OPTIMIZATION OF MACHINING PARAMETERS DURING ROUGHING MACHINING STRATEGIES OF POCKETING PROFILES – AEROSPACE PARTS

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DEDICATION

To my beloved parents,

family and all my supportive friends.

ABSTRACT

In recent years, aluminum materials have grabbed attention from industries, especially in the aerospace industry due to their properties. In the aerospace industry, there are some issues with the surface quality of the aluminum due to the cutting parameters that need to be resolved. The main goal of this experiment is to investigate the effect of machining parameters namely cutting speed (Vc) and feed per tooth (fz) with respect to the surface finish, and dimensional accuracy during roughing of pocketing profiles for a sample of aerospace part. Furthermore, the optimum machining parameters to achieve the most optimum surface finish, and dimensional accuracy are expected to be obtained at the end of this project milestone. The material to be used in this research is Aluminum Alloys Al-6061 T651 which is exactly the similar material used by the aerospace industry. The Design of Experiment (DoE) technique shall be deployed in the present work namely the Taguchi method L9 orthogonal array which consists of 9 experiments test, based on 3 levels and 3 variables. The Minitab Software will be utilized to plan the data from the Taguchi approach. Moreover, the physical machining operation will be carried out by using the 3-axis milling center (DMGMORI DMU 60 Evo). The surface roughness measurement will be evaluated by using Mitutoyo Surftest SJ-410. On the other hand, WENZEL XO 50 Coordinate Measuring Machine (CMM) will be deployed to measure the dimensional accuracy of the machined parts. The result from this experiment will reveal the optimum cutting parameters which are expected to indicate the most optimum result for the surface roughness and the dimensional accuracy.

ABSTRAK

Dalam beberapa tahun terakhir, bahan aluminium telah menarik perhatian dari industri, terutama dalam industri penerbangan disebabkan oleh sifat-sifatnya. Dalam industri penerbangan, terdapat beberapa isu berkaitan dengan kualitas permukaan aluminium yang disebabkan oleh parameter pemotongan yang perlu diselesaikan. Tujuan utama eksperimen ini adalah untuk menyelidiki pengaruh parameter pemachining, khususnya kelajuan pemotongan (Vc) dan pemakanan setiap mata pahat (fz) terhadap kehalusan permukaan dan ketepatan dimensi semasa proses roughing profil saku untuk sampel bahagian aerospace. Selanjutnya, parameter pemachining optimum untuk mencapai kehalusan permukaan dan ketepatan dimensi yang paling optimum dijangkakan diperolehi pada akhir fasa projek ini. Bahan yang akan digunakan dalam penyelidikan ini adalah Alooy Aluminium Al-6061 T651, yang sama dengan bahan yang digunakan oleh industri penerbangan. Teknik Reka Bentuk Eksperimen (DoE) akan digunakan dalam kerja ini, khususnya kaedah Taguchi L9 orthogonal array yang terdiri daripada 9 ujian eksperimen, berdasarkan 3 aras dan 3 pembolehubah. Perisian Minitab akan digunakan untuk merancang data dari pendekatan Taguchi ini. Selain itu, operasi pemachining fizikal akan dilakukan dengan menggunakan pusat pengilangan 3 paksi (DMGMORI DMU 60 Evo). Pengukuran kekasaran permukaan akan dinilai dengan menggunakan Mitutoyo Surftest SJ-410. Di sisi lain, Mesin Pengukuran Koordinat WENZEL XO 50 (CMM) akan digunakan untuk mengukur ketepatan dimensi bagi bahagian yang dimachining. Hasil dari eksperimen ini akan mendedahkan parameter pemotongan optimum yang dijangka akan menunjukkan hasil yang paling optimum untuk kekasaran permukaan dan ketepatan dimensi.

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LIST OF SYMBOLS AND ABBREVIATIONS

Vc	-	Cutting Speed
Vf	-	Feed rate
Fz	-	Feed per tooth
N	-	Spindle Speed
DoE	-	Design of Experiment
CAD	-	Computer Aided Design
CAM	-	Computer Aided Manufacturing
CNC	-	Computer Numerical Control
ADOC	-	Axial Depth of Cut
RDOC	-	Radial Depth of Cut
Al	-	Aluminum
Ra	-	Arithmetic average roughness
Rz	-	Vertical distance between max and min height of the profile
Rq	-	Root means square roughness
RPM	-	Revolutions per minute
ANOVA	-	Analysis of Variance
RSM	-	Response surface methodology
mm	-	Millimeters
min	-	Minutes
sec	-	Seconds
D	-	Diameter
ft	-	Feet
TL	-	Total length
CL	-	Cutting length
Zc	-	Number of effective teeth
IGES	-	Initial Graphics Exchange Specification
SN	-	Signal to Noise Ratios

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CHAPTER 1

INTRODUCTION

1.1 Background

The physical machining processes known as computer numerical control (CNC) machining are utilized to create machined parts based on dimensional designs produced by CAD software. These designs are then translated into NC programs through computer-aided manufacturing (CAM) systems. The generated NC program is subsequently loaded into the CNC machine, which produces specific cutting tools and strategies to manufacture the desired parts. However, high precision machining in the manufacturing industry faces a few challenges such as extended setup time, dimensional accuracy requirements, and the need to achieve high quality surface finishes.

The technology of CNC milling machines has significantly grown in the present to fulfil current demands in many production sectors, especially the precision metal cutting operations. The fundamental machining operation of milling is one of the CNC industrial machining techniques. The most common technique for cutting metal is end milling. It is widely used in a variety of manufacturing industries. Several studies have examined the effect of various machining parameters which is spindle speed, feed, and depth of cut on the surface roughness due to its effect on a product's appearance, performance, and solidity. The surface finish of a machined surface is of the highest priority when producing high-quality products. As stated by Amit Joshi (2012), The quality of the surface plays a very important role in the performance of milling as a good-quality milled surface significantly improves. In addition, dimensional accuracy also plays an important role, it happens due to the economic factors of the industries such as cost reduction, material waste will depend on dimensional accuracy.

Nowadays, the aerospace industries always make an effort to reduce machining costs while also improving the surface finish which reduces surface roughness of the machined products. Surface roughness needs to be considered attentively when machining in the aerospace industries. Based on the industries problem, optimization of cutting conditions can solve the problem such as economical factor, and can increase the productivity as the machining time is reduce in. Thus, mindfully deciding machining parameters such as cutting speed, feed rate, depth of cut, tool angles, and nose radius, a better surface finish can be achieved during machining operations.

In the aerospace industry, most of the aerospace parts are utilized the aluminum alloys materials. Aluminum plays a vital role in the construction of airplane. Its high resistance to corrosion and good weight to strength to cost ratio makes it the perfect material for aircraft construction. Aluminum is the perfect material to use when it comes to manufacturing airplanes, its unique properties and characteristics which are strong, lightweight, predictable, and inexpensive can beat the other material. Though steel and iron are both stronger than aluminum, strength alone isn't enough to consider its use in aerospace manufacturing. As shown in Figure 1-1, it can be seen that aluminum usage in aerospace industry is the second highest which is 20% before the 50% of composite material.

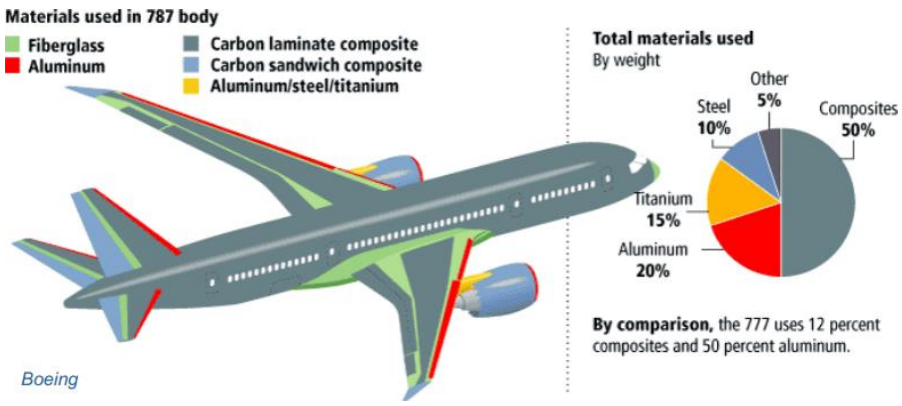


Figure 1-1: Materials used in Boeing 787 body (Aero Coating, 2014) (https://degradationworld.wordpress.com/2014/12/14/new-materials-being-used-in-aircraft-industry/)

The objective of this study is to determine the optimum machining parameters namely feed per tooth and cutting speed with respect to surface roughness. Other than that, the dimensional accuracy of the machined part shall be analyzed. Although these investigations reported many interesting results, little work has examined dimensional accuracy. In particular, the effect of cutting parameters dimensional accuracy remains unexplored. On the other hand, the qualitative data, such as the surface roughness of the machined sample aerospace parts, would be the main concern of this study as it is a significant deformation.

1.2 Problem Statement

The aerospace industry requires high precision of dimensional accuracy as well as the acceptable required range of surface quality especially in machining pocketing profiles. Surface quality is an important quality characteristic in manufacturing industries, as it directly impacts the performance and functionality of the machined parts. However, achieving the desired surface quality can be challenging due to the complex interactions between various machining parameters. These parameters may include cutting speed, feed rate, and depth of cut. Moreover, there are some issues with the surface roughness/quality based on specific cutting conditions that need to be resolved.

In addition, dimensional accuracy issue which main consideration in industries can be overcome due to the optimum machining parameters. The high demand of the high-quality machined parts by using CNC milling machine, the researchers must mindfully machine the part by using the optimum machining parameters.

Typical problems which are normally found in industry are related to economical impact due to machining time, which is this issue can be tackled by deciding the optimum machining parameters. Thus, this action can save much cost of material and reduce the waste of material. Other than that, it can increase productivity due to cycle time reducing.

1.3 Objective

The objective of this research is: -

i. To investigate the effect of machining parameters namely cutting speed and feed per tooth with respect to the machining results, surface finish, and dimensional accuracy during roughing of pocketing profiles for Al-6061 T651 of aerospace part.

ii. To determine the most optimum machining parameters (cutting speed and feed per tooth) in roughing operation of pocketing features for Al-6061 T651 of aerospace part.

1.4 Scope

The scope of this project is defined by the earlier targets which is emphasis the machining parameters with respect to surface roughness. In addition, further analysis to be carried out in this research is also related to the dimensional accuracy. The cutting parameters to be focused on this experiment are feed rate, Vf and cutting speed, Vc. The Design of Experiment (DoE) is approved as the main experimental design and analysis. Taguchi method orthogonal array L9 will be used in this experiment to analyze the significant factors. Minitab Statistical Software will be used to plan the Taguchi method data. This investigation is mainly focused on the closed pocketing profiles which is rectangular pocket and circular pocket of the sample aerospace parts. Since the aluminum alloys are frequently utilized in the aerospace industries, an actual aerospace aluminum alloy Al-6061 T651 material will be used in this experiment. Furthermore, the cutting tool used during this investigation is uncoated solid carbide material of end mill with diameter 8mm and 4 flutes. The roughing process of milling in this experiment is going to be performed utilizing DMGMORI DMU 60 Evo, a CNC Milling Machine 5-Axis. In order to perform the machining process, CATIA V5 shall be adopted as the main CAD/CAM platform focuses on roughing operation by applying the chosen machining parameters. The analysis of the surface roughness is to be executed using Mitutoyo Surftest SJ-410. Meanwhile, the dimensional accuracy process of the machined parts will be performed by WENZEL XO 50 Coordinate Measurement Machine (CMM).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the previous work on this project is to study and elaborate the literature review regarding the title to understand better for this research. Literature review discusses the relevant information in relevant areas of study. At the early stage of the studies, reference books, research journals, online articles, and magazines were gathered as the main sources of thesis guides. In order to make the initiative more successful, the information acquired will be used. A few literature studies were undertaken to better comprehend the research work.

2.2 Aluminum Materials

Over the last decade, the use of aluminum alloys in the manufacturing industry has grown because these alloys have a special ability to combine their two properties which are low weight and strength in a single material.

In the aerospace industry, Titu (2020) discovered there are several types of aluminum classes were mainly use which is 2xxx, 7xxx and 6xxx. The author discovered in the aerospace industries, they use aluminum due to the high strength and the low weight of these materials but also the fact that they can replace steel and cast iron in parts manufacturing. Author initiated the research begins with the first original contribution made by him namely comparative graphs about the state of aluminum alloys in the world. Another study by the author showed the impact on the environment is also reduced because of the low weight of the aluminum. The first graphs have been drawn and describe the aluminum alloys used as a percentage in the aerospace industry in the 2005-2019 period based on Figure 2-1. From the graph made by the author, it can be seen that the majority of Al6061 reaches 26%, followed by Al7075 at 22%. The aluminum alloy study is also used in the aviation industry.

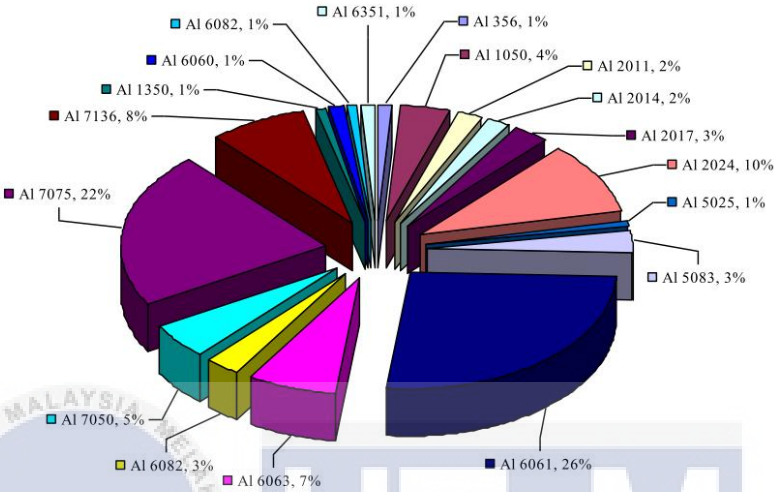


Figure 2-1: The aluminum alloys used as a percentage in the aerospace industry in the 2005-2019 period. (Titu, 2020)

Previous studies have primarily concentrated on aluminum offers weight saving because of its light weight. For engineering purposes, the use of aluminum can be limited because of the softness of this metal. However, the aerospace industry, which demands a high strength-to-weight ratio, requires this metal due to their strengthening. According to author, the strengthening of the aluminum is done by alloying it with some elements such as Cu, Zn, Mn, Mg, Si, and Li.

Table 2-1: Four-digit numerical designation

Alloying elements	Series designation
Pure aluminium	AA1XXX
Copper	AA2XXX
Manganese	AA3XXX
Silicon	AA4XXX
Magnesium	AA5XXX
Magnesium and silicon	AA6XXX
Zinc	AA7XXX
Lithium	AA8XXX

General descriptions of the relevant literature, the aluminum alloys were categorized in series, which is AA1XXX, AA2XXX, AA3XXX, AA4XXX, AA5XXX, AA6XXX, AA7XXX and AA8XXX. As highlighted by author, a four-digit numerical designation is used to specify aluminum and its alloys given in Table 2-1, where the first digit denotes the principal alloying element except AA1XXX series, which stands for purity of aluminum. The second digit stands for the changes to impurity limits. The minimum %Al (for AA1XXX series) and different aluminum alloys in the group (for other series) are represented by the third and fourth digits. (Prantik Mukhopadhyay, 2012)

2.3 Machining Parameters

In recent years, several studies have focused on machining parameters. The machine parameters play an important role in obtaining the best surface roughness. There are some machining parameters that need to be considered such as spindle speed, feed rate, depth of cut, coolant flow, diameter of drill tool, speed of cutting, number of passes etc. From the above parameters, two of them which are cutting speed and feed per tooth are prioritized considered to obtain the best surface roughness. Deciding the optimum and the best machining parameters, which are cutting speed and feed per tooth will improve the surface quality of machined parts. As stated by Bhardwaj (2013), cutting speed, depth of cut, and feed rate are the three machining factors which have major effects on surface roughness. The performance of any fundamental machining process is mostly determined by these three factors. Cutting speed or spindle speed refers to the cutting tool speed rotation during removing the material process. However, feed rate refers to the speed of the cutting tool moving. It can be better understood by referring to Figure 2-2 and Figure 2-3. These parameters are set and controlled to achieve desired outcomes during the material removal process.

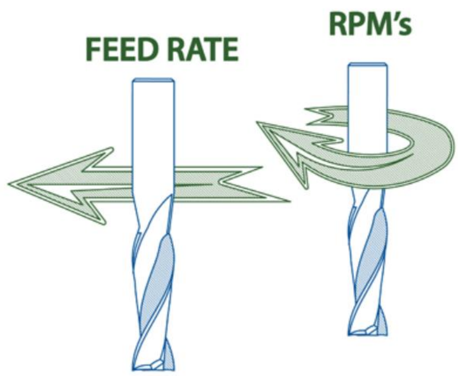


Figure 2-2: Feed rate vs spindle speed (RPM) (Woodworking Magazine, 2023)

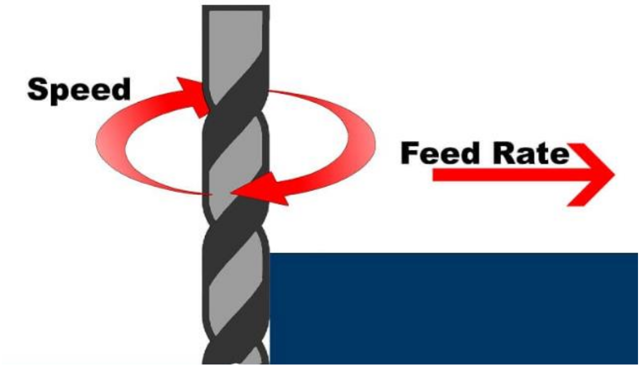


Figure 2-3: Spindle speed and feed rate movement (John, 2022)

Gunay M (2011) performed an experiment about the machining parameters on 6Al-4V alloy to surface roughness and cutting force (fx). In his study, only two parameters need to be considered as input which is cutting speed and feed rate. Thus, each parameter was designed to have three levels which is level 1, level 2 and level 3 as illustrated in Table 2-2.

Table 2-2: Three levels of each parameter (Gunay M, 2011)

Symbol	Machining parameters	Level 1	Level 2	Level 3
A	Cutting Speed, V_c (m/min)	100	140	180
B	Feed rate, f (mm/min)	250	500	750

From the experimental results as shown in Table 2-3, author concluded that resultant cutting forces and surface roughness increased with an increase in feed rate, whereas decreased with increase in cutting speed. Furthermore, author summarized that optimum machining conditions for surface roughness (Ra) were obtained at cutting speed of 180 m/min and feed rate of 250 mm/min. Surface roughness variations measured on machined surface according to the cutting speed and feed rate are shown in Figure 2-4.

Table 2-3: Experimental results (Gunay M, 2011)

Experiment no.	A (m/min)	B (mm/min)	F_x (N)	F_y (N)	F_z (N)	F_R (N)	R_a (µm)
1	100	250	65.48	16.05	95.4	116.82	0.64
2	100	500	92.97	43.47	110.92	151.12	1.20
3	100	750	122.52	78.4	138.65	200.95	1.30
4	140	250	57.4	17.8	62.1	86.42	0.42
5	140	500	76.38	38.44	105.68	135.94	0.83
6	140	750	110.81	59.7	136.15	185.42	0.93
7	180	250	41.5	6.87	44.71	61.39	0.40
8	180	500	67.78	32.84	107.6	131.34	0.80
9	180	750	79.71	39.12	100.64	134.21	0.85

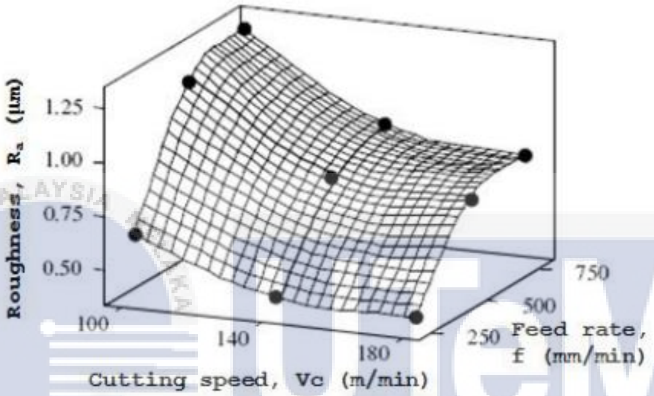


Figure 2-4: Surface roughness to cutting speed and feed rate (Gunay M, 2011)

Amit Joshi (2012) investigated the effect of machining parameters on surface finish of aluminum alloys. The machining parameters of this investigation are already set, and Table 2-4 shows the selected input parameters that will be used for this investigation.

Table 2-4: Selected parameters with symbol (Amit Joshi,2012)

Control factor	Symbol
Spindle speed	**Factor A**
Feed Rate	**Factor B**
Depth of cut	**Factor C**

According to this experiment, Design of Experiment (DoE) for this investigation utilized Taguchi method orthogonal array L9 based on Table 2-5. The author observed that optimal value of surface finish is obtained at first level of factor A, third level of factor B and second level of factor C which is 800 RPM, 100 mm/min and 0.3 mm respectively. Author concluded that Feed rate has highest effect on the response spindle speed has second highest effect on response and depth of cut has least effect on response.

Table 2-5: Design of Experiment (DoE) for this investigation (Amit Joshi,2012)

Experiment no	1 (A) Spindle speed (RPM)	2 (B) Feed Rate (mm/min)	3 (C) Depth of cut (mm)
1	800	60	0.2
2	800	80	0.3
3	800	100	0.4
4	1000	60	0.3
5	1000	80	0.4
6	1000	100	0.4
7	1200	60	0.4
8	1200	80	0.2
9	1200	100	0.3

In another study by Maiyar L (2013) measured the machining parameters on surface roughness and material removal rate of Inconel 718 super alloy. The author describes the main objective of the present work is to investigate the influence of different machining parameters on end milling of Inconel 718 super alloy. Design of Experiment used in this experiment is Taguchi's L9 orthogonal array to define the 9 trial conditions. The process parameters and levels are listed in Table 2-6, which is cutting velocity, feed rate and dept of cut. The experimental setup for milling operation as shown in Figure 2-5.

Table 2-6: Parameters and levels (Maiyar L 2013)

Parameter	Unit	Level 1	Level 2	Level 3
Cutting velocity (v)	m/min	25	50	75
Feed rate (f)	mm/tooth	0.06	0.09	0.12
Depth of cut (d)	mm	0.2	0.4	0.6

Figure 2-5: Experimental setup for milling operation (Maiyar L 2013)

Based on the experimental results shown in Table 2-7, researchers found that the optimal cutting parameters for the machining process lies at 75m/min for cutting velocity, 0.06 mm/tooth for feed rate and 0.4 mm for depth of cut.

Table 2-7: Experimental results (Maiyar L 2013)

Expt. No.	Process parameter			Average Response Values	
	Cutting velocity	Feed rate	Depth of cut	Surface roughness (microns)	Material removal rate (mm^3/sec)
1	1	1	1	0.21	4.308
2	1	2	2	0.25	4.480
3	1	3	3	0.29	4.503
4	2	1	2	0.2	5.643
5	2	2	3	0.27	5.731
6	2	3	1	0.27	5.904
7	3	1	3	0.21	6.906
8	3	2	1	0.23	7.080
9	3	3	2	0.27	7.530

Abdulrazaq M (2019) researched the effect of feed rate and spindle speed on surface roughness of Al-7024 alloy. The experiment is conducted by running 9 experimental tests based on 3 levels of 3 variables. The variables were spindle speed, feed rate, and depth of cut. The levels of machining parameters are listed in Table 2-8. The experimental setup is shown in Figure 2-6.

Table 2-8: The variables and levels of machining parameters (Abdulrazaq M 2019)

No	Parameter	Level 1	Level 2	Level 3	Units
1	Spindle speed	800	1000	1200	*rpm*
2	Feed rate	60	80	100	*mm/min*
3	Depth of cut	0.2	0.4	0.6	*mm*

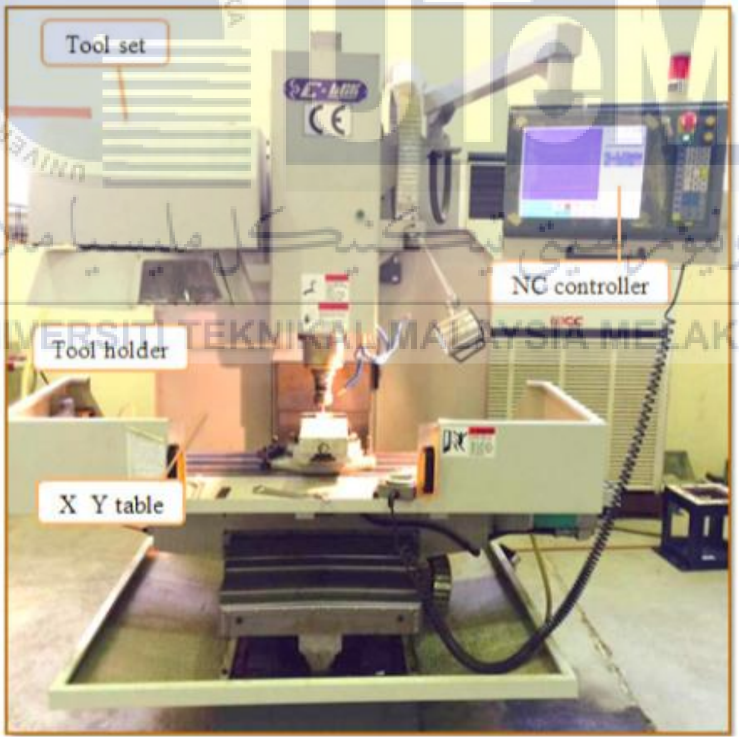


Figure 2-6: Experimental setup (Abdulrazaq M 2019)

From the experiment, author found the best surface roughness (0.41 µm) is achieved with the values (100 mm/min), (1000 RPM), and (0.2 mm) for the feed rate, spindle speed, and depth of cuts respectively. As shown in Figure 2-7, it is observed that the increase in feed rates leading to a decrease in surface roughness gives a better quality for the machining surfaces, while increasing the spindle speed results in higher surface roughness.

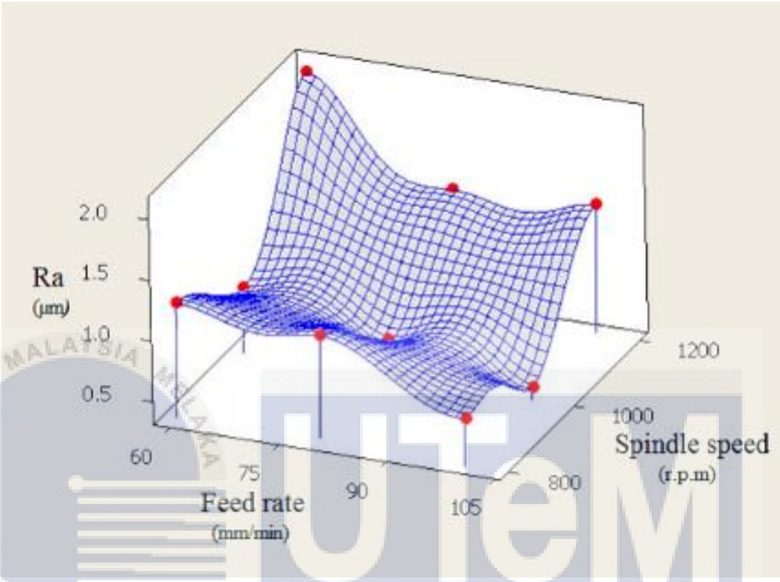


Figure 2-7: Effect of feed rate and spindle speed on surface roughness

(Abdulrazaq M 2019)

In another study conducted by Sharma A (2019), author research about the effect of milling parameters on surface roughness of Aluminum Alloy AA6062. The input parameters of milling process of this experiment are depth of cut, spindle speed and feed rate based on Table 2-9. The input parameters are set by using the Taguchi method L16 array based on Table 2-10. From this investigation, the optimal value of surface roughness is obtained in run 3 based on Table 2-11 which is 0.01mm/sec, 1600 rpm and 1.0mm of feed rate, spindle speed and depth of cut respectively. Author summarized that the surface roughness is mainly influenced by feed rate which is followed by spindle speed and depth of cut.

Table 2-9: The input parameters of milling process of experiment (Sharma A 2019)

Level	Factor		
	Feed rate (mm/sec)	Spindle speed (rpm)	Depth of cut (mm)
1	0.01	1040	0.6
2	0.02	1450	0.8
3	0.03	1600	1.0
4	0.04	1850	1.2

Table 2-10: Experimental setup by using the Taguchi method L16 array (Sharma A 2019)

Run	Feed Rate (mm/sec)	Spindle Speed (rpm)	Depth of cut (mm)
1	0.01	1040	0.6
2	0.01	1450	0.8
3	0.01	1600	1.0
4	0.01	1850	1.2
5	0.02	1040	0.8
6	0.02	1450	0.6
7	0.02	1600	1.2
8	0.02	1850	1.0
9	0.03	1040	1.0
10	0.03	1450	1.2
11	0.03	1600	0.6
12	0.03	1850	0.8
13	0.04	1040	1.2
14	0.04	1450	1.0
15	0.04	1600	0.8
16	0.04	1850	0.6

Table 2-11: Experimental results for surface roughness (Sharma A 2019)

Run	Feed Rate (mm/sec)	Spindle Speed (rpm)	Depth of cut (mm)	Surface Roughness (μm)
1	0.01	1040	0.6	1.253
2	0.01	1450	0.8	1.426
3	0.01	1600	1.0	0.789
4	0.01	1850	1.2	0.948
5	0.02	1040	0.8	0.854
6	0.02	1450	0.6	1.258
7	0.02	1600	1.2	1.820
8	0.02	1850	1.0	1.419
9	0.03	1040	1.0	2.876
10	0.03	1450	1.2	4.122
11	0.03	1600	0.6	1.961
12	0.03	1850	0.8	1.427
13	0.04	1040	1.2	2.316
14	0.04	1450	1.0	1.867
15	0.04	1600	0.8	1.732
16	0.04	1850	0.6	2.339

The study by Özsoy (2019), author performed the experimental investigation on surface roughness of cutting parameters by utilized 7075-T6 aluminum alloy milling process. In the experiments, three different parameters were selected which are cooling type, spindle speed and feed per tooth. The input parameters are selected by using the 4 levels of each parameter based on Table 2-12.

Table 2-12: The 4 levels of each parameter (Özsoy, 2019)

Symbols	Parameters	Level 1	Level 2	Level 3	Level 4
A	Spindle speed (rpm)	3000	3500	4000	4500
B	Feed per tooth	0.04	0.06	0.08	0.1
C	Cooling type	Air	Liquid	-	-

The author studied that the feed per tooth was determined the most important parameter which has 66.46% of contribution rate. He concluded, the best surface roughness value was obtained with 0.04 mm/tooth feed per tooth and 3000 rpm spindle speed. The spindle speed and cooling type showed the lower effect which is 17.6% and 13.29% respectively for their contribution rate. This study also serves to determine the contribution of each machining parameter and their interaction for surface roughness. Based on the variance analysis of this experiment, 95% of confidence level was observed to be remarkable on the mean surface roughness of all the parameters process.

Another research by Kumar S (2020), author studies the effect of machining parameters on surface roughness on AISI 1005 carbon steel. Spindle peed, depth of cut and feed rate are considered to be important cutting parameters for milling of AISI 1005 carbon steel plate. The machining parameters which need to be studied utilized Taguchi method orthogonal array L9 as in Table 2-13 surface roughness can be produced with lower feed rate

Table 2-13: Machining parameters setup utilized Taguchi method (Kumar S, 2020)

Serial Number	Milling parameter levels		
	Spindle speed	Feed rate	Depth of cut
1	1000	100	0.25
2	1000	150	0.50
3	1000	200	0.75
4	1250	100	0.75
5	1250	150	0.25
6	1250	200	0.50
7	1500	100	0.50
8	1500	150	0.75
9	1500	200	0.25

Based on the main effects plot for means of surface roughness result, author concludes that it is observed that surface roughness was smaller at third level of spindle speed, third level of feed rate and second level of depth of cut which is 1500, 100 and 0.5 respectively as illustrates in Figure 2-8. Author also concluded that spindle speed is the most influencing parameter in machining process and it directly affects the stability of the machining process.

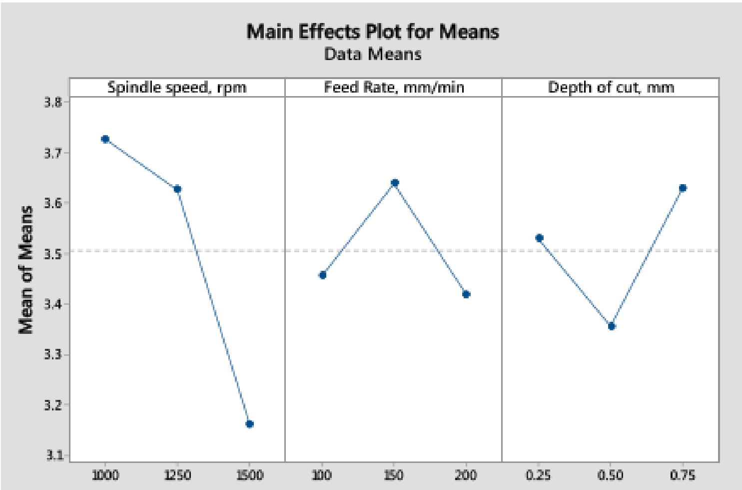


Figure 2-8: Main Effects Plot for Means of Surface Roughness (Kumar S 2020)

Table 2-14: Summary of machining parameters findings

No	Researcher	Year	Material	Findings
1	Guney M	2011	6Al-4V aluminum alloy	The optimum machining conditions for surface roughness (Ra) were obtained at cutting speed of 180 m/min and feed rate of 250 mm/min.
2	Amit Joshi	2012	Aluminum Alloys	The author observed that optimal value of surface finish is obtained which is 800 rpm for spindle speed, 100 mm/min for feed rate and 0.3 mm for depth of cut.
3	Maiyar L	2013	Inconel 718 super alloy	The optimal cutting parameters for the machining process lies at 75m/min for cutting velocity, 0.06 mm/tooth for feed rate and 0.4 mm for depth of cut.
4	Abdulrazaq M	2019	Al-7024 aluminum alloy	The best surface roughness (0.41 µm) is achieved with the values (100 mm/min), (1000 rpm), and (0.2 mm) for the feed

				rate, spindle speed, and depth of cuts respectively.
5	Sharma A	2019	Aluminum Alloy AA6062	The optimal value of surface roughness is obtained which is 0.01mm/sec, 1600 rpm and 1.0mm of feed rate, spindle speed and depth of cut respectively
6	Özsoy	2019	7075-T6 aluminum alloy	The best surface roughness value obtained with 0.04 mm/tooth feed per tooth and 3000 rpm spindle speed.
7	Kumar S	2020	AISI 1005 carbon steel	Surface roughness was smaller at third level of spindle speed, third level of feed rate and second level of depth of cut which is 1500, 100 and 0.5 respectively.

2.4 Roughing Process

Roughing in machining is the process of removing large amounts of material from a workpiece in preparation for semi-finishing and finishing operations. It involves using high value feed rate and cutting depth to remove the excess material rapidly and efficiently as possible, often it may leave rough surface finish. Based on Figure 2-9, it can be seen the roughing operation basically used higher Radial Depth of Cut (RDOC) instead of Axial Depth of Cut (ADOC) compared to the finishing operation.

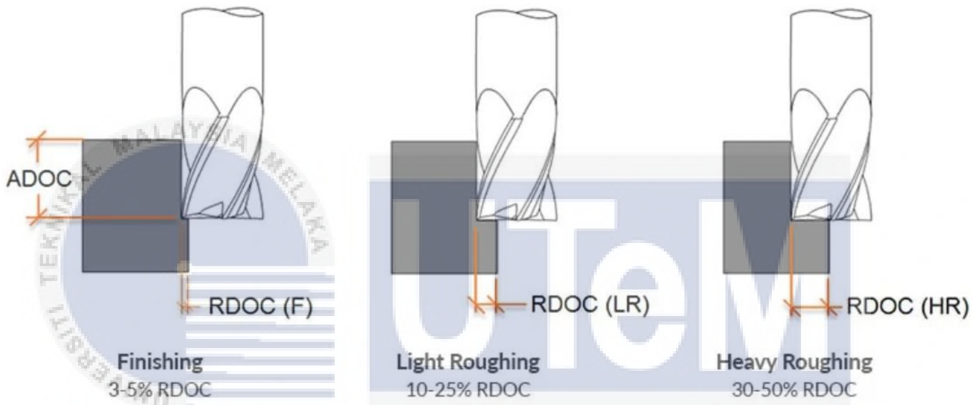


Figure 2-9: Finishing operation vs roughing operation (Harvey Performance, 2017)

(https://www.harveyperformance.com/in-the-loupe/depth-of-cut/)

As stated by Dodok et al (2020), machining strategy provides a cutting mode for the tool during a particular machining operation, determining the axial and radial depth of cut and the recommended trajectories for the cutting tool. The three main types of milling strategies are roughing, pre-finishing, and finishing. To eliminate the majority of material in a short period of time, roughing strategies are performed. The largest diameter of the tool is used according to the size of the workpiece. The goal of finishing strategies is to produce the best surface quality possible.

2.5 Pocketing Profile

Pocket milling is one of the basic machining processes in manufacturing. Roughness of the pocket's surface is a direct indicator of its quality characteristic of the product's performing properties. Pocket milling has been considered as one of the most widely used operations in machining. It is widely utilized in the shipbuilding and aerospace industries. Effective pocketing processes can lead to a reduction in machining time and cost since pocket milling has become important. There are several types of pocketing profiles which are closed pocket and open pocket as shown in Figure 2-10.

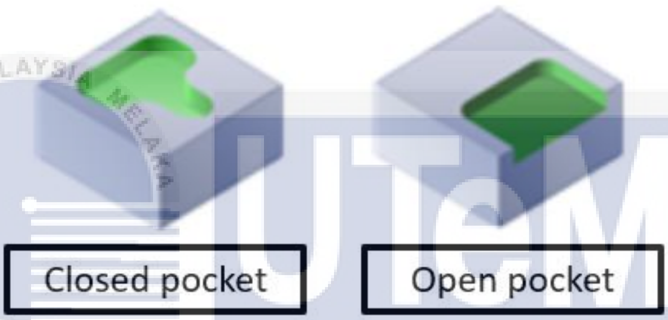


Figure 2-10: Closed pocket vs Open pocket

Rajyalakshmi M (2021) has stated the use of pocket milling application is high in ship building and aerospace industries. In order to mill the pocket surface various tool trajectories may be used. Author reported that the surface roughness of pocketing profiles is one of the quality parameters to accept products. At the same time, production time must be reduced in order to lower the production cost. It is also important to consider the machining parameters to get good surface finish and less production time.

2.6 Design of Experiment

Design of Experiments (DoE) is a systematic approach used in research and industrial settings to plan, conduct, and analyze experiments efficiently and effectively. It is a statistical methodology which allows researchers to identify and understand the relationship between input variables and the response of a process. The main objective of DoE is to make the best use of experimental resources by carefully choosing the variable combinations that will be evaluated. DoE enables researchers to gather sufficient data to reach significant decisions regarding how the factors impact the response variables by carefully modifying the factors and determining the related responses.

2.6.1 Taguchi Method

Taguchi method was created by Genichi Taguchi which is a method to use when conducting experiments. The benefit of Taguchi design is that multiple components can be taken into direct consideration. Furthermore, industries are able to significantly shorten the design and production cycle times for new products by using Taguchi methods, which lowers costs and increases profit. In addition, the Taguchi design method allows the investigation of unpredictability caused by noise factors, which are typically ignored in the standard design of experiment method.

The research from Maiyar L (2013) states that Taguchi method has become a powerful tool for improving productivity during research and development so that high quality products can be produced quickly and at low cost. For robust design, Taguchi's parameter design is an important tool. Taguchi method uses orthogonal arrays design to study the input parameters with a small number of experiments.

Titu A (2020) describes the mathematical methods used to optimize the aluminum alloy cutting processes that were analyzed. Based on Figure 2-11, the results show that the most studied methods are ANOVA with 35%, RSM with 26% and Taguchi with 24%. Author discovered the Taguchi method is an effective tool that is widely accepted by industrial engineers to approach the highest possible production at the right price and at the right time. The factors influencing the response are arranged in the form of a lattice square model; this pattern is called an orthogonal array. The design and selection of the orthogonal structure and the reasons for the experiments are the main foundations of the Taguchi process.

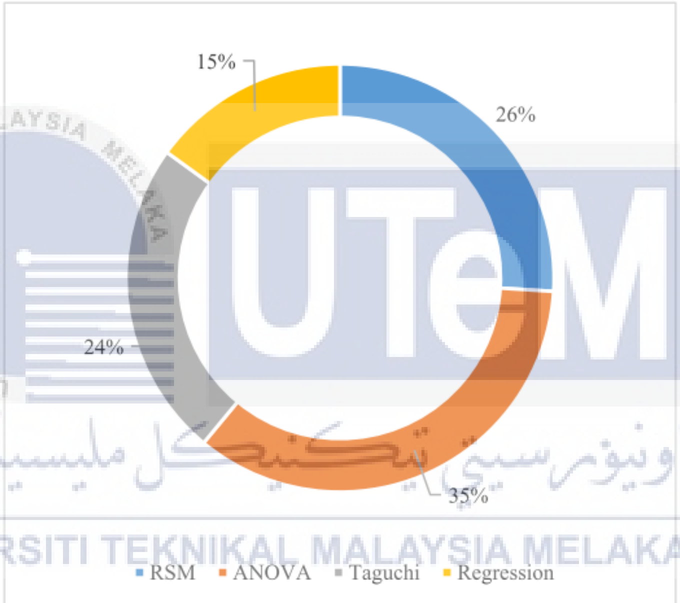


Figure 2-11: The methods used to optimize the aluminum alloy (Titu A 2020)

Previous studies have primarily concentrated on Taguchi method, author describes Taguchi method as the best method to optimize a parameter, where a response variable can be determined. In order to obtain the optimum machining parameters Taguchi is used for the investigation. Taguchi orthogonal method design can be determined accurately by matrix experiments. By using this method, the frequency of simulation test can be reduced, and the experimental data can be obtained (Fadly, 2020)

As stated by Kumar S (2020) the orthogonal array of Taguchi method allows him to gain the process parameters with minimum number of experiments. Author describes Signal-to-noise ratio is recommended to determine the quality characteristics in the design problems. Taguchi method helps to obtain a sound design of experiment by using the systematic orthogonal array. Taguchi orthogonal array is useful to have accurate experimental design.

2.7 Surface Roughness

In recent years, several studies have focused on surface roughness. Surface roughness is the measurement of the relative smoothness of a surface's profile, it can be measured and analyzed by using surface roughness tester and microscope camera. Surface roughness is commonly quantified using parameters such as Ra (arithmetical average roughness), Rz (the vertical distance between maximum and minimum height of the profile) and Rq (root mean square roughness), as indicates in Figure 2-12. Surface roughness is a critical factor in determining the functional and aesthetic quality of machined components. Surface roughness can affect various aspects of a machined part, including its appearance, functionality, and performance. For example, in aerospace industries where parts need to fit together precisely, surface roughness plays a vital role in ensuring proper mating and sealing.

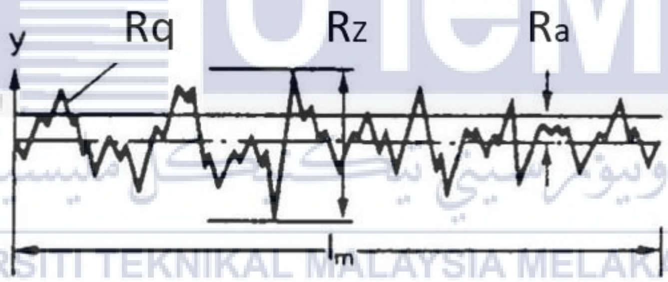


Figure 2-12: Pictorial representation of surface roughness (Stahli USA 2023) (https://www.stahliusa.com/stahli-publication/the-technique-of-lapping/surface-finish-quality)

A study by Hayajneh (2007) stated that the demand for high quality and fully automated production focuses attention on the surface condition of the product, especially the roughness of the machined surface, because of its effect on product appearance, function, and reliability. From that, it is important to maintain the quality of the surface finish. The research study by Selvan (2017) concluded that surface roughness optimization in the end milling operation shows that spindle speed, feed rate and depth of cut have been commonly chosen as the control factors. He describes the average surface roughness (Ra) has been the most common parameter to define the surface roughness of the machined part.

Amit Joshi (2012) found the quality of the surface plays a very important role in the performance of milling. He also stated that surface roughness is affected negatively if the applied force is increased. He concluded, with the more precise demands of modern engineering products, the control of surface texture together with dimensional accuracy has become more important. Similarly, Ribeiro (2017) found the preparation of quality surfaces is very important process in surface engineering. The surface roughness will influence the quality and effectiveness of the surface finish quality. For these reasons, the authors of the present work have focused on manufacturing parameters that influence the surface quality.

2.8 Dimensional Accuracy

Nowadays, with the more precise demands of modern engineering products, dimensional accuracy has become more important. It is because the problem of dimensional accuracy will give the impact to the product functionality. Thus, designing parts and components for the aerospace industry requires extremely high levels of accuracy. Precision is such a vital consideration, lack of attention to detail and production errors simply cannot happen.

Several studies investigating the dimensional accuracy have been carried out, as stated by Gunay M (2011) high cutting forces can cause significant tool deflections which this thing can impact the dimensional tolerances. According to Omar M (2014) increasing the spindle speed over 800 rpm improves pocket dimensional accuracy. Thus, cutting speed is better to be limited to 800 rpm, feed rate should be kept minimum and increasing the depth of cut to 5% of the cutter diameter improved the accuracy pocket diameter and pocket roundness.

In addition, Ribeiro J (2017) describes obtaining the manufactured parts with better surface and dimensional can influence the economic factors of the industries. More recently, Fadly (2020) proposed the surface roughness are the parameters that have effect on dimensional precision and performance of parts.

2.9 Summary

In finding the optimum machining parameters to obtain the best surface quality, this chapter covered wide area of machining parameter from various materials. From the literature review, most of the researchers utilized Taguchi method for their experimental design. Thus, Taguchi method L9 orthogonal array is widely used. In deciding the optimum machining parameters, most of the researchers reported that machining parameters are the major factors to the surface quality. The general parameters that have been used are feed rate, spindle speed or cutting speed. Moreover, there are still many researchers and industries investigating, evaluating, and analyzing the optimum machining parameters of aluminum alloys.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, general process and methodology for this research will be explained. The methodology has been divided into two phases which are Phase I and Phase II. Phase I included the literature review, searching for CAD model and analyzing the CAD model. However, Phase II the process starts with preparation of CAM program, material, and tool selection, decide the machining parameters and surface roughness measurement. Other than that, this chapter also will tell about the machine specifications of the machine that will be used. In general, Phase I needs to be done on PSM 1 and Phase II on PSM 2.

3.2 Process Flowchart

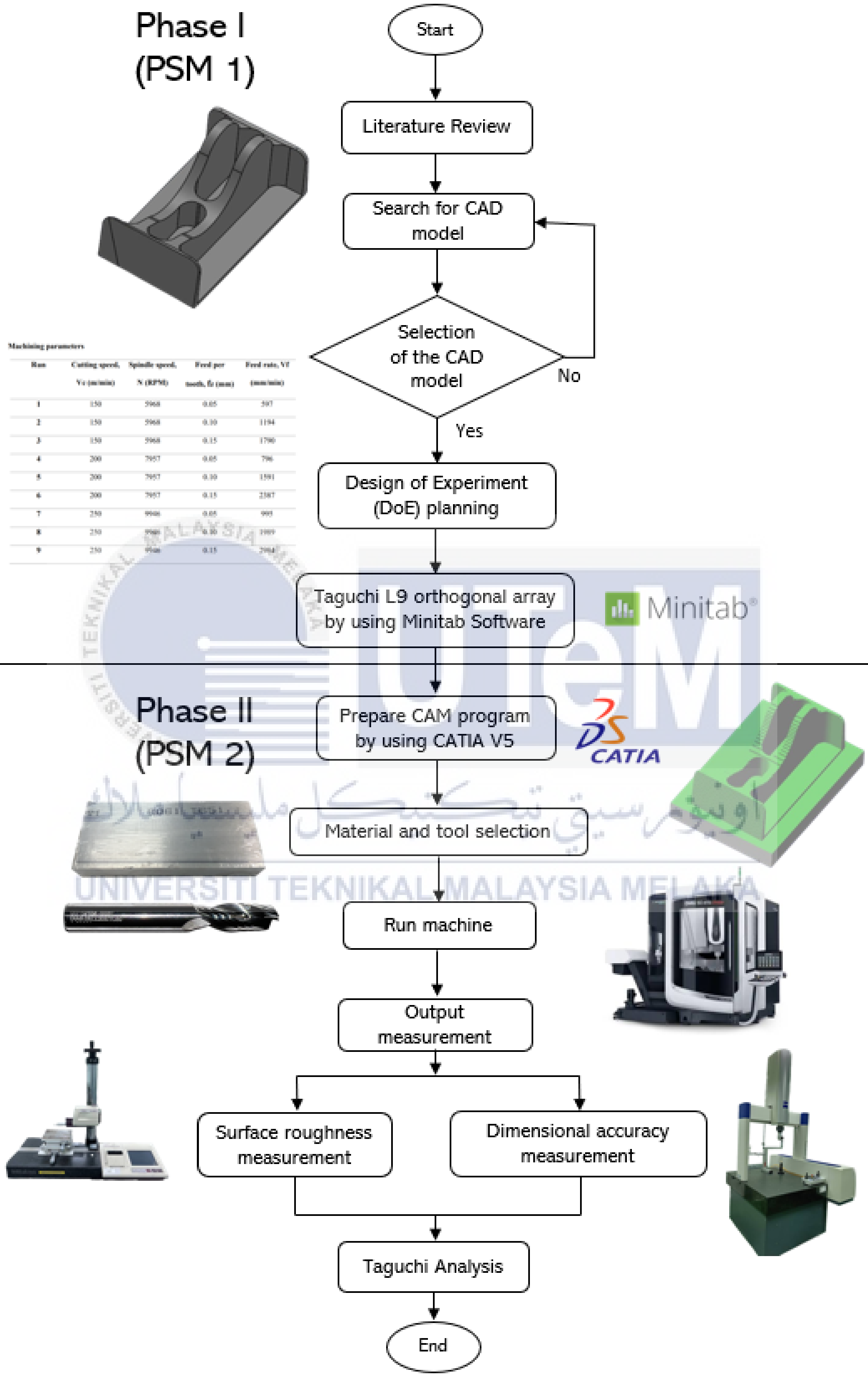


Figure 3-1: Process flowchart

3.3 CAD Model Selection

In searching the aerospace parts CAD model for this experiment, the searching process is utilized the Grab CAD websites, there are so many aerospace parts have been found in these websites, but the main focus here is to find the parts that have pocketing profiles (closed pocket & open pocket) due to this research need to study the surface roughness on pocketing profiles. Thus, there are several aerospace parts which have pocketing profiles that have been found. However, after the discussion with the supervisor, the meeting agreed with the aerospace parts namely GE Engine Bracket as shown in Figure 3-2.

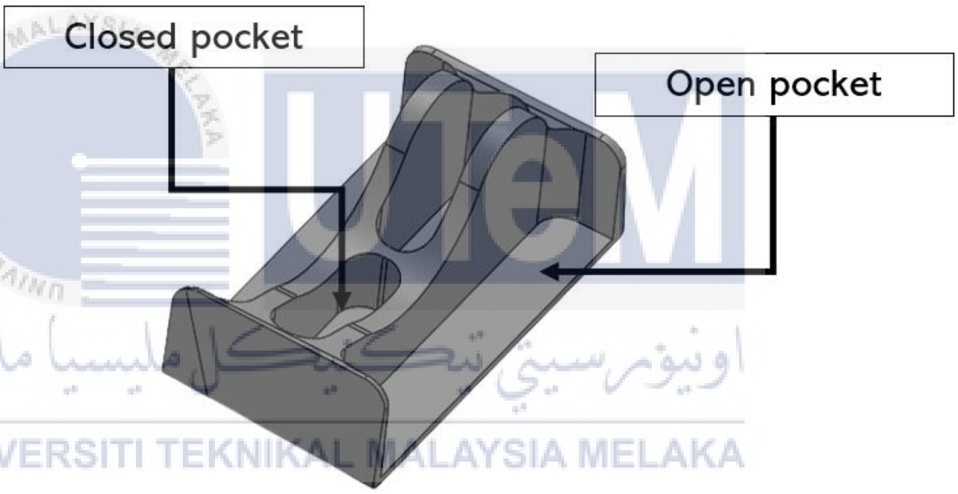


Figure 3-2: CAD model of aerospace parts

In phase analysis of the CAD model, it has been shown that this CAD model has a larger dimension than expected. This CAD model dimension is larger than the raw stock material. From that, it is necessary to scale this CAD model for better size. After the dimension was observed, the CAD model is scaled to 0.6 by using SolidWorks 2023 software.

3.4 CAM Program Preparation

This experiment provided an important opportunity to advance the understanding of using CATIA V5 software. In order to successfully complete this experiment, it is necessary to prepare the CAM program by using CATIA V5 software. However, the process involved in this CAM program preparation is roughing only. It is most important to consider the machining parameters in order to achieve the main objective of this experiment. The CAM program preparation will be shown step by step in this section.

3.4.1 Transfer CAD file to CATIA V5 software.

To transfer the CAD file to the CATIA V5 software, it is necessary to convert the CAD file to the STP file as shown in Figure 3-3.

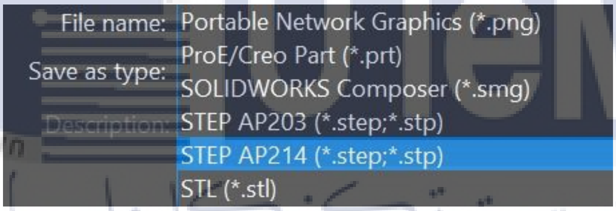


Figure 3-3: STP file locators

3.4.2 Stock Preparation

Stock preparation is the important step before starting the CAM program. In order to create a stock, first of all it is needed to sketch on the face of the part as shown in Figure 3-4. After the sketch is done, pad the sketch to extruded the sketch to become a stock as in Figure 3-5.

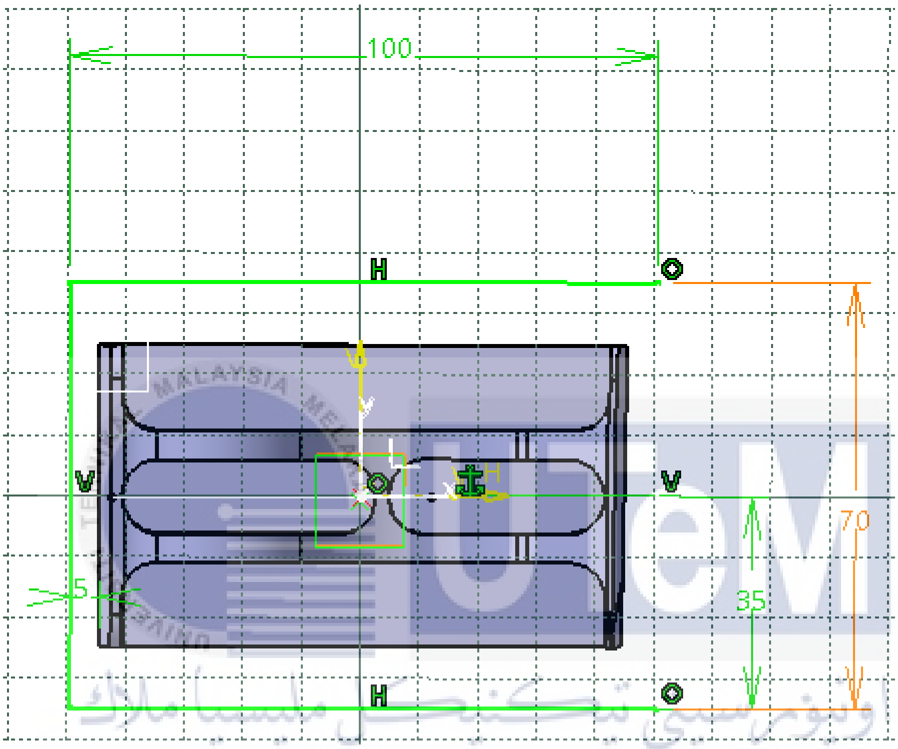


Figure 3-4: Sketch on face of the part

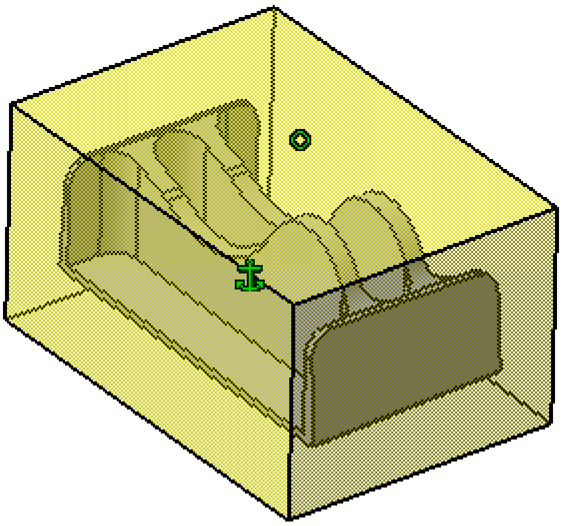


Figure 3-5: Stock in CATIA V5 software

Before proceeding to the next stage, the stock needs to have an axis system based on Figure 3-6. An axis system is composed of an origin point and three orthogonal axes.

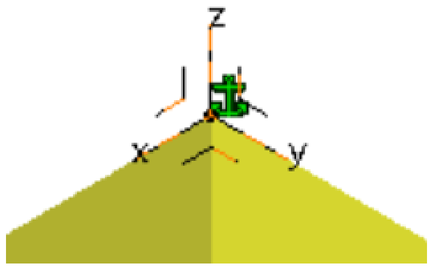


Figure 3-6: Axis system on stock

3.4.3 Plane System Creation

The plane system plays a vital role before we proceed in advanced machining processes. Thus, planes can then be used as reference planes or support when creating other items. The plane system has two references planes which are safety plane and approach plan as shown in Figure 3-7. Safety plane refers to the cutting tool safety position and approach plane refers to the cutting tool approach position.

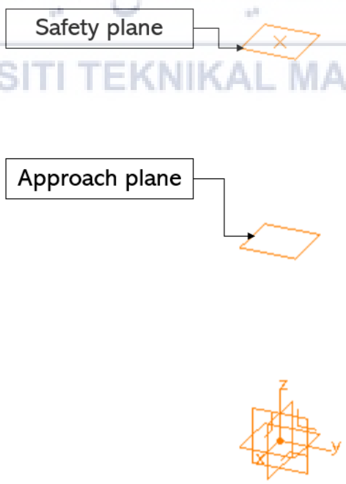


Figure 3-7: Plane system with axis system

3.4.4 Assembly Process

After the plane system and stock creation on parts are ready, it is needed to assembly the plane system and stock. The assembly process of the plane system and stock will appear based on Figure 3-8.

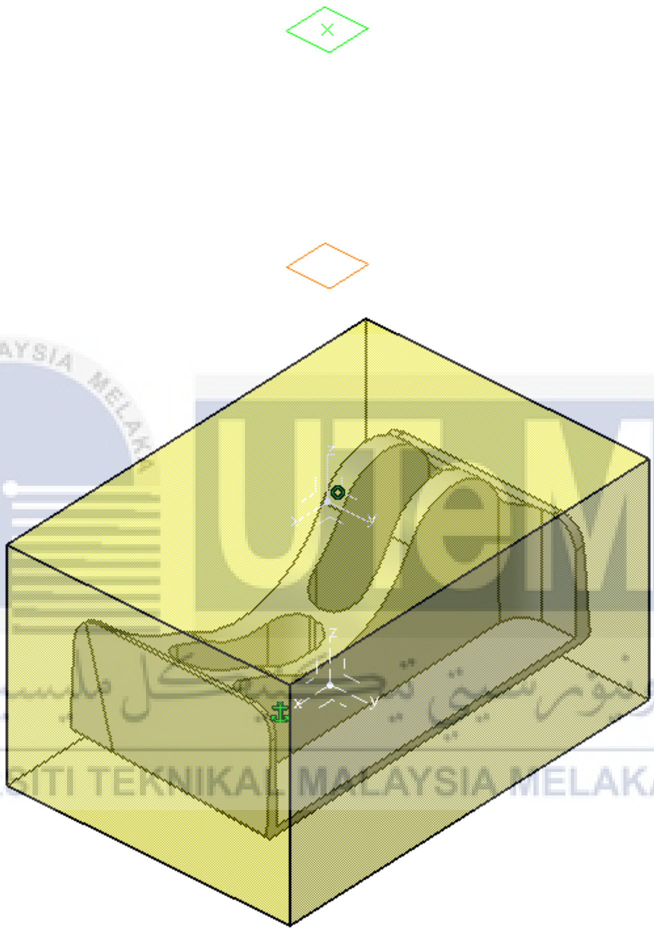


Figure 3-8: Assembly of plane system and stock

3.4.5 Advanced Machining Process

Advanced machining process is the major step in order to program the CAM program. In this process, there are various steps of machining involved such as part operation setup, selection of cutting tool, the machining strategies setup and so on. First step in this process is to set up the part operation. The part operation setup is shown in Figure 3-9. Thus, the part operation setup involves the selection of the machine used, reference machining axis system, part selection and stock selection in order to make the program understand the needs of the programmer.

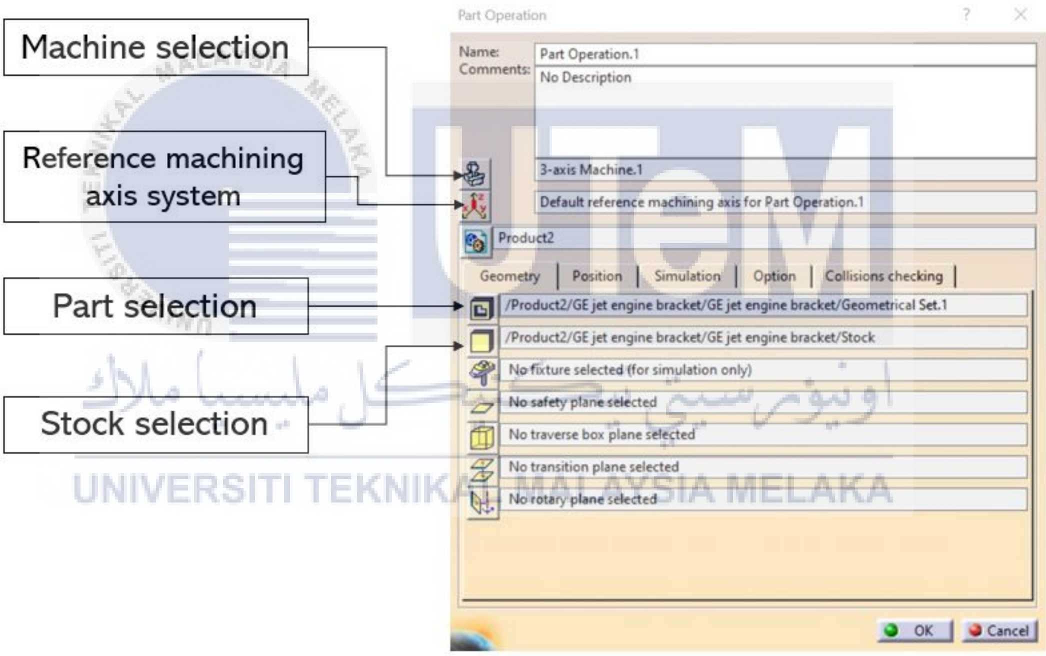


Figure 3-9: Part operation setup

The next step is to make a selection of a cutting tool under the resources list as listed in Figure 3-10. The resources list shown the machine used and cutting tool used which is 3 axis Machine and End mill D8 respectively.

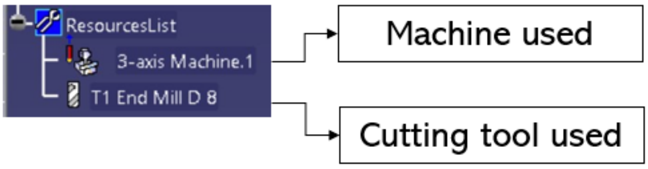


Figure 3-10: Resources list

After that, the roughing process is proceeded in this section. The roughing strategy parameters are distributed into 5 tabs. The roughing operation on CATIA V5 can be seen as illustrates in Figure 3-11. By default, all 5 tabs are displayed with all their parameters as shown in Table 3-11.

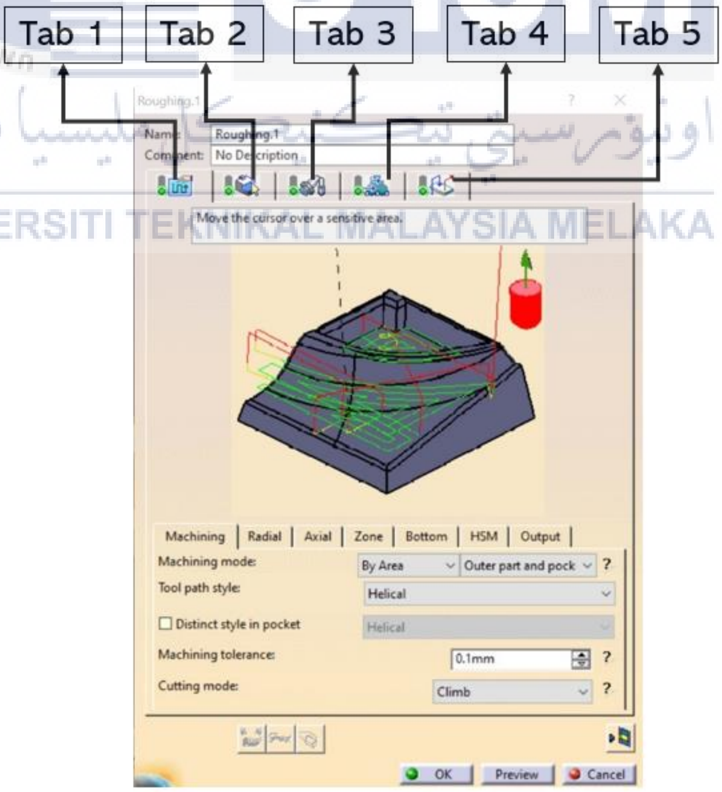
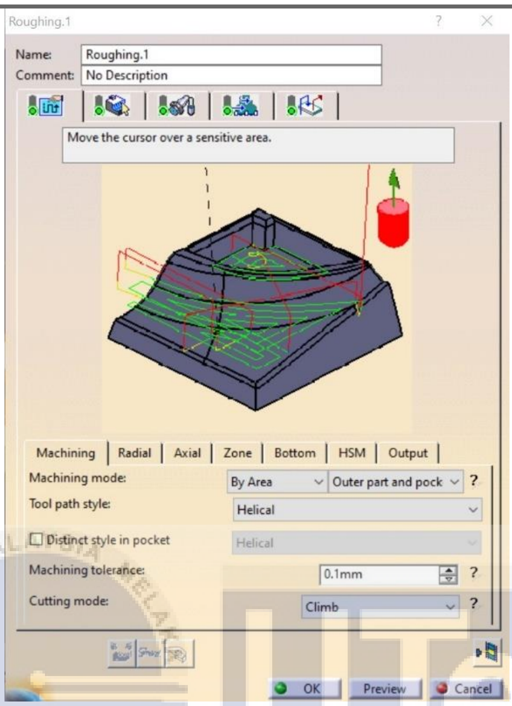
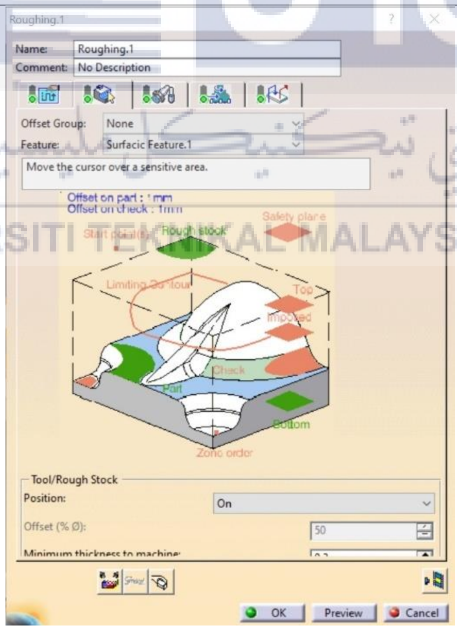
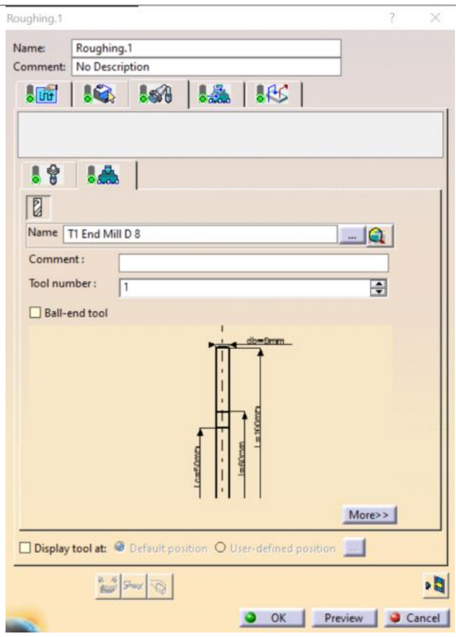
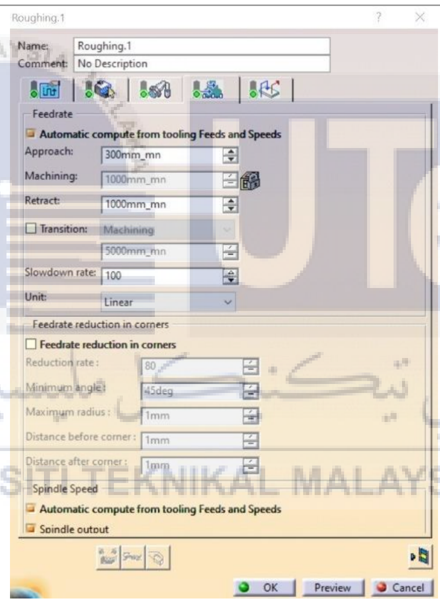
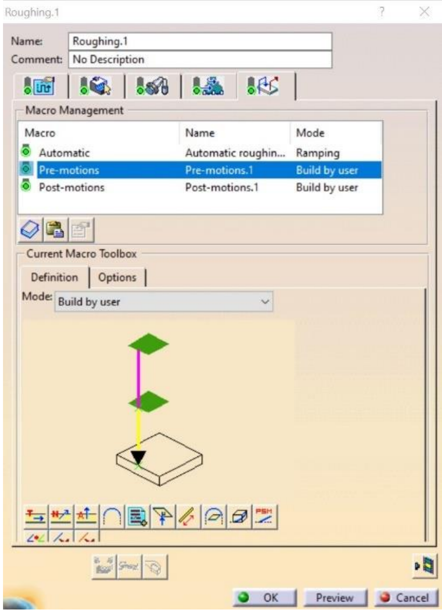


Figure 3-11: Roughing operation on CATIA V5

Table 3-1: 5 tabs of roughing process

Tab number	Figure	Description
1		Tab number 1 of the roughing process is basically the strategy used to machine the parts. It involved the strategy such as axial strategy, radial startegy and so on.
2		The second is refer to define the rough stock, part, bottom of the part and so on. This can help the program understand better the programmer needs.

3		Tab 3 is utilized to make a selection of cutting tool in roughing process.
4		The machining parameters (feed rate and spindle speed) can be setting in tab number 4. The approach and retract feed rate can be different by setting the parameter in this tab.

5		Tab 5 refers to the macro plane, which define the approach plane and safety plane. Pre-motions refers to approach and post motions refers to retract.

After the 5 tabs of roughing process has been setting up. The simulation of the roughing process can be run. The simulation result can be shown in Figure 3-12.

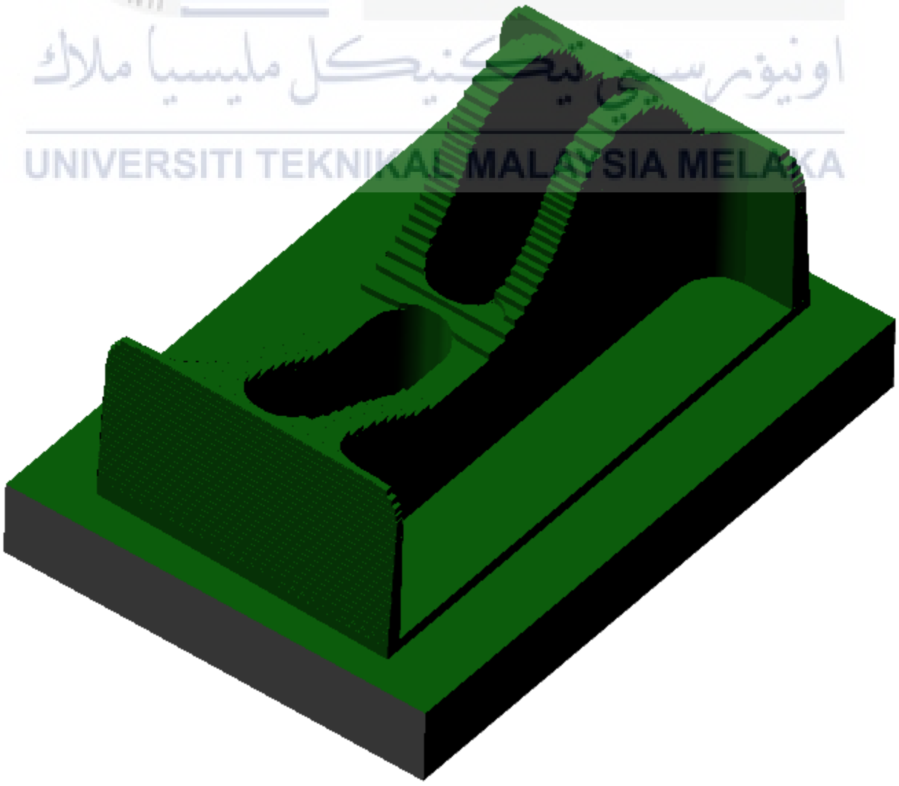


Figure 3-12: Simulation result of roughing process

3.5 Machine Specifications

The machine used for this experiment was DMGMORI DMU 60 Evo based on Figure 3-13, a CNC 3-axis Milling Machine. Specification of the machine is given in Table 3-2.

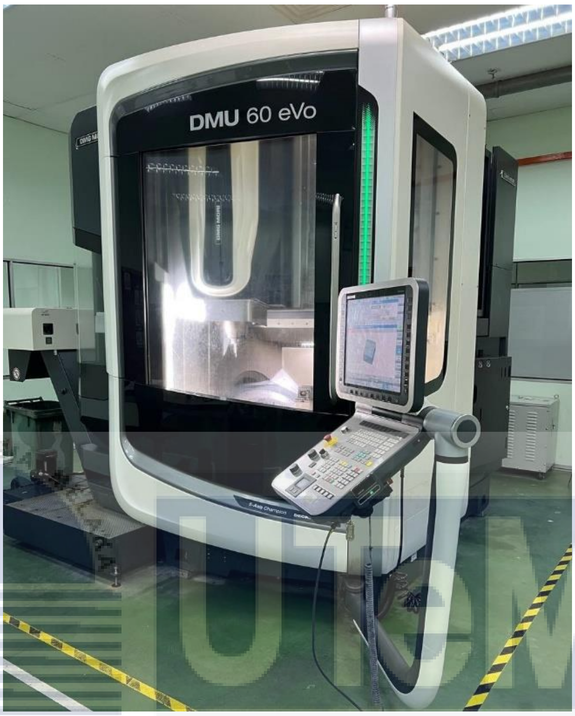


Figure 3-13: DMGMORI DMU 60 Evo CNC 3-Axis Milling Machine

Table 3-2: Specification of DMGMORI DMU 60 Evo CNC 3-Axis Milling Machine

Parameters	Specifications
Spindle speed range	20-24000 rpm
Maximum spindle speed	24000 rpm
Maximum feed speed	50 m/min or 164 ft/min
Maximum X-axis travel distance	600 mm
Maximum Y-axis travel distance	500 mm
Maximum Z-axis travel distance	500 mm

3.6 Tool Geometry

The cutting tool used in this experiment is only one type of cutting tool which is uncoated end mill carbide with diameter 8mm, 2 number of flutes and standard helix angle 30° based on Figure 3-14. However, the number of cutting tools used in this experiment is 9 since the Taguchi method L9 was utilized. The drawing of cutting tool is shown in Figure 3-15. The cutting tool specification is stated on Table 3-3.

Figure 3-14: Uncoated end mill carbide with D8, 2 flutes and helix angle 30°

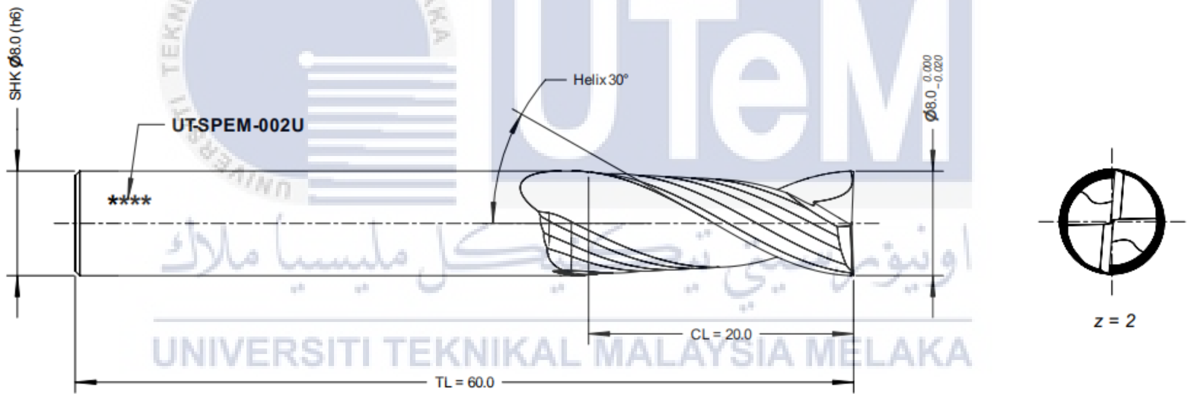


Figure 3-15: Drawing of cutting tool

Table 3-3: Cutting tool specification

Type of cutting tool	Diameter (mm)	Number of flutes	Helix angle (°)	Cutting length (mm)	Total length (mm)
End mill	8.0	2	30	20.0	60.0

3.7 Material Details

The material used in this experiment was Aluminum Alloys 6xxx series which is Al-6061 T651 according to Figure 3-16 below. The 6xxx series aluminum alloys refer to a group of aluminum alloys that primarily consist of aluminum, magnesium, and silicon as the major alloying elements. It typically contains approximately 97.9% aluminum, 1% magnesium, and 0.6% silicon.

Figure 3-16: Aluminum Alloys Al-6061 T651

3.8 Machining Parameters

The machining parameters used during the roughing of aluminum alloy 6xxx series material using DOE method. Taguchi method, which is L9 orthogonal arrays was used. Minitab software was utilized to set the number of runs and 2 factors that were used in this roughing process. Based on Table 3-4, it shows the machining parameters generated by Minitab software referring to the Taguchi L9 approach. Relationship between cutting speed (V_c), spindle speed (N), feed per tooth (f_z) and feed rate (V_f) are given by the formulas below:

Feed rate:

$$v_f = f_z \times n \times z_c \tag{3.1}$$

Cutting speed:

$$v_c = \frac{\pi \times D \times N}{1000} \tag{3.2}$$

Spindle speed:

$$N = \frac{v_c \times 1000}{\pi \times D} \tag{3.3}$$

Feed per tooth:

$$f_z = \frac{v_f}{N \times z_c} \tag{3.4}$$

Where, Vf = feed rate, Vc = cutting speed, N = spindle speed, fz = feed per tooth, D = diameter of cutting tool

Table 3-4: Machining parameters used in this experiment

Run	Cutting speed, Vc (m/min)	Spindle speed, N (RPM)	Feed per tooth, f_z (mm)	Feed rate, Vf (mm/min)
1	150	5968	0.05	597
2	150	5968	0.10	1194
3	150	5968	0.15	1790
4	200	7957	0.05	796
5	200	7957	0.10	1591
6	200	7957	0.15	2387
7	250	9946	0.05	995
8	250	9946	0.10	1989
9	250	9946	0.15	2984

3.9 Surface Roughness Measurement

In order to obtain the value of surface roughness (Ra), the machined parts are measured using surface roughness tester Surftest SJ-410 manufactured by Mitutoyo. This machine is a common type of surface roughness tester that is used in current industry for surface inspection of machined materials. Furthermore, SJ-410 has the ability to measure surface with various parameters. As shown in Figure 3-17, stylus is a small sensor that is used to measure the roughness of a surface. Stylus will move with distance 4mm on each measurement. It will take 5 reading points of each measurement and the average reading will determine the Ra value.

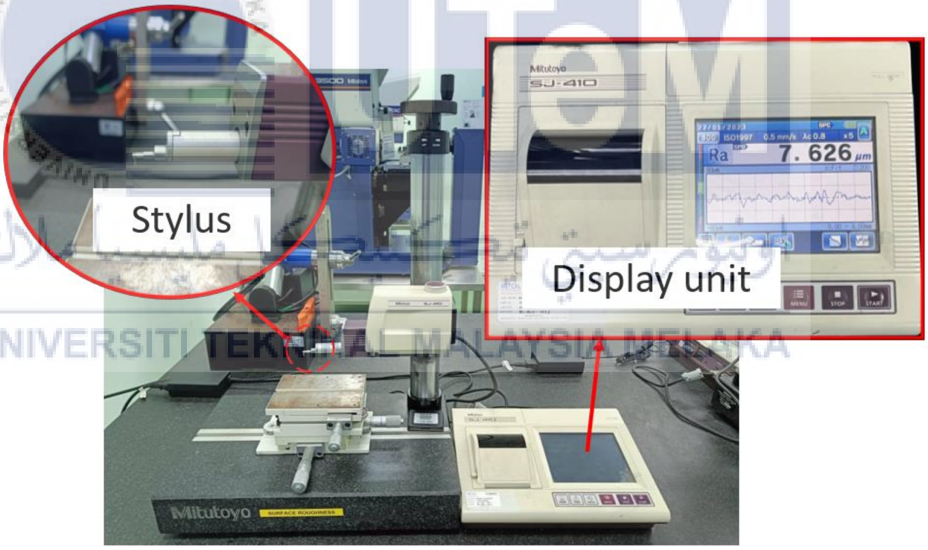


Figure 3-17: Surface roughness tester Surftest SJ-410

3.10 Dimensional Accuracy

Analysis of the dimension's accuracy of the sample aerospace machined parts is performed by using CMM (Coordinate Measurement Machine) namely WENZEL XO 50. The function of the CMM is to determine the geometric size of the part. Based on Figure 3-18, probe is a one part in process analysis of accuracy. In addition, probe is used to hold the stylus system while stylus system acts as positions the stylus system. The format used to transfer the CAD model to the CMM is IGES format.

Figure 3-18: CMM (Coordinate Measurement Machine)

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

In this chapter, the results obtained from this experiment namely surface roughness, and dimensional accuracy were analyses. The problem regarding this analysis was discussed. By determining the optimal machining parameters and understanding their impact on surface quality, it can enhance manufacturing processes, improve dimensional accuracy, and reduce tooling costs. The discussion part would be discussed to determine the optimum machining parameters for roughing pocketing profiles in the aerospace industry. The optimum machining parameter will be obtained at the end of this chapter.

4.2 Surface Roughness Analysis

Surface roughness plays a vital role in obtained high quality surface finish of machined aluminum material in production. Factors such as cutting speed, spindle speed, and feed rate play a role in influencing the surface finish. The first analysis conducted in this experiment is surface roughness analysis. This analysis was carried out using surface roughness tester Surftest SJ-410 manufactured by Mitutoyo as described in Section 3.9. The analysis is conducted on two sections of the pocket, namely the open pocket and the closed pocket. There are 7 points on the closed pocket and 12 points on the open pocket. All these points are illustrated in Figures 4-1, 4-2, and 4-3.

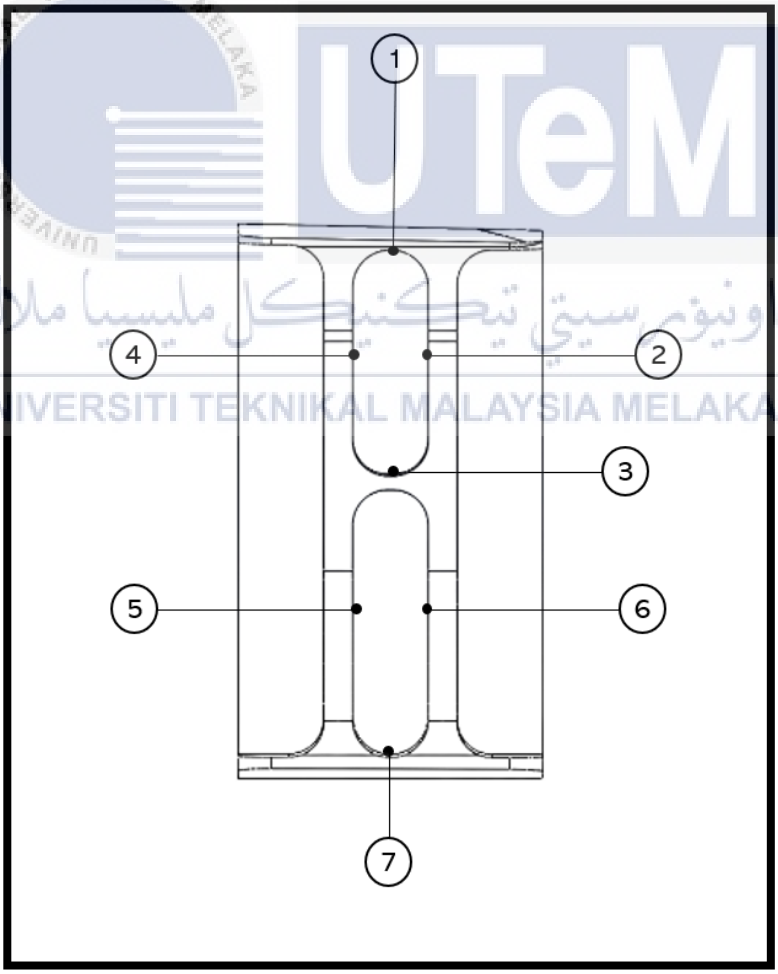


Figure 4-1: Points taken for surface roughness analysis on the ***closed pocket***

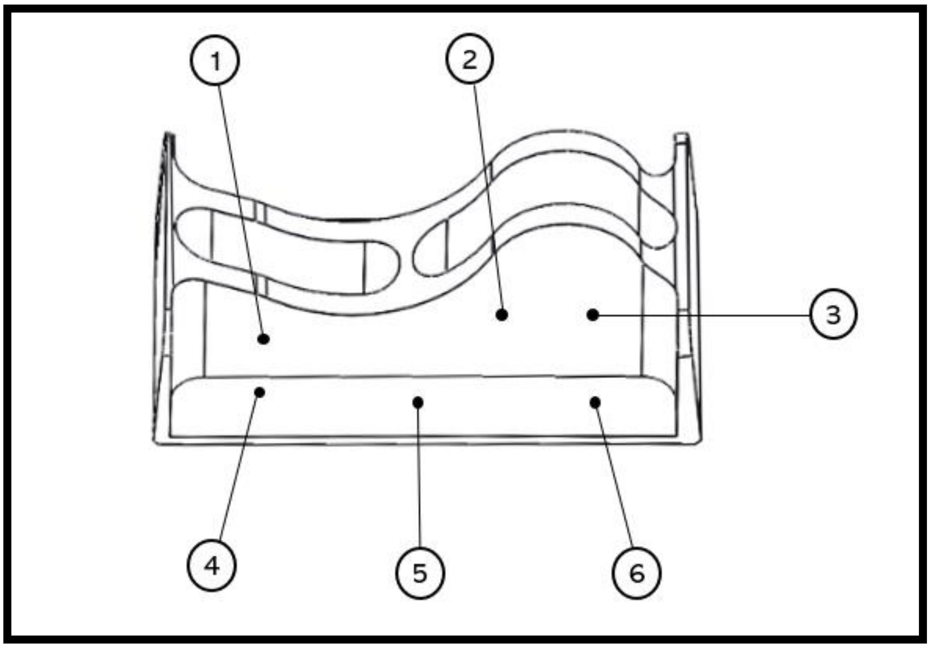


Figure 4-2: Points taken for surface roughness analysis on the right side of ***open pocket***

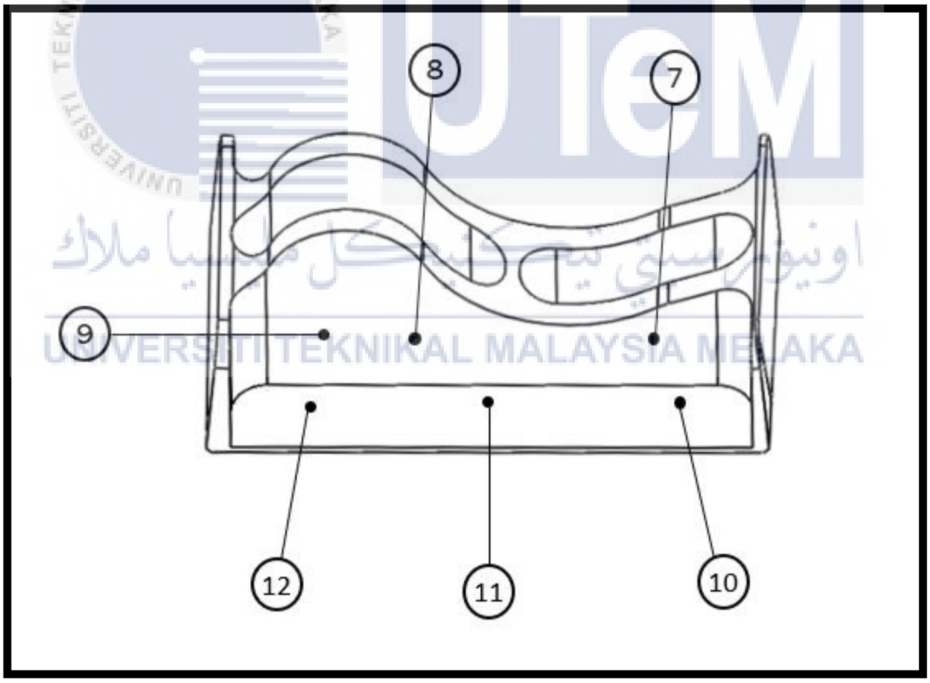


Figure 4-3: Points taken for surface roughness analysis on the left side of ***open pocket***

Table 4-1: Data for surface roughness analysis on the ***closed pocket*** of the part.

Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)	Run	Surface roughness (µm)									
			Closed pocket 1				Average	Closed pocket 2			Average	Avg. all surface
			1	2	3	4		5	6	7		
150	0.05	1	2.877	0.732	2.348	1.934	1.973	4.076	1.572	2.465	2.704	2.339
	0.10	2	2.418	0.376	1.326	1.367	1.372	1.886	2.457	1.957	2.100	1.736
	0.15	3	2.684	1.639	1.542	2.699	2.141	1.946	1.828	2.319	2.031	2.086
200	0.05	4	2.436	0.235	1.625	1.363	1.415	3.721	3.183	2.259	3.054	2.235
	0.10	5	2.987	1.676	1.779	2.466	2.227	2.623	2.038	2.747	2.469	2.348
	0.15	6	2.455	2.101	1.820	2.291	2.167	1.278	2.828	2.206	2.104	2.135
250	0.05	7	2.537	2.234	3.004	2.228	2.501	1.960	1.631	2.550	2.047	2.274
	0.10	8	2.296	1.690	2.113	2.029	2.032	3.076	2.070	2.620	2.589	2.310
	0.15	9	2.345	0.393	2.430	2.100	1.817	1.871	2.614	2.839	2.441	2.129

Table 4-2: Data for surface roughness analysis on the ***open pocket*** of the part

Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)	Run	Surface roughness (µm)																
			Open pocket 1			Average	Open pocket 2			Average	Open pocket 3			Average	Open pocket 4			Average	Avg. all surface
			1	2	3		4	5	6		7	8	9		10	11	12		
150	0.05	1	1.292	1.613	1.522	1.476	0.340	0.433	0.791	0.521	1.723	1.339	1.487	1.516	1.187	0.514	0.937	0.879	1.098
	0.10	2	1.558	2.005	1.637	1.733	0.785	0.533	1.085	0.801	1.670	1.141	1.561	1.457	0.853	0.921	0.492	0.755	1.187
	0.15	3	2.740	2.250	1.734	2.241	1.292	0.958	1.353	1.201	1.641	1.642	1.629	1.637	1.036	1.241	1.438	1.238	1.580
200	0.05	4	1.502	1.954	1.506	1.654	1.183	0.635	1.375	1.064	1.785	1.190	1.593	1.523	0.797	0.615	0.523	0.645	1.222
	0.10	5	3.179	2.728	2.496	2.801	1.083	0.855	1.409	1.116	1.058	2.096	1.337	1.497	1.073	0.634	1.089	0.932	1.586
	0.15	6	2.160	2.258	2.240	2.219	1.174	0.999	1.524	1.232	1.581	2.454	1.692	1.909	1.425	0.797	1.082	1.101	1.616
250	0.05	7	2.450	2.057	2.148	2.218	1.264	1.025	1.185	1.158	3.073	2.944	2.340	2.786	1.044	0.897	0.952	0.964	1.782
	0.10	8	2.286	1.740	1.746	1.924	0.951	0.893	0.716	0.853	1.903	2.883	2.883	2.556	1.400	0.943	0.956	1.100	1.608
	0.15	9	3.514	1.876	1.818	2.403	1.375	1.107	1.838	1.440	2.182	2.269	2.121	2.191	1.697	1.677	1.342	1.572	1.901

4.2.1 Surface Roughness Data Analysis – Closed Pocket

In accordance with Table 4-1, the surface roughness data for the closed pocket had been analyzed in a number of different graphs to investigate any significant effects or trends. The average data for each surface was used for the overall analysis. The graph in Figure 4-4 presents the average surface roughness data for the closed pocket versus number of runs. The Y axis represents the average value for the surface roughness of all closed pocket surfaces in µm. Meanwhile, the X axis represents the nine runs of the experimental setup.

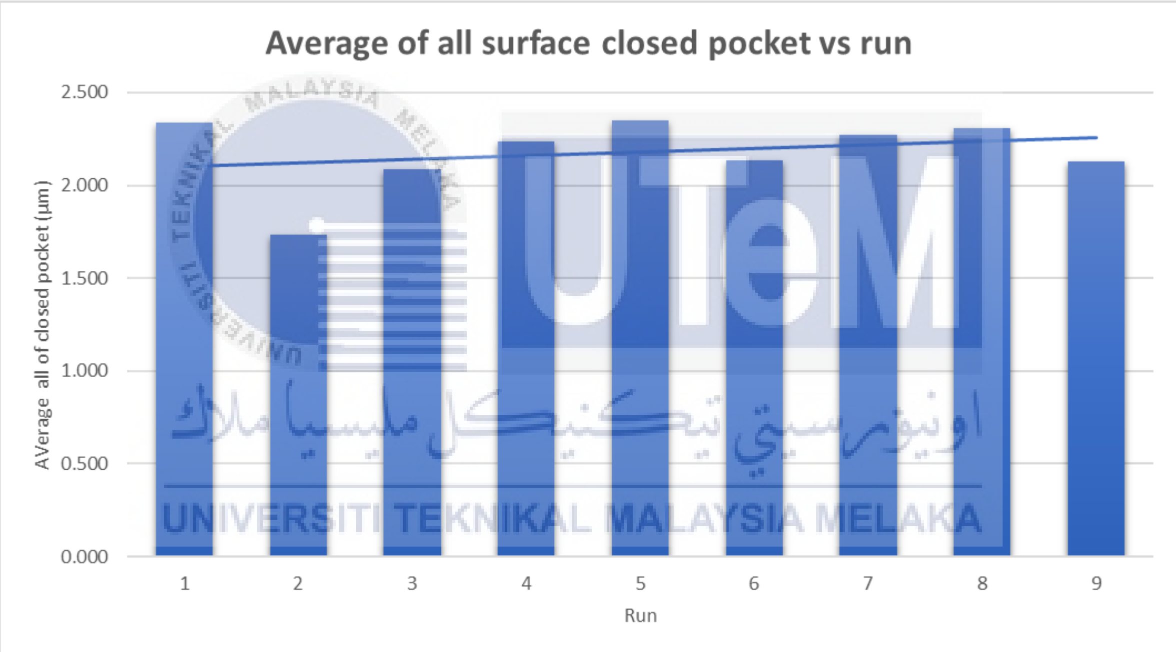


Figure 4-4: Graph data for surface roughness analysis on the ***closed pocket*** of the part

From the graph in Figure 4-4, it is evident that the trendline shows an upward trajectory from run 1 to run 9. This is attributed to the increase in readings for cutting speed as observed in the machining parameter table as mentioned in Section 3.8 (Table 3-4). A hypothesis that can be formulated is that an increase in cutting speed is directly associated with an increase in surface roughness readings.

4.2.2 Surface Roughness Data Analysis – Open Pocket

Analyzing the surface roughness data for the open pocket from Table 4-2 involved the examination of various graphs to identify any significant effects or trends. The overall analysis utilized the average data for each surface. Based on Figure 4-5, the graph illustrates the average surface roughness data for the open pocket plotted against the number of runs. The Y-axis denotes the average surface roughness value for all surfaces within the open pocket, measured in micrometers (μm). Simultaneously, the X-axis corresponds to the nine runs conducted in the experimental setup.

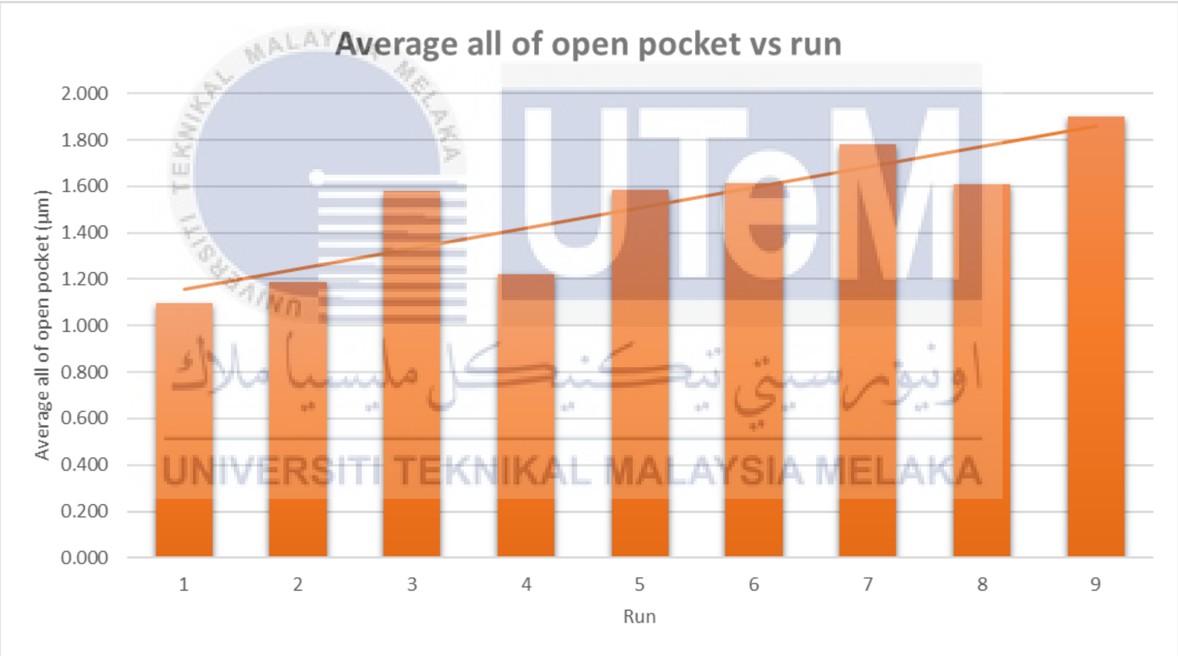


Figure 4-5: Graph data for surface roughness analysis on the ***open pocket*** of the part

In the analysis of surface roughness for open pockets, the trendline displayed in the graph on Figure 4-5 appears to be similar when compared with the graph for closed pockets. This indicates that the study accurately asserts that an increase in cutting speed corresponds to an increase in surface roughness readings.

4.3 Dimensional Accuracy Analysis

The second analysis for this experiment will be conducted to determine the dimensional accuracy of the machined pocketing profiles. This analysis is carried out by the CMM (Coordinate Measurement Machine) as described in Section 3.11. To carry out the dimensional accuracy analysis, this machined part is divided into three aspects: surface, perpendicularity, and flatness. The surface represents the area to be tested, perpendicularity assesses the precision between two surface planes, and flatness evaluates the straightness of each surface. The surface and perpendicularity have 6 points, while flatness has 10 points as shown in Figure 4-6, 4-7 and 4-8. According to Table 4-3, if the deviation percentage reading is less than 50%, it will be displayed in green, while a deviation percentage exceeding 50% will result in a yellow color. Furthermore, when the deviation percentage surpasses 100%, it will be indicated in red.

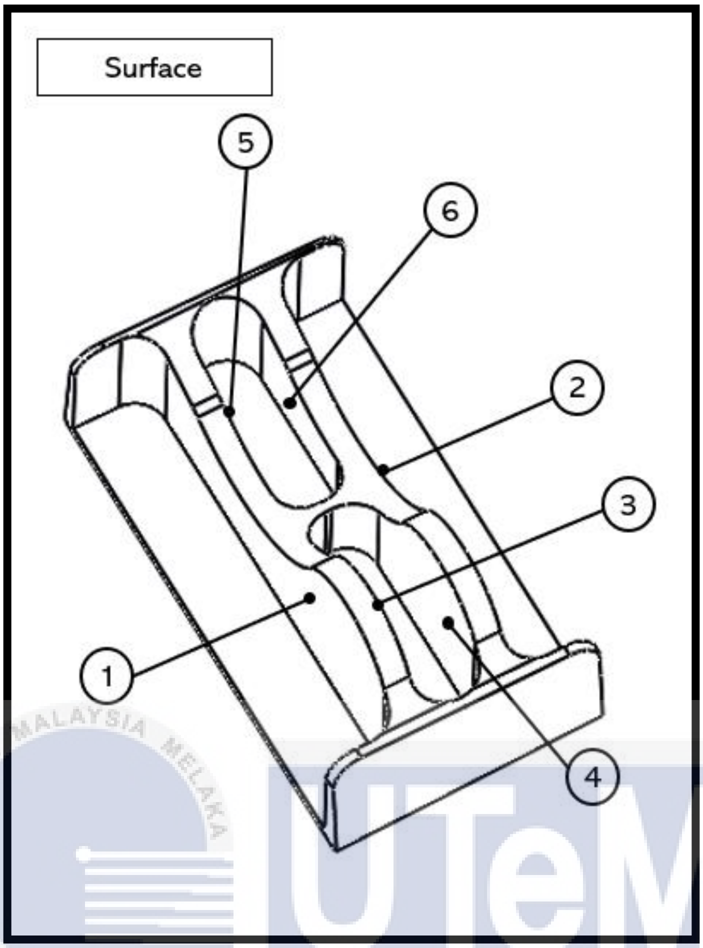


Figure 4-6: Points taken for dimensional accuracy of the ***surface*** aspects

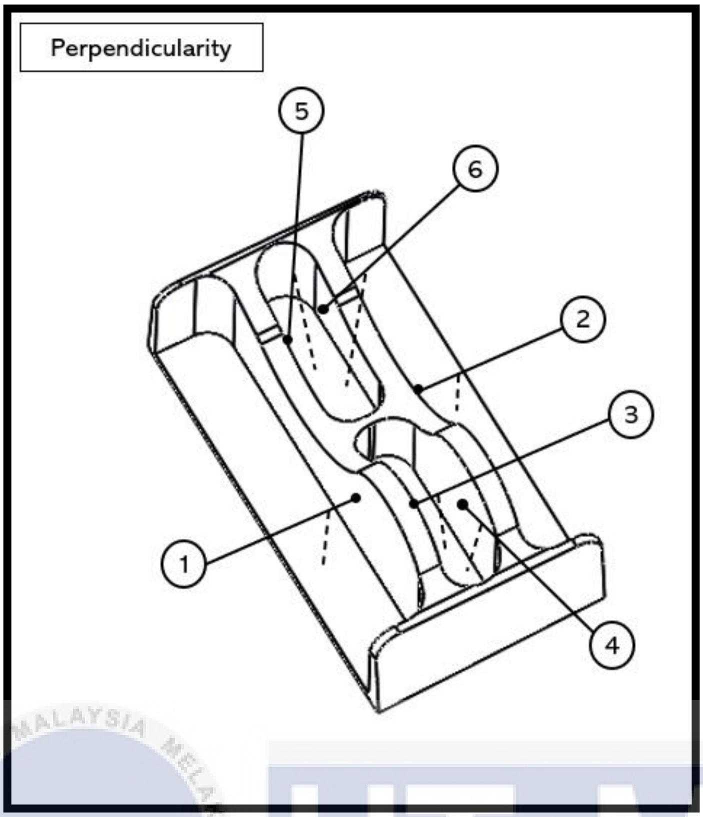


Figure 4-7: Points taken for dimensional accuracy of the ***perpendicularity*** aspects

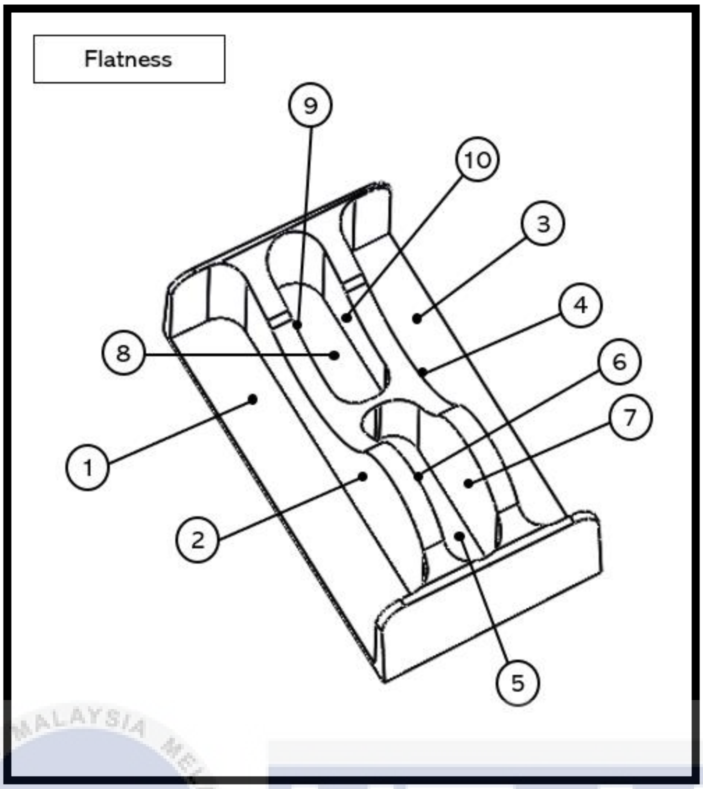


Figure 4-8: Points taken for dimensional accuracy of the ***flatness*** aspect

Table 4-3: Deviation percentage data for ***surface, perpendicularity,*** and ***flatness***

Run\Point	Deviation percentage (%)																								
	Surface						Average surface	Perpendicularity						Average perpendicularity	Flatness										Average flatness
	1	2	3	4	5	6		1	2	3	4	5	6		1	2	3	4	5	6	7	8	9	10	
1	43	16	27	28	20	41	29	49	9	15	10	5	6	15	1	1	0	1	0	1	6	0	1	5	1
2	12	9	22	19	22	42	21	15	40	10	30	30	2	21	3	3	1	1	10	11	2	1	4	1	4
3	26	18	89	16	33	41	37	23	28	40	12	10	3	19	0	5	3	16	6	2	8	6	2	12	6
4	34	13	28	31	35	49	32	55	27	11	2	1	12	18	3	4	0	6	0	4	13	0	3	2	4
5	30	30	33	44	33	54	37	71	31	17	17	48	12	32	1	9	3	29	1	0	1	3	5	0	5
6	13	10	23	47	27	44	27	74	29	97	58	25	20	51	4	1	2	3	17	1	1	5	9	1	4
7	106	35	85	126	67	76	82	38	1	13	9	33	23	19	1	7	3	5	1	19	8	3	11	4	6
8	58	17	44	44	42	57	44	22	11	3	9	21	46	19	1	2	3	10	6	2	2	1	22	17	7
9	49	14	112	64	76	86	67	32	44	7	26	38	59	34	1	0	3	4	4	6	2	6	12	5	4

4.3.1 Dimensional Accuracy Data Analysis – Surface

According to the table deviation percentage data for surface, perpendicularity, and flatness as indicated in Table 4-3, numerous graphs have been derived from this data. These graphs are divided into three sections: surface, perpendicularity, and flatness. In Figure 4-9, the graph illustrates the graphical data for dimensional accuracy analysis on the surface aspects against the number of runs. The Y-axis denotes the average deviation percentage (%) of surface aspects. Concurrently, the X-axis corresponds to the nine runs conducted in the experimental setup.

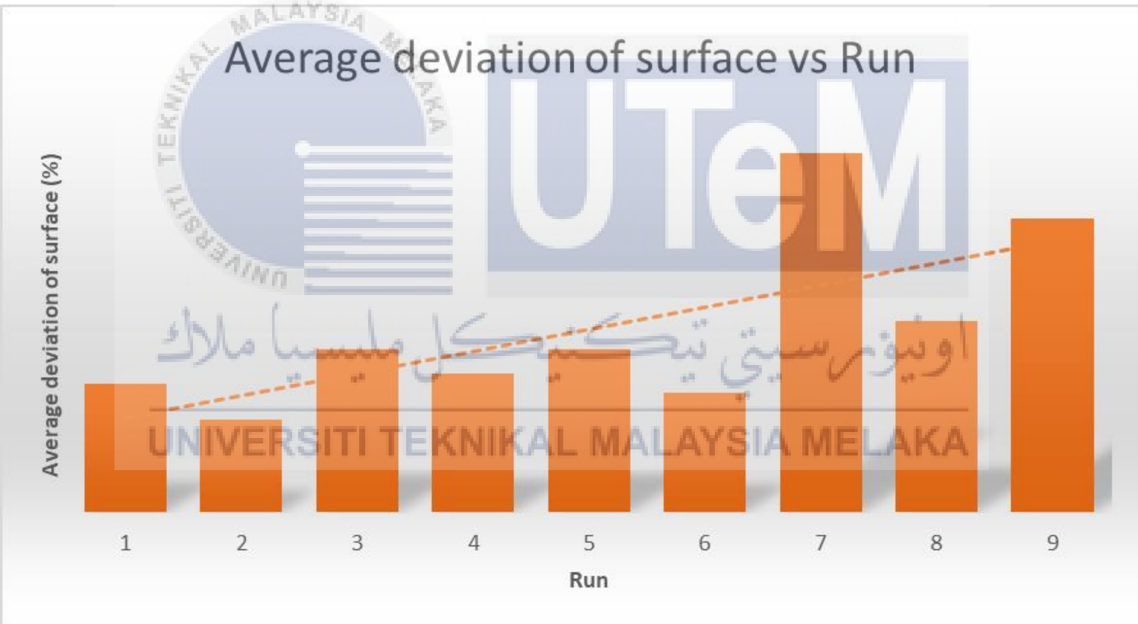


Figure 4-9: Graph data for dimensional accuracy analysis on the ***surface***

As illustrates on the graph in Figure 4-9, the trendline on the graph indicates an upward trend. The cutting speed readings from run 1 to 9 show an increasing trend. From this information, it suggests that as the cutting speed readings increase, the deviation readings for dimensional accuracy also increase.

4.3.2 Dimensional Accuracy Data Analysis – Perpendicularity

Figure 4-10 displays graphical data depicting the analysis of dimensional accuracy in perpendicularity aspects over the course of the number of runs. The Y-axis represents the average deviation percentage (%) of perpendicularity aspects, while the X-axis corresponds to the nine runs performed in the experimental setup.

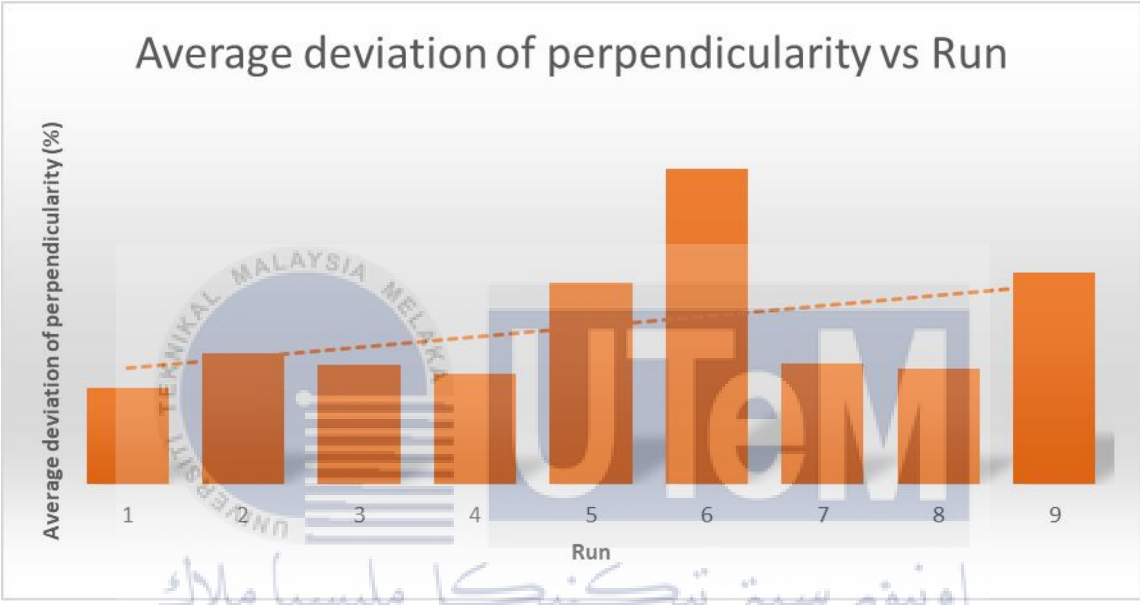


Figure 4-10: Graph data for dimensional accuracy analysis on the ***perpendicularity***

In the analysis of dimensional accuracy for perpendicularity aspects, the trendline on the graph in Figure 4-10 also indicates an upward trend, similar to the graph for surface aspects as mentioned in Figure 4-9. Therefore, it can be confidently stated that an increase in cutting speed corresponds to an increase in deviation readings.

4.3.3 Dimensional Accuracy Data Analysis – Flatness

Graphical data in Figure 4-11 illustrates the analysis of dimensional accuracy in flatness aspects throughout the various runs. The Y-axis indicates the average deviation percentage (%) related to flatness aspects, while the X-axis correlates with the nine runs executed in the experimental setup.

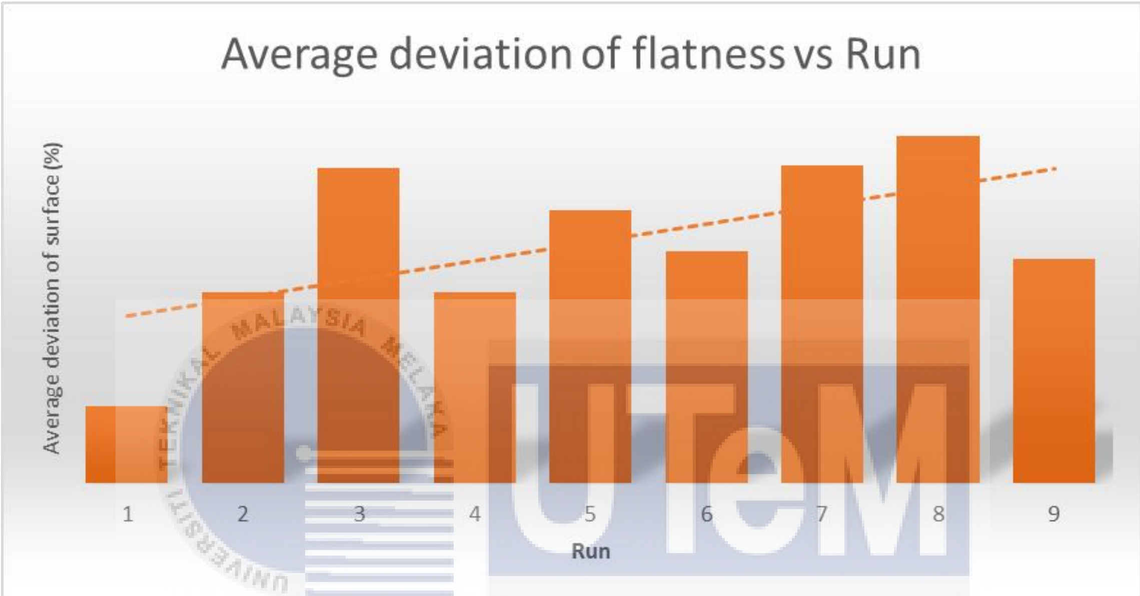


Figure 4-11: Graph data for dimensional accuracy analysis on the ***flatness***

Regarding the dimensional accuracy in flatness aspects, the trendline on Figure 4-11 shows an upward pattern, much like the trends seen in the graphs for surface and perpendicularity aspects in Figures 4-9 and 4-10. Hence, it is strongly indicated that as the cutting speed increases, the deviation readings also increase. It can be concluded that lower cutting speed readings contribute to better dimensional accuracy in the parts.

4.4 Signal to Noise Ratios Analysis

One of the methods used to analyze data for process optimization is Signal to Noise Ratios Analysis. In this analysis, there are five analyses involved which is in terms of surface roughness is closed and open pockets, in terms of dimensional accuracy are surface, perpendicularity and flatness aspects. This analysis was obtained by utilized of Minitab 21 software.

The first analysis for Signal-to-Noise Ratios is surface roughness for closed pocket. Figure 4-12 shows mean of SN ratios for cutting speed and feed per tooth in terms of surface roughness for closed pocket obtained. The gradient of the graphs clearly shows that cutting speed is the most significant factor, followed feed per tooth. In addition, the result was supported by the response table for signal to noise ratios as in Table 4-4. The Delta from the response table represents the gradient of the graph. From Table 4-4, it can be seen the Delta value of the cutting speed is higher than feed per tooth. If the Delta value is higher means that the cutting speed represents the factor that influences the surface roughness followed by the feed per tooth.

Table 4-4: Response Table for Signal to Noise Ratios ***(closed pocket)***

Response Table for Signal to Noise Ratios

Smaller is better

Level	Cutting Speed	Feed per tooth
1	-6.185	-7.166
2	-6.996	-6.493
3	-6.991	-6.513
Delta	0.811	0.673
Rank	1	2

The highest mean SN values determine the optimal condition. As illustrated in Figure 4-12, the optimal cutting speed and feed per tooth for achieving the desired surface roughness in the closed pocket are 150 m/min and 0.10 mm, respectively.

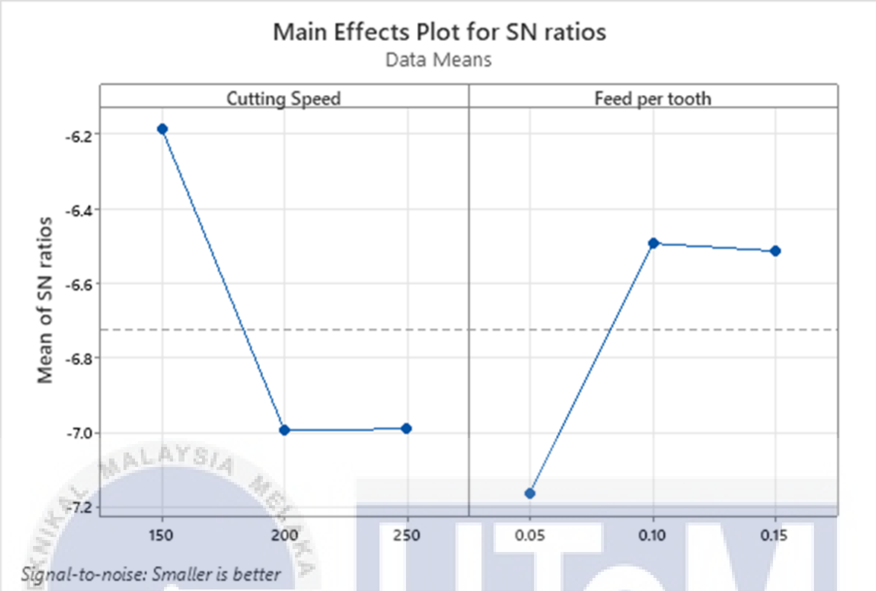


Figure 4-12: Mean of SN ratios for cutting speed and feed per tooth ***(closed pocket)***

The second analysis for Signal-to-Noise Ratios is surface roughness for open pocket. The response table for signal to noise ratios in Table 4-5 reveals that the Delta value for cutting speed exceeds that of feed per tooth which is 2.818. This indicates that cutting speed holds greater significance as a factor influencing the surface roughness of the open pocket. As illustrates in Figure 4-13 visually shows the higher value of cutting speed and feed per tooth is 150 m/min and 0.05 mm, it represents the optimal condition for cutting speed and feed per tooth, identified as 150 m/min and 0.05 mm, respectively.

Table 4-5: Response Table for Signal to Noise Ratios ***(open pocket)***

Response Table for Signal to Noise Ratios

Smaller is better

Level	Cutting Speed	Feed per tooth
1	-2.090	-2.522
2	-3.304	-3.208
3	-4.908	-4.573
Delta	2.818	2.050
Rank	1	2

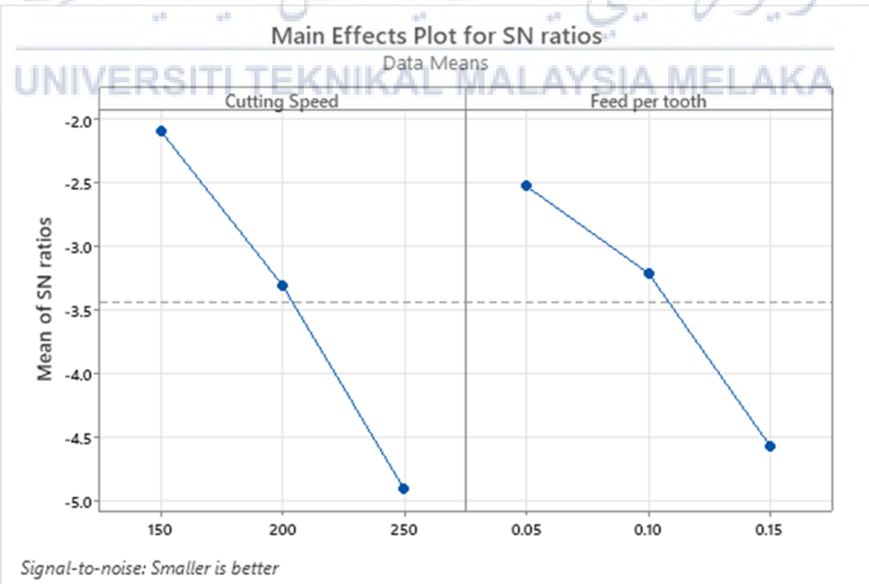


Figure 4-13: Mean of SN ratios for cutting speed and feed per tooth ***(open pocket)***

The third examination involves assessing Signal-to-Noise Ratios concerning dimensional accuracy in relation to surface aspects. The response table in Table 4-6 indicates a Delta value of 6.79 for cutting speed, which is higher than that for feed per tooth. This suggests that cutting speed has a more substantial impact on the dimensional accuracy of surface aspects. As depicted in Figure 4-14, the graph visually presents the higher values for cutting speed and feed per tooth, identified as 150 m/min and 0.10 mm, respectively. These values represent the optimal conditions for cutting speed and feed per tooth in terms of achieving dimensional accuracy.

Table 4-6: Response Table for Signal to Noise Ratios ***(surface)***

Response Table for Signal to Noise Ratios

Smaller is better

Level	Cutting speed	Feed per tooth
1	-29.07	-32.55
2	-30.04	-30.21
3	-35.86	-32.21
Delta	6.79	2.34
Rank	1	2

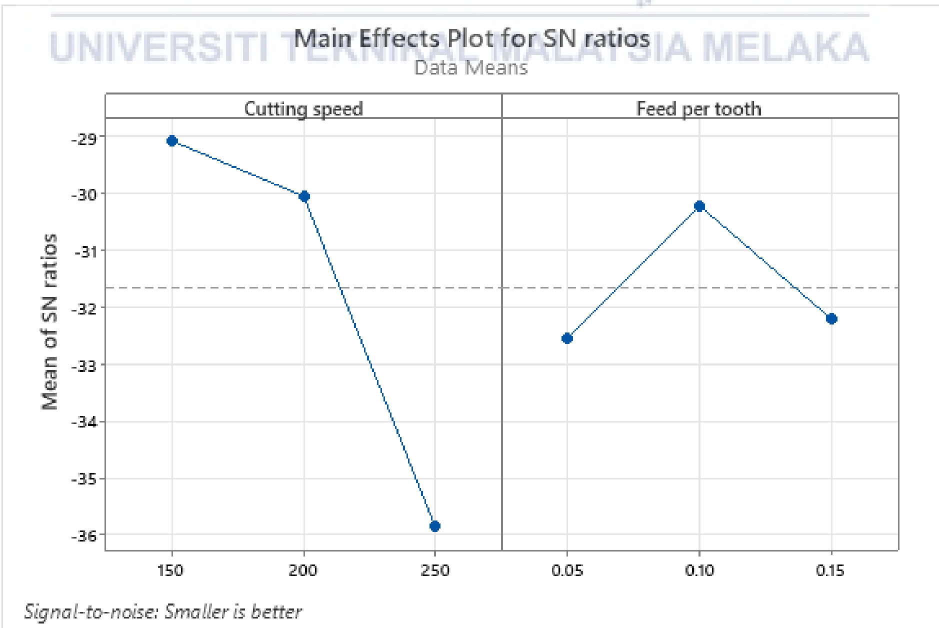


Figure 4-14: Mean of SN ratios for cutting speed and feed per tooth ***(surface)***

The fourth investigation focuses on evaluating Signal-to-Noise Ratios in terms of dimensional accuracy with respect to perpendicularity aspects. The response table presented in Table 4-7 indicates that the Delta value for feed per tooth is higher than that of cutting speed, specifically at 5.33. This suggests that feed per tooth plays a more substantial role in influencing dimensional accuracy in perpendicularity aspects. As depicted in Figure 4-15, the graph visually represents the higher values for cutting speed and feed per tooth, identified as 150 m/min and 0.05 mm, respectively. These values signify the optimal conditions for cutting speed and feed per tooth in achieving dimensional accuracy.

Table 4-7: Response Table for Signal to Noise Ratios ***(perpendicularity)***

Response Table for Signal to Noise Ratios

Smaller is better

Level	Cutting speed	Feed per tooth
1	-25.33	-24.86
2	-29.80	-27.39
3	-27.30	-30.19
Delta	4.47	5.33
Rank	2	1

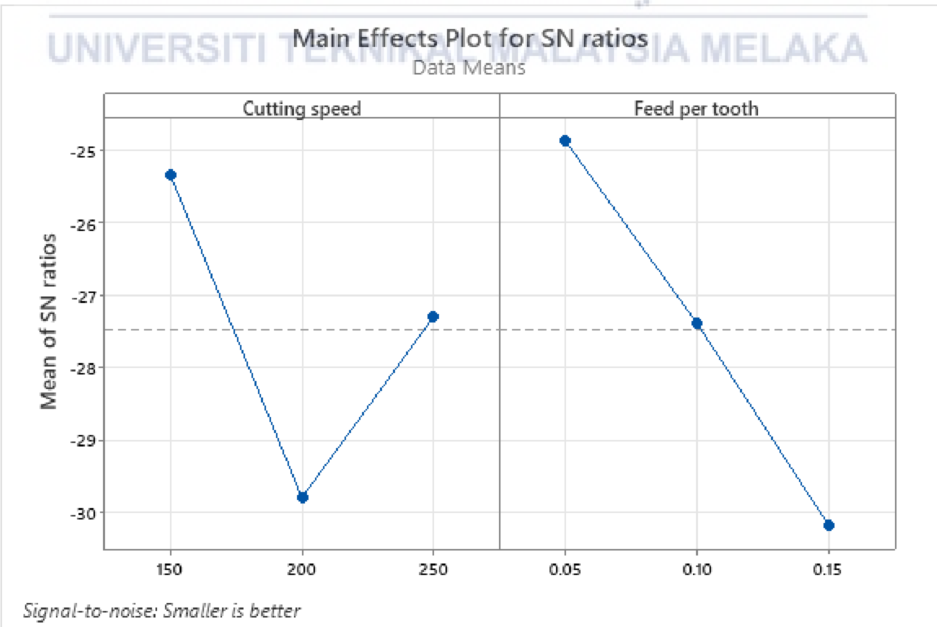


Figure 4-15: Mean of SN ratios for cutting speed and feed per tooth ***(perpendicularity)***

The fifth examination revolves around assessing Signal-to-Noise Ratios concerning dimensional accuracy with regards to flatness aspects. The response table provided in Table 4-8 shows that the Delta value for cutting speed surpasses that of feed per tooth, notably at 4.85. This implies that feed per tooth holds a more significant role in impacting dimensional accuracy in perpendicularity aspects. As illustrated in Figure 4-16, the graph visually depicts the elevated values for cutting speed and feed per tooth, specifically identified as 150 m/min and 0.05 mm, respectively. These values indicate the optimal conditions for cutting speed and feed per tooth to attain dimensional accuracy.

Table 4-8: Response Table for Signal to Noise Ratios ***(flatness)***

Response Table for Signal to Noise Ratios

Smaller is better

Level	Cutting speed	Feed per tooth
1	-10.00	-10.03
2	-12.78	-13.95
3	-14.86	-13.66
Delta	4.85	3.92
Rank	1	2

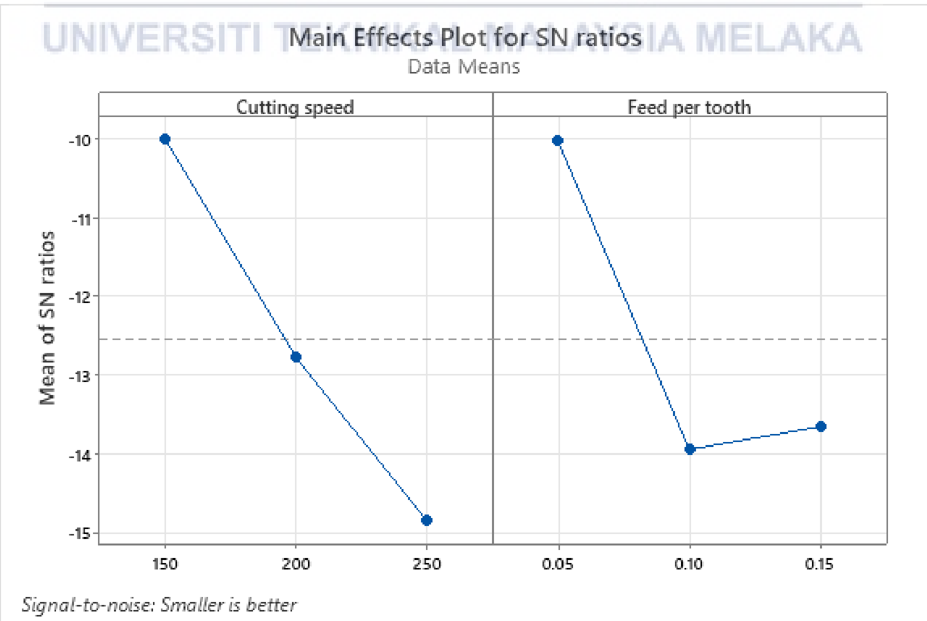


Figure 4-16: Mean of SN ratios for cutting speed and feed per tooth ***(flatness)***

4.5 Summary

Table 4-9: Summary table for optimization of machining parameters in terms of surface roughness and dimensional accuracy

		Optimization of machining parameter	
		Cutting speed, Vc (m/min)	Feed per tooth, fz (mm)
Surface Roughness Analysis	**Closed pocket**	150	0.10
	Open pocket	150	0.05
Dimensional Accuracy Analysis	**Surface**	150	0.10
	Perpendicularity	150	0.05
	Flatness	150	0.05

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter discusses the conclusion and future work that can be implemented from the investigation on the effect of machining parameters in closed and open pockets for aluminum material of the aerospace parts. This chapter also discusses the achievement of this research objective and emphasizes the overall performance. Providing recommendations and proposals for future work in terms of enhancing and contributing to the improvement of productivity in the aerospace industry.

5.2 Conclusion

In conclusion, the effect of machining parameters namely cutting speed and feed per tooth are successfully observed and evaluated. There were two main analyses carried out namely surface roughness, and dimensional accuracy. The influence of cutting speed and feed per tooth variations to the mentioned analyses in machining open pocket and closed pocket surfaces are successfully analyzed using the Signal to Noise Ratios graph. The results from the dimensional accuracy analysis concluded that the two factors namely the feed rates and spindle speeds affected the dimensional accuracy on the surface, perpendicularity, and flatness of the machined part. The optimized machining parameter to get best quality of surface quality is low cutting speed and low feed rate and worst cutting condition are high cutting speed and high feed rate. In this study, it is observed that to obtain the optimal cutting condition for surface roughness of closed pocket is 150 m/min and 0.10 mm for cutting speed and feed per tooth, respectively. However, the optimum cutting parameters for surface roughness of open pocket is 150 m/min for cutting speed and 0.05 mm for feed per tooth. In terms of dimensional accuracy analysis, the optimum machining parameters for obtaining the accurate surface dimension of the machined parts is 150 m/min for cutting speed and 0.10 mm for feed per tooth. On the other hand, the optimization of machining parameters in terms of perpendicularity and flatness aspects for dimensional accuracy share the same value of cutting speed and feed per tooth, which is 150 m/min and 0.05 mm respectively.

5.3 Recommendations

In the final stages of the research milestone, various suggestions and recommendations are offered to further enhance the outcomes obtained in the presented study. Firstly, investigate different toolpath optimization strategies for pocketing profiles in CNC milling. Evaluate the impact of toolpath variations on the efficiency and quality of the roughing process. This could include exploring adaptive toolpath planning algorithms. Next, explore the impact of different cutting tool technologies on the optimization process. Investigate the use of advanced tool coatings, materials, and geometries to enhance the efficiency and effectiveness of the roughing process. Lastly, conduct a parametric study to optimize machining parameters specifically for different materials commonly encountered in CNC milling. Investigate how material properties influence the optimal parameter settings and adapt the optimization process accordingly.

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APPENDICES

V10-Optimization of Machining Parameters during Roughing Machining Strategies of Pocketing Profiles – Aerospace Parts

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