and die making industry. This characteristic is applied in light metals and steels and cast iron.

High surface quality is necessary to produce precise and special components in tool and die making, precision machining and optical industry. Then, low cutting force is required in aerospace, automotive industry and household appliances in order to produce components that have thin walled.

Other than that, high exciting frequency and heat dissipation through chips characteristics are necessary in precision machining and optical industry which applied vibration-free and distortion-free machining process.

Table 2.3 Characteristic, application and example of high speed machining

Characteristics	Applications	Examples
High material removal volume in time	• Light metals • Steels and cast iron	• Aerospace • Mould and die
High surface quality	• Precision machining • Special components	• Mould and die • Precision components • Optical industry
Low cutting forces	• Machining of thin-walled components	• Aerospace • Automotive • Household appliances
High exciting frequencies	• Vibration-free machining of difficult components	• Precision components • Optical industry
Heat dissipation through chips	• Distortion-free machining • Colder workpiece	• Precision components • Magnesium alloys

Source: Schulz (1999)

2.1.7 Recommendations

Machining operation in high speed milling should be divided into at least three procedures which are shown in Table 2.4. All of these procedures should be carried out with specified and optimised cutting tool. For example for roughing process suitable cutting tools are round insert cutters or end mills with big corner radius.

Table 2.4 Type of procedure and recommended cutting tool

Procedures	**Cutting tool**
Roughing	Round insert cutters, end mills with big corner radii
Semi-finishing	Round insert cutters, toroid cutters, ball nose end mills
Finishing	Round insert cutters (where possible), toroid cutters, ball nose end mills (mainly)
Restmilling (included in semi-finishing and finishing operation)	Ball nose end mills, end mills, toroid and round insert cutters

Source: Sandvik Coromant (1999)

Table 2.5 shows the comparison of speeds between conventional machining and high speed machining for specified workpiece material. As seen on the table, there are different in cutting speed between high speed machining and conventional machining process for both type cutting tools which are solid tools and indexable tools.

Table 2.5 Conventional vs. HSM

Work material		**Solid tool (end mills, drills)** ***WC, coated WC, PCD, ceramic***		**Indexable tools (shell mills, face mills)** ***WC, ceramic, sialon, CBN, PCD***	
		Typical cutting speed (m/min)	**High cutting speed (m/min)**	**Typical cutting speed (m/min)**	**High cutting speed (m/min)**
Aluminum		>305 (*WC, PCD*)	>3050 (*WC, PCD*)	>610	>3658 (*WC, PCD)*
Cast iron	Soft	152	366	366	1219 (*sialon, ceramic*)
	Ductile	107	244	244	914 (*ceramic*)
Steel	Free mach. steel	107	366	366	610
	Alloy	76	244	213	366
	Stainless	107	152	152	274
	Hardness HRC65	24	122	30 (*WC*) 91 (*CBN, ceramic*)	46 (*WC*) 183 (*CBN, ceramic*)
Titanium		38	61	46	91
Superalloy		46	76	84 (*WC*) 213 (*sialon*)	366 (*sialon, ceramic)*

Source: Pasko et al. (2002)

Table 2.6 shows typical cutting data for solid carbides end mills to machine hardened steels which have HRC 45-58. This data is categorised into four type of processing which are roughing, semi-finishing, finishing and superfinishing. Cutting speed is much higher in finishing process compare to roughing process in order to get high surface quality and high dimensional accuracy.

Table 2.6 Typical cutting data for solid carbides end mills with Ti(C, N) or TiAlN – coating in hardened steel (HRC 45-58)

Type of processing	**V_c (m/min)**	**a_p (%) of the cutter diameter**	**a_e (%) of the cutter diameter**	**f_z (mm/tooth)**
Roughing	100	6 – 8	35 – 40	0.05 – 0.1
Semi-finishing	150 – 200	3 – 4	20 – 40	0.05 – 0.15
Finishing and super-finishing	200 – 250	0.1 – 0.2	0.1 – 0.2	0.02 – 0.2

Source: Sandvik Coromant (1999)

Table 2.7 shows high speed machining cutting data obtain by experience. This data shows that the cutting speed is higher for high speed machining compare to conventional machining process for specified materials. Cutting speed for roughing and finishing process also different where finishing process used higher cutting speed.

Table 2.7: HSM cutting data by experience (R – roughing, F – finishing)

Material	**Hardness**	**Conv. V_c**	**HSM V_e,R**	**HSM V_e,F**
Steel 01.2	150HB	<300	>400	<900
Steel 02.1/2	330HB	<200	>250	<600
Steel 03.11	300HB	<100	>200	<400
Steel 03.11	39 – 48 HRC	<80	>150	<350
Steel 04	48 – 58 HRC	<40	>100	<250
GCI 08.1	180HB	<300	>500	<3000
Al/Kirksite	60 – 75 HB	<1000	>2000	<5000
Non-ferr	100HB	<300	>1000	<2000

Source: Sandvik Coromant (1999)

2.2 SURFACE ROUGHNESS

2.2.1 Surface Texture

Definition of surface texture is used widely but it is complex to be defined because sometimes surface finish are described as rough, good smooth, glossy, mirror and others. This is inaccurate because the meaning of surface finish is different for some people and some application.

Surface texture can be divided into four components which are roughness, waviness, lay and flaws as shown in Figure 2.4 (Lou et al. 1998 and Kalpakjian and Schmid, 2010). But in some journals and articles, surface texture can be described into three components which are roughness, waviness and form errors as shown in Figure 2.5 (Lou et al. 1998 and Tabenkin, 1999).

Roughness is an irregularity of the surface which is consists of closed space peaks and valleys. It is can be measured on its height, width, and distance. This irregularity is influenced by geometry, size and motion of the cutting tool (Lou et al. 1998 and Tabenkin, 1999).

Waviness is regular spacing which is resulted from distance between tool and workpiece during machining process. This is caused by instability and vibration of the machine and cutting tool (Tabenkin, 1999). It can be measured by *waviness width* (space between the crests of the waves) and *waviness height* (valleys of the waves) (Kalpakjian and Schmid, 2010).

Flaws are unwanted surface defects such as scratches, cracks, holes, depressions, seams, tears, or inclusions (Kalpakjian and Schmid, 2010).

Lay is directionally predominant surface pattern which is influenced by machining operations (Lou et al. 1998). There are four types of lay which are parallel, perpendicular, angular and nondirectional lay (Kalpakjian and Schmid, 2010).

Error of form is a magnitude which is because of lack of straightness or flatness in the machining operations. This error might occur many times as the machine will follow the same out-of-straight cutting tool path (Tabenkin, 1999).

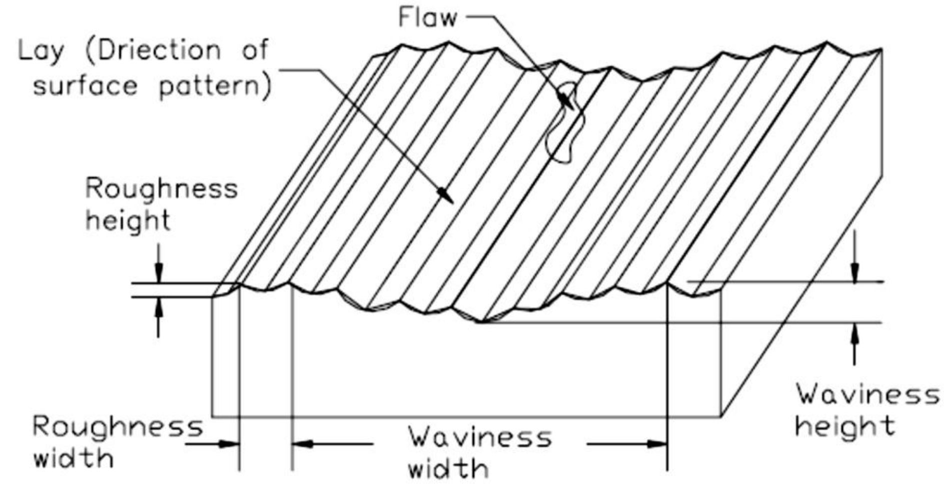

Figure 2.4 Roughness and waviness profiles

Source: Lou et al. (1998)

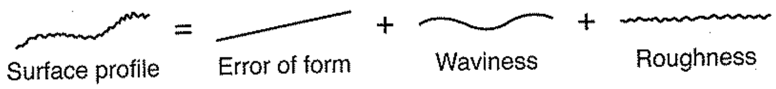

Figure 2.5 Components of surface texture

Source: Kalpakjian and Schmid (2010)

2.2.2 Parameters

There are some parameters that are commonly used to determine surface roughness. Some of them are average surface roughness (R_a), root-mean-square roughness (R_q *or RMS*) and maximum roughness height (R_t) (Kalpakjian and Schmid, 2010).

- Average surface roughness or arithmetic mean value (R_a) is average height from centre line average (*CLA*) as shown in Figure 2.4. It can be defined as shown in Eq. (2.1)

$$R_a = \frac{h_a + h_b + h_c + \dots + h_n}{n} \tag{2.1}$$

Where,
h_n is distance from centre line average to reading.
n is the number of readings.

- The root-mean-square roughness (R_q *or RMS*) as defined in Eq. (2.2)

$$R_q = \sqrt{\frac{h_a^2 + h_b^2 + h_c^2 + h_n^2}{n}} \tag{2.2}$$

- The maximum roughness height (R_t *or* R_{max}) is defined as the distance between lowest valley to highest peak. It is mainly used to determine how much material should be removed to have smooth surface.

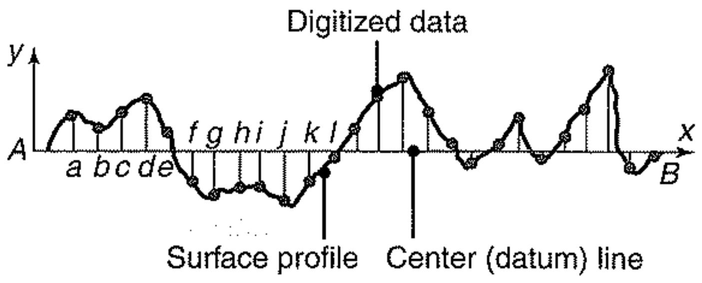

Figure 2.6 Coordinates for surface roughness measurement

Source: Kalpakjian and Schmid (2010)

2.2.3 Measurement Instruments

Kalpakjian and Schmid (2010) have explained some instruments that are used to measure and record surface roughness. The instruments that are can be used such as:

- **Surface profilometers**

  This instrument used a diamond stylus which moves along a straight line (distance travels called cutoff) over the surface while measuring surface roughness. A profilometer use a diamond stylus which travels along a straight line over the surface.

- **Optical-interference microscopes**

  The instrument works by produce light and it is reflected by reflective surface and records the interference fringes and waves.

- **Atomic-force microscopes (AFMs)**

  Mechanism of this machine same as surface profilometer but it is equipped with a laser which used to measure position of the probe. It can measure with high accuracy and with atomic scale vertical resolution.

2.2.4 Factors

Surface roughness is affected by some factors such as machining parameters, tool geometry, material of workpiece and cutting tool, lubrication fluid types, and vibration between machine, cutting tool and workpiece (Tabenkin, 1999 and Oktem, 2009).

One of the factors is machining parameters which can be controlled during machining process. The parameters include cutting speed, feed rate depth of cut. Another factor that affects surface roughness is cutting tool geometry such as nose radius, rake angle and cutting speed. Besides that, material and quality of cutting tool also influenced surface irregularities (Lou et al. 1998 and Zhang et al. 2010).

Other factors that influenced surface roughness include workpiece material, type of lubrication fluid used during machining, and also vibration between the workpiece, machine and cutting tool (Jiang et al. 2010 and Prakasvudhisarn et al. 2009).

2.3 TAGUCHI METHOD

2.3.1 Introduction

Dr. Genichi Taguchi is an expert in quality management who has introduced a statistical design of experiment which called as Taguchi Method. This method is systematic approach for optimization of various process parameters which could improve performance and quality while reduce cost.

It works by eliminating the causes of poor quality and then makes the process performance insensitive to variation. Because of that, this method has been used extensively in engineering analysis and research so that a high quality process can be designed (Antony, and Antony, 2001; Gopalsamy et al. 2009, and Cicek et al. 2011).

Taguchi method used orthogonal array in designing experiments that usually requires only a fraction of the full factorial combinations. Orthogonal array ensure the design is balanced so that factor levels are weighted equally. Because of this, each factor can be evaluated independently of all the other factors, so the effect of one factor does not influence the estimation of another factor.

The advantage of orthogonal array is it can be applied to an experiment which consist a large number of design factors. But, orthogonal array also has disadvantages as it could not be applied to factors that vary in time which cannot be calculated exactly (Katleen et al. 1995).

2.3.2 Concepts

Katleen et al. (1995) have stated there are four general concepts of quality proposed by Taguchi:

- **Quality should be designed into the product from the start, not by inspection and screening.**

  Quality improvement should begin at the design stages, and then follow during production phase. Means that quality problem should be prevented but not repaired.

- **Quality is best achieved by minimizing the deviation from the target, not failure to confirm to specifications.**

  Reducing variation is the key to improving quality which means it should be insensitive to uncontrollable environment and surrounding factors.

- **Quality should not be based on the performance, features or characteristics of the product.**

  Performance, features or characteristics cannot indicate quality of a product but indicate the capability and functionality of the product.

- **The cost of quality should be measured as a function of product performance variation and the losses measured system-wide.**

  The deviation from a target are measured in terms of the overall life cycle cost of the product which includes cost of rework, inspection, warranty servicing, returns and replacement.

2.3.3 Taguchi Process Diagram

Figure 2.7 shows a process that has been affected by various factors that could influence response or outcome from the process.

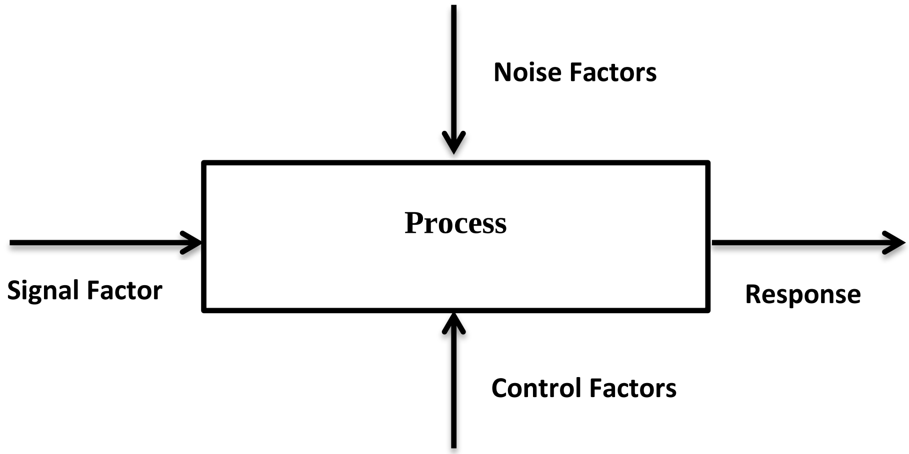

Figure 2.7 Process diagram

Source: Kshirsagar et al. (2012)

- **Process diagram:** Visualize how some factors affecting a process.

- **Signal factor:** Signal factors are factors that affect the mean performance of the process.

- **Control factors:** Control factors are factors that can be controlled under normal production conditions.

- **Noise factors:** Noise factors are factors that either too difficult or too expensive to control under normal production conditions.

- **Response:** Response is the result of the process which is influenced by signal factor, changes in control factors and noise factors. Usually, response is defined in term of signal-to-noise ratio (S/N ratio) which is calculated from equations below:

i. **Larger is better:** Used when the goal is to maximize the response.

$$SN = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right) \tag{2.3}$$

ii. **Nominal is best:** Used when the goal is to target the response and S/N ratio is based on standard deviations.

$$SN = 10\log\left(\frac{\bar{y}}{s_y^2}\right) \tag{2.4}$$

iii. **Smaller is better:** Used when the goal is to minimize the response.

$$SN = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}y_i^2\right) \tag{2.5}$$

Where,
$\bar{y}$ is the mean of observed data.
s_y^2 is the variance of y.
n is the number of observations.
y is the observed data (Nalbant et al. 2007).

2.3.4 Advantages

Esme (2008) has explained that important step in Taguchi method is to optimize process parameters which helped to obtained high quality with cost reduction. Compare to the classical approach, this method is much easier to implement. Other advantages of Taguchi method such as:

- Highlight the average performance characteristic value which is close to the target value.
- Easy to be implemented.
- Limit the scope of a research.

2.3.5 Disadvantages

Esme (2008) also stated that in his research few disadvantages of Taguchi method which are:

- Not accurately emphasize which parameters have much impact on the performance characteristic value.
- Could not be used with all relationships between all variables
- Hard to calculate interactions between parameters.
- Not suitable for a dynamic process.

CHAPTER 3

METHODOLOGY

3.1 FLOWCHART OF THE PROJECT

Figure 3.1 shows the flowchart of the project where in this flowchart it indicates the important steps during realizing this project. It is started from project proposal and finished when final report or thesis is submitted.

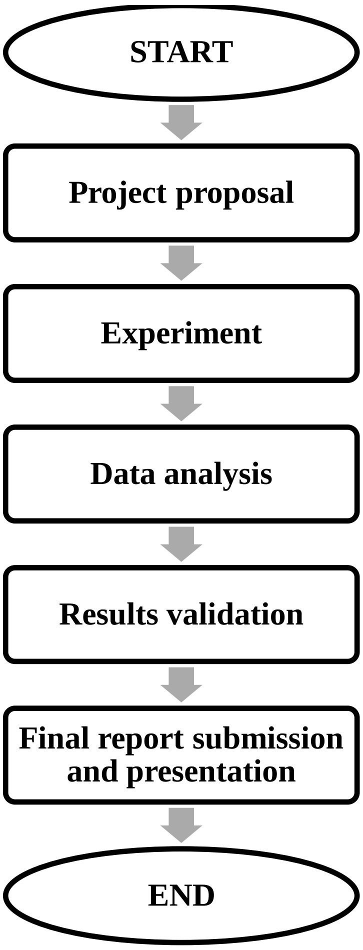

Figure 3.1 Flowchart of the project

The most important part of this project is experiment. In this step, design of experiment was constructed which using Taguchi Method which used three different factors and levels means that each factor has three levels. Three machining parameters have been selected as control factors which are feed rate, cutting speed and depth of cut. These factors are then divided into three levels which are low, medium and high. Full explanation about the experiment will be explained on another topic in this chapter.

After the experiment is performed, data is measured by surface roughness tester to find the value of surface roughness, R_a. Then, data is analyzed to find signal-to-noise ratio (S/N ratio) in order to find optimal machining parameters. After that, analysis of variance (ANOVA) was used to investigate and model the relationship between a response variable and one or more predictor variables. Detail about this stage is discussed on Chapter 4.

Another step is result validation where during this stage optimal machining parameters that have been analyzed are confirmed by carried out an experiment. This is important as to know whether the optimal machining parameters are correct or not. Then, noise factors which are from uncontrollable factors such as vibration and chatters can be estimated. After that, conclusions are made in order to know whether this project successfully meets the objectives and propose some recommendation for further research.

Last step of this project is preparation of the final report and presentation. All of the works done during completing this project is documented in this report which includes related information about this project, project implementation, results and others. Then, a presentation about the project is performed in front of respected panel and supervisor to evaluate this project.

3.2 DESIGN OF EXPERIMENT

In this project, the experiment was designed step by step according to Taguchi method as shown in Figure 3.2. This is because using this method it is possible to get effective results with doing less experiment if compare to full factorial design of experiment. In order to determine quality of a machined surface, smaller is better principle has been used to calculate the results from the experiments.

1. **Formulation of the problem.**
2. **Identification of the output performance characteristics.**
3. **Identification of control factors, noise factors and signal factors**
4. **Selection of factors levels and the degrees of freedom.**
5. **Design of an appropriate orthogonal array (OA).**
6. **Preparation of the experiment.**
7. **Running of the experiment with appropriate data collection.**
8. **Statistical analysis and interpretation of experimental results.**
9. **Validation of the results.**

Figure 3.2 General steps of Taguchi Method

Source: Antony and Antony (2001)

In this project, there are two experiments for two type of cutting method or tool path which are Helical and Back and Forth. Parameters used in this project are feed rate (mm/min), cutting speed (rpm) and depth of cut (mm) which were selected as control factors and their levels were determined as shown in Table 3.1. The range of the feed rate was selected to be 240 – 480 mm/min and cutting speed was selected in the range between 2000 – 3000 rpm. The depth of cut was chosen to be in the range of 0.3 – 0.5 mm while the levels for control factors are low, medium and high.

Table 3.1 Experiment factors and their levels

Parameters	A – Feed (mm/min)	B – Speed (rpm)	C – Depth of cut (mm)
Level 1 (low)	240	2000	0.3
Level 2 (medium)	360	2500	0.4
Level 3 (high)	480	3000	0.5

The fifth step of the Taguchi method is to select an appropriate orthogonal array where it can provide an effective experimental performance with a minimum number of experimental trials. The configuration of orthogonal arrays is determined with respect to total degrees of freedom (DOF) of the targeted function. Degrees of freedom are defined as the number of comparisons between machining parameters that need to be made to determine which level is better and specifically how much better it is.

The total degrees of freedom for the parameters are equal to 8 because each parameter has three levels. Theoretically, the degrees of freedom for the orthogonal array can be more than or at least equal to the determined machining parameters. Because of that, an L_9 orthogonal array with three columns and nine rows was implemented in this study as shown in Table 3.2. Each row of this table indicates an experiment with different combination of parameters and their levels.

Table 3.2 Taguchi L_9 experiment design

Experiment no.	**Variables**	**A (mm/min)**	**B (rpm)**	**C (mm)**
1	$A_1B_1C_1$	240	2000	0.3
2	$A_1B_2C_2$	240	2500	0.4
3	$A_1B_3C_3$	240	3000	0.5
4	$A_2B_1C_2$	360	2000	0.4
5	$A_2B_2C_3$	360	2500	0.5
6	$A_2B_3C_1$	360	3000	0.3
7	$A_3B_1C_3$	480	2000	0.5
8	$A_3B_2C_1$	480	2500	0.3
9	$A_3B_3C_2$	480	3000	0.4

3.3 EXPERIMENT PROCEDURE

3.3.1 Material and Cutting Tool Selection

In this project, AISI P20 (DIN 1.2311) has been selected as the material to be used in the experiment. AISI P20 is chromium-molybdenum alloyed steel which is mainly used to make plastic mould and zinc die-casting tooling. It is also used for high tensile application such as shafts, gears and others. The properties of this steel are it is quenched and tempered plastic mould steel. This material hardness is 280 – 325 HB and has tensile strength about 950 – 1100 MPa. AISI P20 has good machinability, better polishability and capable for texturing. Table 3.3 indicates the composition of AISI P20.

Table 3.3 The composition of AISI P20

C %	**Si %**	**Mn %**	**Cr %**	**Mo %**
0.28 - 0.40	0.20 – 0.80	0.60 – 1.00	1.40 – 2.00	0.30 – 0.55

Source: Song et al. (2006)

The cutting tool used for experiment was micrograin solid carbide end mill as shown in Figure 3.3. This tool diameter is 6mm, two flute end mill and has helix angle of 30°. This tool hardness is about 30 HRC. Based from tool catalogue, this tool can achieve maximum cutting speed about 3200 min^{-1}.

Figure 3.3 Two flute micrograin solid carbide end mill

3.3.2 Computer Aided Manufacturing

In this project, CATIA V5 has been used to generate machining programs that have been used in the experiment. Firstly, 3D model has been designed using Part Design module to create the experiment sample where the dimension is 45 mm x 25 mm x 25 mm as shown in Figure 3.4.

Figure 3.4 Experiment sample

After 3D model has been designed, then it is used in Prismatic Machining module to create the simulation of the machining operation where pocketing operation has been selected. Here, the tool path strategies selected are Inward Helical and Back and Forth as shown in Figure 3.5 and 3.6 respectively.

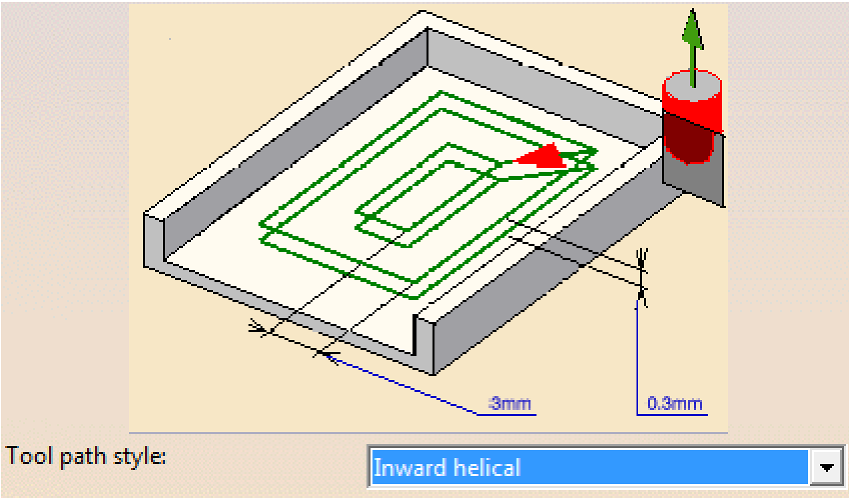

Figure 3.5 Inward helical tool path strategy.

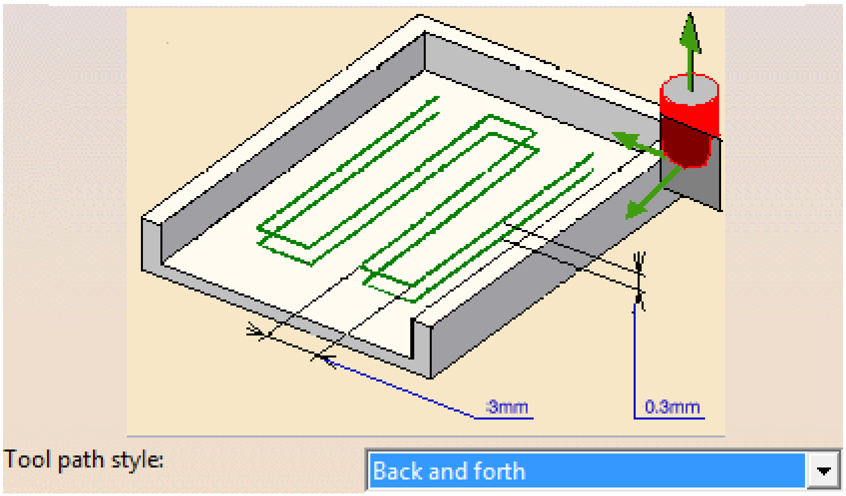

Figure 3.6 Back and forth tool path strategy.

Based on Taguchi method experimental design, some parameters have been changed according to the Table 3.2 in order to generate machining operation simulation and program. Figure 3.7 shows the option to select maximum depth of cut used in this project where it is range from 0.3 mm to 0.5 mm.

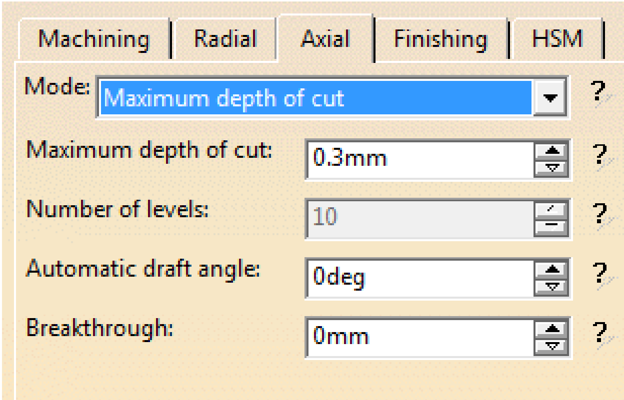

Figure 3.7 Maximum depth of cut

In Figure 3.8, it shows option to select feed rate used in the experiment which is range about 240 mm/min – 480 mm/min. Figure 3.9 shows the option to select cutting speed used in the experiment which is range from 2000 rpm to 3000 rpm.

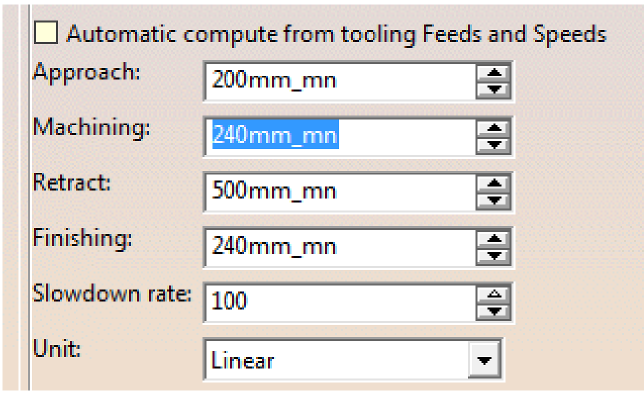

Figure 3.8 Example of machining feed rate of the experiment

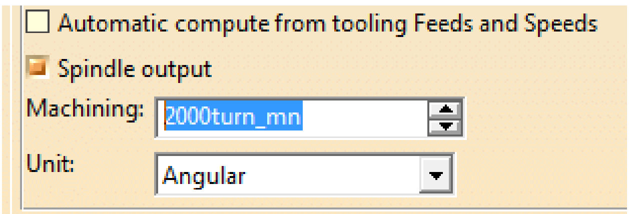

Figure 3.9 Spindle speeds option

Another option that is changed is cutting tool used in the experiment where it shown in Figure 3.10. The cutting tool has been used is flat end mill diameter 6 mm. The tool is selected from tool library inside the CATIA V5.

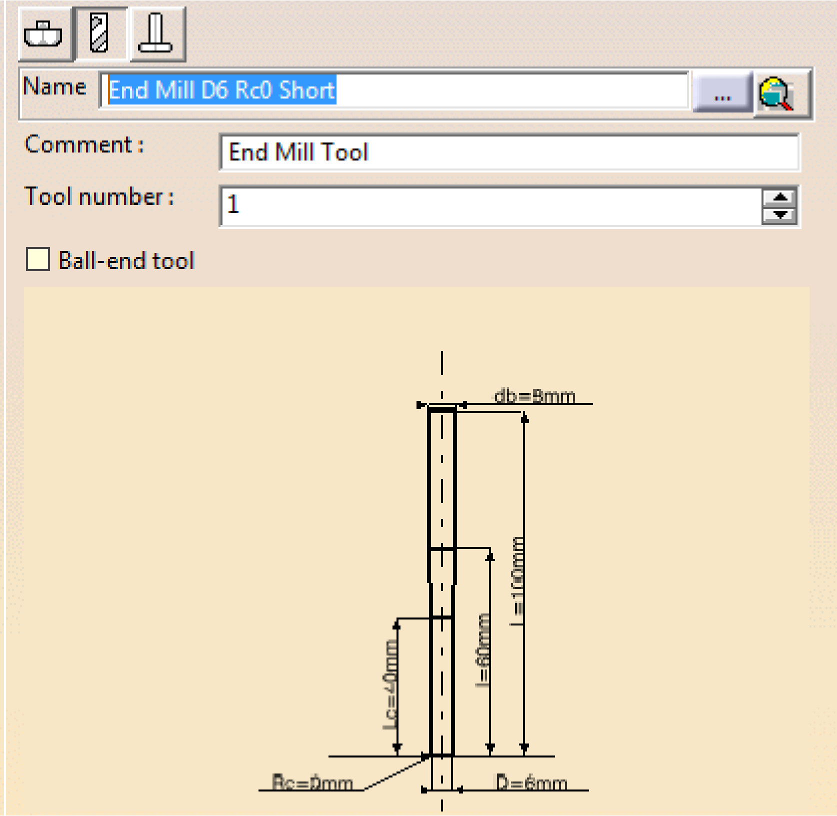

Figure 3.10 Cutting tool option

After all the parameters have been changed, the machining operation simulation as shown in Figure 3.11 is created in order to verify the tool path and check if tool collision is happened. From this simulation machining operation is then generate into NC code where it is transfer to the machine.

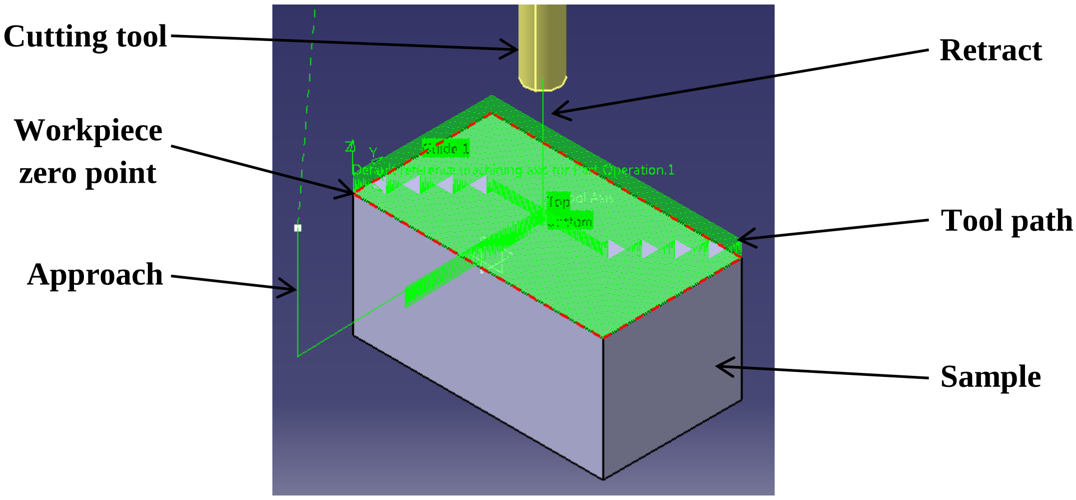

Figure 3.11 Machining operation simulations

3.3.3 CNC Machining Operation

In the experiment, Makino KE55 milling machine was used as shown in Figure 3.12. This machine use FANUC 20i controller for Computer Numerical Control (CNC) application. In order to carry out the experiment, Direct Numerical Control mode has been chosen where the NC codes are transferred directly from computer into controller using NC Links software (free version). Maximum spindle speed of the machine is 4000 min^{-1}.

Figure 3.12 Makino KE55 milling machine

3.3.4 Surface Roughness Measurement

After the machining has been done, the samples were taken to Metrology laboratory to measure the surface roughness. The surface roughness tester used is Zeiss Surfcom 130A surface roughness tester as shown in Figure 3.13. The settings of the tester as follow:

- Cutoff type : Gaussian
- Tilt correction : Least square straight
- Measurement length : 40 mm
- Cutoff wave length : 0.8 mm
- Measurement magnification : X 2K
- Measurement speed : 0.3 mm/s
- Pickup : Standard pickup
- Cutoff ratio : 300
- Radius of stylus tip : 2 µm
- Tolerance : ± 0.1 mm

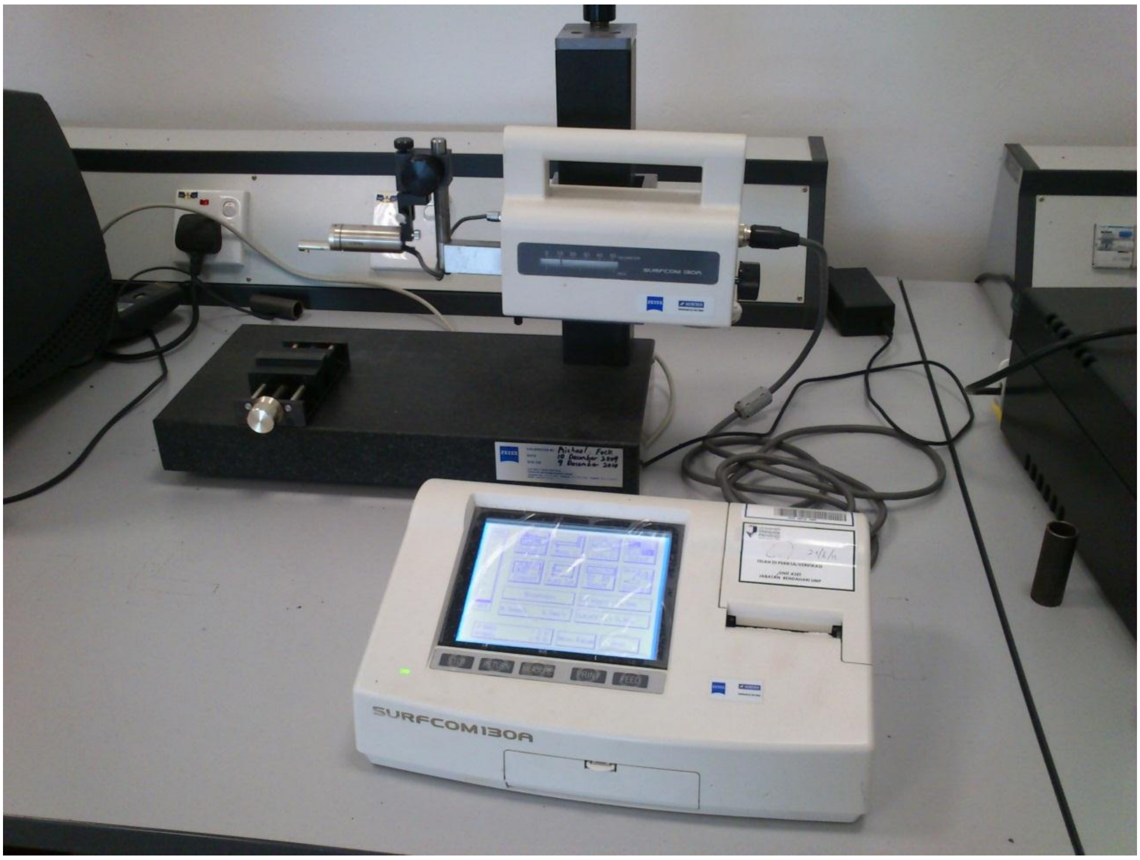

Figure 3.12 Surface roughness tester

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 EXPERIMENTAL RESULTS FOR SURFACE ROUGHNESS

Table 4.1 and 4.2 shows the experimental results of surface roughness for two types of tool path strategies which is Helical and Back and Forth respectively. There are three trials carried out and average value for surface roughness has been calculated.

Table 4.1 Results for helical tool path strategy

Exp no.	A (mm/min)	B (rpm)	C (mm)	Surface Roughness (µm)			
				Trial 1	**Trial 2**	**Trial 3**	**Mean**
1	240	2000	0.3	0.776	0.740	0.776	0.7640
2	240	2500	0.4	0.500	0.580	0.578	0.5527
3	240	3000	0.5	0.375	0.317	0.345	0.3457
4	360	2000	0.4	1.258	1.304	1.322	1.2947
5	360	2500	0.5	0.993	0.936	0.916	0.9483
6	360	3000	0.3	1.193	1.214	1.173	1.1933
7	480	2000	0.5	0.682	0.611	0.631	0.6413
8	480	2500	0.3	1.324	1.384	1.356	1.3547
9	480	3000	0.4	1.074	1.100	1.010	1.0613

From Table 4.1, it shows mean of surface roughness for helical tool path strategy experiment. It can be summarized that from this table surface roughness is increased while feed rate is increased. This is because the lowest value for surface roughness is when feed rate at 240 mm/min, cutting speed at 3000 rpm and depth of cut at 0.5 mm. While, the highest value for surface roughness is when feed rate at 480 mm/min, cutting speed at 2500 rpm and depth of cut at 0.3 mm.

Table 4.2 Results for back and forth tool path strategies

Exp no.	A (mm/min)	B (rpm)	C (mm)	Surface Roughness (μm)			
				Trial 1	Trial 2	Trial 3	Mean
1	240	2000	0.3	0.705	0.713	0.719	0.7123
2	240	2500	0.4	0.563	0.525	0.558	0.5487
3	240	3000	0.5	0.704	0.700	0.716	0.7067
4	360	2000	0.4	1.127	1.142	1.114	1.1277
5	360	2500	0.5	0.615	0.548	0.595	0.5860
6	360	3000	0.3	0.911	0.899	0.908	0.9060
7	480	2000	0.5	1.351	1.299	1.375	1.3417
8	480	2500	0.3	0.761	0.720	0.770	0.7503
9	480	3000	0.4	0.718	0.815	0.710	0.7477

From Table 4.2, it shows mean of surface roughness for back and forth tool path strategy experiment. It can be summarized that from this table same as helical tool path strategy, surface roughness is increased while feed rate is increased. This is because the lowest value for surface roughness is when feed rate at 240 mm/min, cutting speed at 2500 rpm and depth of cut at 0.4 mm. While, the highest value for surface roughness is when feed rate at 480 mm/min, cutting speed at 2000 rpm and depth of cut at 0.5 mm.

4.2 ANALYSIS OF THE SIGNAL-TO-NOISE (S/N) RATIO

S/N ratio is used in Taguchi method to determine the variations of the experimental design. The smaller is better principle was selected because the desired results is lowest value of surface roughness. The equation for this principle can be referred to Eq. 2.5 on Chapter 2. Table 4.3 shows the S/N ratio for helical and back and forth tool path strategies for each experiment.

Table 4.3 S/N ratio for both tool path strategies

Exp no.	A (mm/min)	B (rpm)	C (mm)	S/N ratio (µm)	
				Helical	Back and Forth
1	240	2000	0.3	2.3360	2.9461
2	240	2500	0.4	5.1311	5.2097
3	240	3000	0.5	9.2065	3.0153
4	360	2000	0.4	-2.2450	-1.0441
5	360	2500	0.5	0.4556	4.6321
6	360	3000	0.3	-1.5361	0.8573
7	480	2000	0.5	3.8489	-2.5553
8	480	2500	0.3	-2.6381	2.4913
9	480	3000	0.4	-0.5225	2.5082

From Table 4.3, it shows there are different on S/N ratio for both tool path strategies. It can be assumed that, both tool path strategies do not produce same results although the machining parameters used are same. For helical tool path, experiment number 3 shows the highest S/N ratio and for this experiment the combination of parameters and their levels is $A_1B_3C_3$. While for back and forth tool path, experiment number 2 shows the highest S/N ratio and for this experiment the combination of parameters and their levels is $A_1B_2C_2$. This result agree with results from the experiment where for both experiment numbers it resulted least surface roughness value among all of experiment.

Basically, meaning of signal is input or desired value and noise is uncontrollable factors that affecting the response of the process. Optimum machining parameters are estimated using highest S/N ratio according to each parameter. The S/N ratio for each level is determined by averaging the S/N ratios at the corresponding level. Table 4.4 and 4.5 shows the response table for S/N ratio of surface roughness obtained for both tool path strategies.

Table 4.4 S/N ratios for helical tool path strategy

Level	A (mm/min)	B (rpm)	C (mm)
1	5.5579	1.3133	-0.6127
2	-1.1085	0.9829	0.7878
3	0.2294	2.3826	4.5037
$\Delta_{max\text{-}min}$	6.6664	1.3997	5.1164
Rank	1	3	2

Table 4.4 shows the average of each response characteristic for each level of each factor for helical tool path strategy. Each factor is ranked according to highest to lowest in order to determine influence of each factor on surface roughness. Feed rate is ranked as number 1, follow by depth of cut and the last one is cutting speed. This means changes in feed rate is most affecting factor while changes in cutting speed could be said give least affecting factor on surface roughness for this tool path.

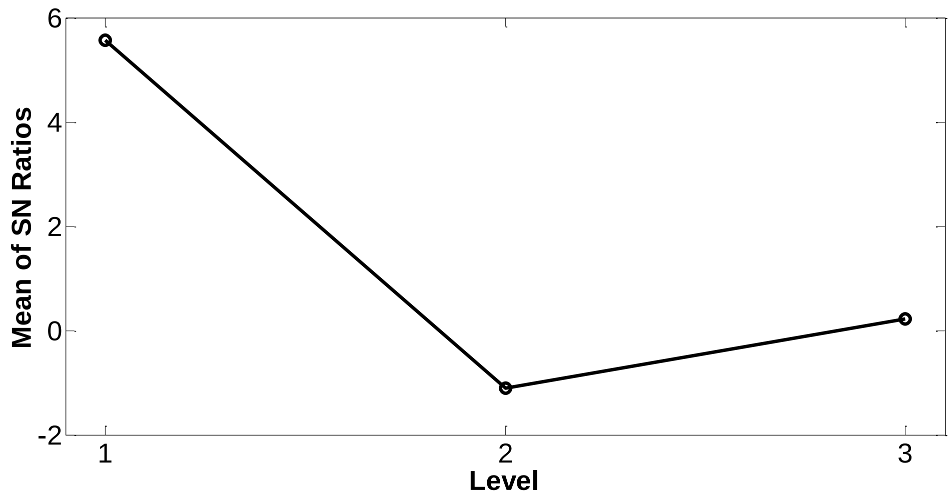

Figure 4.1 Feed rate versus S/N ratio for helical tool path strategy

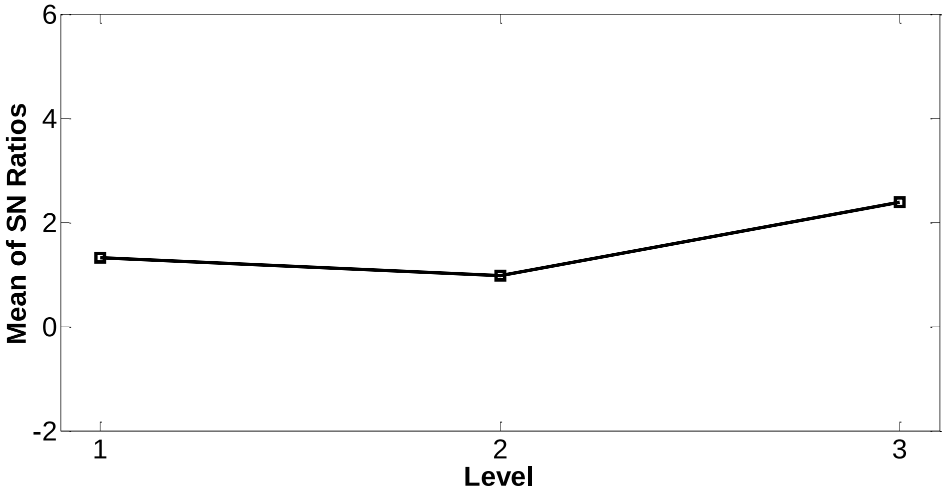

Figure 4.2 Cutting speed versus S/N ratio for helical tool path strategy

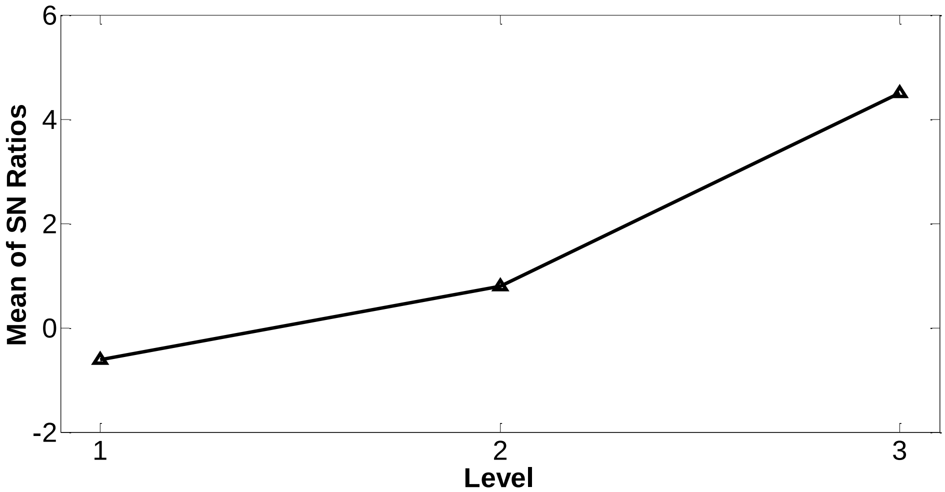

Figure 4.3 Depth of cut versus S/N ratio for helical tool path strategy

Optimum machining parameters are predicted using highest parameter for each factor. From Figure 4.1, it can be analyzed that feed rate at 240 mm/min is the optimum parameter for this factor. Figure 4.2 shows that cutting speed at 3000 rpm is the optimum parameter for this factor. According to Figure 4.3, depth of cut at 0.5 is the optimum machining parameter.

Table 4.5 S/N ratios for back and forth tool path strategy

Level	A (mm/min)	B (rpm)	C (mm)
1	3.7237	-0.2178	2.0982
2	1.4818	4.1110	2.2246
3	0.8147	2.1269	1.6974
$\Delta_{max-min}$	2.9090	4.3288	0.5272
Rank	2	1	3

Table 4.5 shows the average of each response characteristic for each level of each factor for back and forth tool path strategy. Same as Table 4.4, each factor is ranked according to highest to lowest in order to determine influence of each factor on surface roughness. Cutting speed is ranked as number 1, follow by feed rate and the last one is depth of cut. Different from helical tool path, changes in cutting speed is most affecting factor while changes in depth of cut could be said give least affecting factor on surface roughness for this tool path.

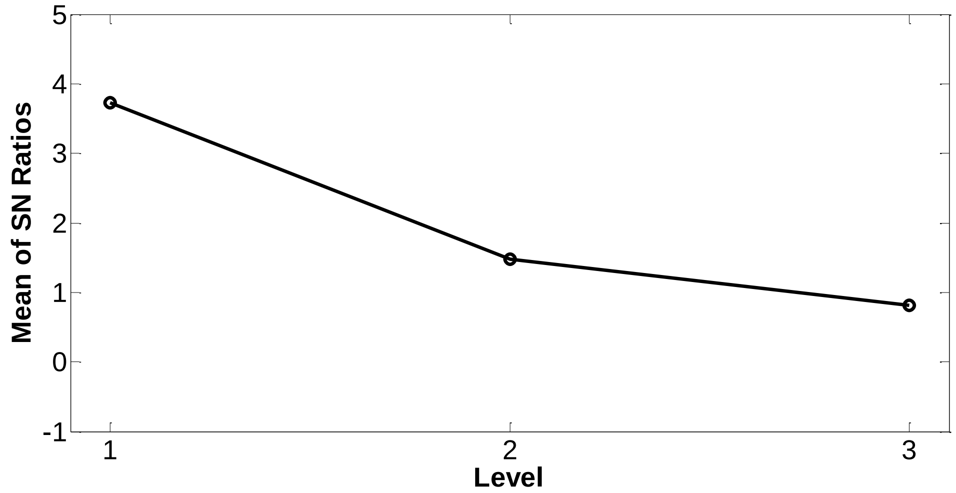

Figure 4.4 Feed rate versus S/N ratio for back and forth tool path strategy

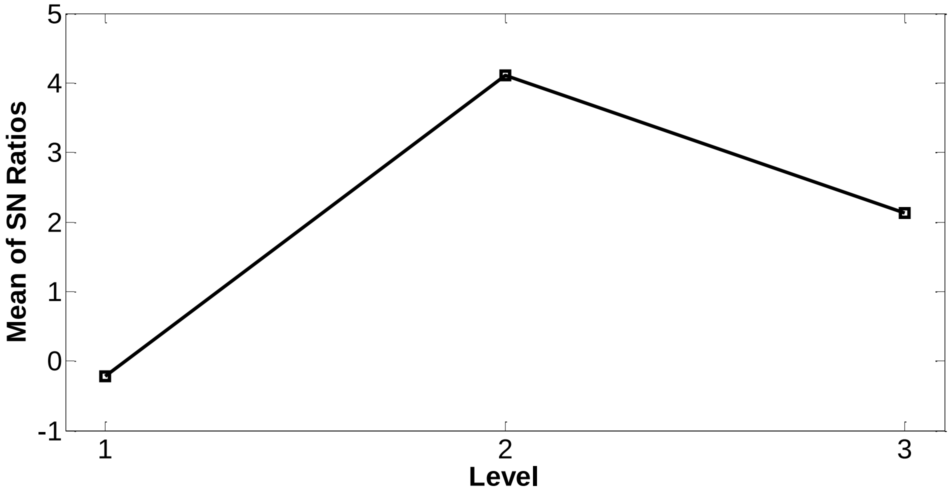

Figure 4.5 Cutting speed versus S/N ratio for back and forth tool path strategy

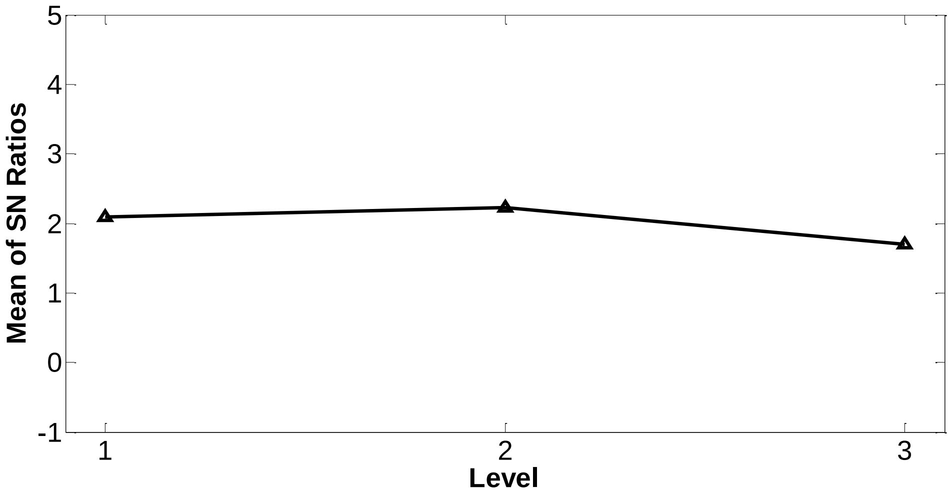

Figure 4.6 Depth of cut versus S/N ratio for back and forth tool path strategy

From Figure 4.4, it can be analyzed that feed rate at 240 mm/min is the optimum parameter for this factor. Figure 4.2 shows that cutting speed at 2500 rpm is the optimum parameter for this factor. According to Figure 4.3, depth of cut at 0.4 is the optimum machining parameter.

From S/N ratio analysis, it can be found that for helical tool path strategy, the optimum machining parameters are $A_1B_3C_3$ which means feed rate at 240 mm/min, cutting speed at 3000 rpm and depth of cut at 0.5 mm can give optimum surface roughness for helical tool path. For back and forth tool path, the optimum machining parameters are $A_1B_2C_2$ which means feed rate at 240 mm/min, cutting speed at 2500 rpm and depth of cut at 0.4 mm can give optimum surface roughness for back and forth tool path. Table 4.6 shows summary of S/N ratio analysis for both tool paths.

Table 4.6 Optimum machining parameters for both tool path strategies

Tool path strategy	Optimum variables	Feed rate	Cutting speed	Depth of cut
Helical	$A_1B_3C_3$	240	3000	0.5
Back and forth	$A_1B_2C_2$	240	2500	0.4

4.3 ANALYSIS OF VARIANCE (ANOVA)

It this project, analysis of variance (ANOVA) was used to analyze the effects of feed rate, cutting speed and depth of cut on surface roughness for helical and back and forth tool path strategies. Multiple regression analysis also was used to derive the mathematical models of the control factors and their interactions.

ANOVA was used for determination of individual interactions of all control factors. In the analysis, the percentage distributions of each control factor were used to measure the effects of control factor on the surface roughness. This analysis was evaluated at a confidence level of 95%.

The results of ANOVA for surface roughness are shown in Table 4.7 and 4.8 which were calculated using MATLAB (refer to Appendices D1 and D2). Basically, value of F is used to determine whether the corresponding factors are significant or not. Larger value of F means the variation of the machining parameter affecting the surface roughness of the machined surface is high. P is known as significance probability value or P value where if $P \leq 0.01$, it indicates that the difference is highly significance and if $P \geq 0.10$, it indicates no significance difference.

Table 4.7 Results of ANOVA for helical tool path

Parameter	Degree of freedom	Sum of square	Variance	F	P
A	2	0.5819	0.2909	9.23	0.0978*
B	2	0.0110	0.0055	0.18	0.8510
C	2	0.3339	0.1670	5.30	0.1588
Error	2	0.0631	0.0315		
Total	8	0.9899			

*Significance

Table 4.7 shows analysis of variance for surface roughness for helical tool path strategy. Based on theory of F and P-value, the major factor that affects surface roughness is feed rate (F – 9.23 and P – 0.0978). Then, depth of cut is another factor that affects surface roughness (F – 5.30 and P – 0.1588). Next, cutting speed is minor factor that affects surface roughness in helical tool path (F – 0.18 and P – 0.8510).

Table 4.8 Results of ANOVA for back and forth tool path

Parameter	Degree of freedom	Sum of square	Variance	F	P
A	2	0.1371	0.0686	1.37	0.4212
B	2	0.2869	0.1434	2.88	0.2580
C	2	0.0131	0.0066	0.13	0.8840
Error	2	0.0998	0.0499		
Total	8	0.5369			

*Significance

Table 4.8 shows analysis of variance for surface roughness for back and forth tool path strategy. Based on F-value in Table 4.8, the major factor that affects surface roughness is cutting speed (F – 2.88 and P – 0.2580). Then, feed rate is another factor that affects surface roughness (F – 1.37 and P – 0.4212). Next, cutting speed is minor factor that affects surface roughness in back and forth tool path (F – 0.13 and P –

0.8840). It is noted in this table no significance value for P. Table 4.9 shows the rank of factors that affecting surface roughness according to type of tool path.

Table 4.9 Rank of factors based on ANOVA for both tool path strategies

Rank	**1**	**2**	**3**
Helical	Feed rate	Depth of cut	Cutting speed
Back and forth	Cutting speed	Feed rate	Depth of cut

Linear regression analysis was used to generate a predictive equation of surface roughness. This equation is based on control factors and their interactions. The surface roughness equation generated for this experiment is shows on Eq. (4.1) and (4.2).

$$R_{a,helical} = 0.9333 + 0.2325A - 0.016611B - 0.22944C \quad (4.1)$$

$$R_{a,back\ and\ forth} = 0.71978 + 0.14533A - 0.13689B + 0.044278C \quad (4.2)$$

Where R^2 (coefficient of determination) value for the surface roughness was calculated as 0.648 for helical tool path and 0.467 for back and forth tool path.

4.4 VALIDATION OF EXPERIMENTAL RESULTS

After the optimum machining parameters have been selected, the final procedure of Taguchi method is to predict and validate the improvement of the surface roughness using the optimum machining parameters. This is important because this procedure is used to check the accuracy of analysis results taken from the experiment. The validation test contributes to increase the effectiveness of the optimum machining parameters.

The validation test was performed by means of the optimum machining parameters for helical and back and forth tool path strategies. The results for validation test are shown in Table 4.10 and 4.11.

Table 4.10 Results for validation test for helical tool path strategy

	Optimum parameters		**Different**	**Percentage**
	Estimation	**Experiment**		
Level	$A_1B_3C_3$	$A_1B_3C_3$		
Average surface roughness (µm)	0.4292	0.3517	0.0775	22.03
S/N ratio		9.0766		

Table 4.11 Results for validation test for back and forth tool path strategy

	Optimum parameters		**Different**	**Percentage**
	Estimation	**Experiment**		
Level	$A_1B_2C_2$	$A_1B_2C_2$		
Average surface roughness (µm)	0.6799	0.6541	0.0258	3.94
S/N ratio		3.6871		

From the validation tests, it shows that there are slight different between predicted and actual surface roughness obtained from the tests. For helical tool path, the result obtained much lower than predicted value where predicted value is 0.4292 µm and actual measurement taken from the experiment is 0.3517 µm. for back and forth tool path, the result obtained is less than predicted value where predicted value is 0.6799 µm and measurement from the experiment is 0.6541 µm.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In this project, there are two types of tool path were selected to determine the relationships of tool path strategy on surface roughness. Taguchi method was used to design the experiment procedure. In the design of experiment, three different machining parameters were selected as control factors.

The machining parameters were selected are feed rate, cutting speed and depth of cut. These factors were later divided into three levels which are low, medium and high. Orthogonal array has been used to arrange specified factors according to levels for the experiments. After the experiments were carried out, the surface of the sample or workpiece was measured to find the surface roughness.

After the experiments were done, results for the experiment were analyzed. There are three analyses that have been carried out which are S/N ratio analysis, analysis of variance (ANOVA) and linear regression analysis.

From S/N ratio analysis, it could be conclude that optimum machining parameters for helical tool path strategy are when feed rate at 240 mm/min, cutting speed at 3000 rpm and depth of cut at 0.5 mm. Then for back and forth tool path, the optimum machining parameters are when feed rate at 240 mm/min, cutting speed at 2500 rpm and depth of cut at 0.4 mm.

From ANOVA, it can be concluded that the major factor that affecting surface roughness for helical tool path is feed rate while for back and forth tool path, the major factor is cutting speed.

Validation test also has been performed where the difference between predicted and experiment for helical tool path is 0.0775 and for helical the difference is 0.0258.

Next, it has been compared that helical tool path has the lowest surface roughness measurement from among all data from the experiments for both tool path where the value is 0.3457 µm. The lowest surface roughness for back and forth tool path is 0.5487 µm which is higher than lowest value for helical.

From the S/N ratio analysis, it has been determined that both tool path has different optimum machining parameters where for helical the optimum machining parameters combination is when $A_1B_3C_3$ and for back and forth, the optimum machining parameters combination is when $A_1B_2C_2$.

Analysis of variance (ANOVA) shows that the major factor that affected both tool path strategies also different. For helical tool path, the major factor is feed rate, then followed by depth of cut and minor factor that affecting surface roughness is cutting speed. Differently, the major factor for back and forth tool path strategy is cutting speed, followed by feed rate and least affecting factor is depth of cut.

In conclusion, helical tool path is best cutting tool path strategy because it result lowest surface roughness measurement if optimum machining parameters that have been determined is used. Other than that, this project has achieved all the objectives where in this project two types of tool paths were selected and results from the experiments were analyzed in order to determine optimum machining parameters.

5.2 RECOMMENDATIONS

In this project, there are many improvement can be done for further research. Some suggestion or recommendation could make this study more effective and thus give more benefit to the manufacturing industry. Some recommendations to improve this study are:

- Add more tool path strategies in order to compare the results of surface roughness.
- Consider interaction between factors in analysis.
- Consider tool wear during machining process.
- Use different method of experimental design and compare results to know effectiveness of the methods used.
- Make profile or shape on workpiece instead of flat surface.
- Use two or more materials for workpiece.

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APPENDIX A1

MATLAB PROGRAMMING FOR HELICAL TOOL PATH

```
%Title: Effect of Tool Path Strategy on Surface Roughness in High
Speed
%Milling
%Name: Abdul Rashid Bin Muhammad
%Matric No: FA09077
%Supervisor: Assoc. Prof. Wan Azhar Bin Wan Yusoff

%This is the program to estimate value for S/N ratio and calculate
ANOVA
%Design of Experiment: Taguchi Method
%Experiment: Helical
%S/N principle: Smaller is better

%Factors:
%A = Feed rate (mm/min) [240 360 480]
%B = Cutting speed (rpm) [2000 2500 3000]
%C = Depth of cut (mm) [0.3 0.4 0.5]

%Clear previous data on command window
clc
clear

%Construct Factors according to levels
FR = [240 360 480];
FR = FR(:);

CS = [2000 2500 3000];
CS = CS(:);

DOC = [0.3 0.4 0.5];
DOC = DOC(:);

%Factors according to levels
F = [FR CS DOC]

LVL = [1:3];
LVL = LVL(:);

%Construct Orthogonal Array
NO = [1:9];
NO = NO(:);

A = [1 1 1 2 2 2 3 3 3];
A = A(:);

B = [1 2 3 1 2 3 1 2 3];
B = B(:);

C = [1 2 3 2 3 1 3 1 2];
C = C(:);
```

```
%Orthogonal Array
OA = [A B C]

%Measured surface roughness(um)
RA1 = [0.776 0.500 0.375 1.258 0.993 1.193 0.682 1.324 1.074];
RA1 = RA1(:);

RA2 = [0.740 0.580 0.317 1.304 0.936 1.214 0.611 1.384 1.100];
RA2 = RA2(:);

RA3 = [0.776 0.578 0.345 1.322 0.916 1.173 0.631 1.356 1.010];
RA3 = RA3(:);

RA = [RA1 RA2 RA3]
R = mean(RA,2)

RA1 = power(RA1,2);
RA2 = power(RA2,2);
RA3 = power(RA3,2);
RA2 = [RA1 RA2 RA3];

MRA = mean(RA2,2)

%Calculation to determine S/N ratio for each experiment
%Use smaller is better principle
SNR = -10*log10(MRA)

%Calculation to find S/N ratio for S/N ratio for each factor
%Calculation to find S/N ratio for A = Feed
SNA1 = (SNR(1)+SNR(2)+SNR(3))/3;
SNA2 = (SNR(4)+SNR(5)+SNR(6))/3;
SNA3 = (SNR(7)+SNR(8)+SNR(9))/3;
SNA = [SNA1 SNA2 SNA3];
SNA = SNA(:)

%Calculation to find S/N ratio for B = Speed
SNB1 = (SNR(1)+SNR(4)+SNR(7))/3;
SNB2 = (SNR(2)+SNR(5)+SNR(8))/3;
SNB3 = (SNR(3)+SNR(6)+SNR(9))/3;
SNB = [SNB1 SNB2 SNB3];
SNB = SNB(:)

%Calculation to find S/N ratio for C = Depth of cut
SNC1 = (SNR(1)+SNR(6)+SNR(8))/3;
SNC2 = (SNR(2)+SNR(4)+SNR(9))/3;
SNC3 = (SNR(3)+SNR(5)+SNR(7))/3;
SNC = [SNC1 SNC2 SNC3];
SNC = SNC(:)

%S/N ratio table
SN = [SNA SNB SNC]

%Linear Regression Model
mdl = LinearModel.fit(OA,R)

%ANOVA
p = anovan(SNR,OA)
```

APPENDIX A2

MATLAB PROGRAMMING FOR BACK AND FORTH TOOL PATH

```
%Title: Effect of Tool Path Strategy on Surface Roughness in High
Speed
%Milling
%Name: Abdul Rashid Bin Muhammad
%Matric No: FA09077
%Supervisor: Assoc. Prof. Wan Azhar Bin Wan Yusoff

%This is the program to estimate value for S/N ratio and calculate
ANOVA
%Design of Experiment: Taguchi Method
%Experiment: Back and Forth
%S/N principle: Smaller is better

%Factors:
%A = Feed rate (mm/min) [240 360 480]
%B = Cutting speed (rpm) [2000 2500 3000]
%C = Depth of cut (mm) [0.3 0.4 0.5]

%Clear previous data on command window
clc
clear

%Construct Factors according to levels
FR = [240 360 480];
FR = FR(:);

CS = [2000 2500 3000];
CS = CS(:);

DOC = [0.3 0.4 0.5];
DOC = DOC(:);

%Factors according to levels
F = [FR CS DOC]

LVL = [1:3];
LVL = LVL(:);

%Construct Orthogonal Array
A = [1 1 1 2 2 2 3 3 3];
A = A(:);

B = [1 2 3 1 2 3 1 2 3];
B = B(:);

C = [1 2 3 2 3 1 3 1 2];
C = C(:);

%Orthogonal Array
OA = [A B C]
```

```
%Measured surface roughness(um)
RA1 = [0.705 0.563 0.704 1.127 0.615 0.911 1.351 0.761 0.718];
RA1 = RA1(:);

RA2 = [0.713 0.525 0.700 1.142 0.548 0.899 1.299 0.720 0.815];
RA2 = RA2(:);

RA3 = [0.719 0.558 0.716 1.114 0.595 0.908 1.375 0.770 0.710];
RA3 = RA3(:);

RA = [RA1 RA2 RA3]
R = mean(RA,2)

RA1 = power(RA1,2);
RA2 = power(RA2,2);
RA3 = power(RA3,2);
RA2 = [RA1 RA2 RA3];

MRA = mean(RA2,2)

%Calculation to determine S/N ratio for each experiment
%Use smaller is better principle
SNR = -10*log10(MRA)

%Calculation to find S/N ratio for S/N ratio for each factor
%Calculation to find S/N ratio for A = Feed
SNA1 = (SNR(1)+SNR(2)+SNR(3))/3;
SNA2 = (SNR(4)+SNR(5)+SNR(6))/3;
SNA3 = (SNR(7)+SNR(8)+SNR(9))/3;
SNA = [SNA1 SNA2 SNA3];
SNA = SNA(:)

%Calculation to find S/N ratio for B = Speed
SNB1 = (SNR(1)+SNR(4)+SNR(7))/3;
SNB2 = (SNR(2)+SNR(5)+SNR(8))/3;
SNB3 = (SNR(3)+SNR(6)+SNR(9))/3;
SNB = [SNB1 SNB2 SNB3];
SNB = SNB(:)

%Calculation to find S/N ratio for C = Depth of cut
SNC1 = (SNR(1)+SNR(6)+SNR(8))/3;
SNC2 = (SNR(2)+SNR(4)+SNR(9))/3;
SNC3 = (SNR(3)+SNR(5)+SNR(7))/3;
SNC = [SNC1 SNC2 SNC3];
SNC = SNC(:)

%S/N ratio table
SN = [SNA SNB SNC]

%Linear Regression Model
mdl = LinearModel.fit(OA,R)

%ANOVA
p = anovan(SNR,OA)
```