



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEVELOPMENT OF VACUUM CLAMPING FOR MILLING MACHINE

This report submitted in accordance with requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for the Bachelor Degree of Engineering Technology (Bachelors of Engineering Technology Process) (Hons.)

by

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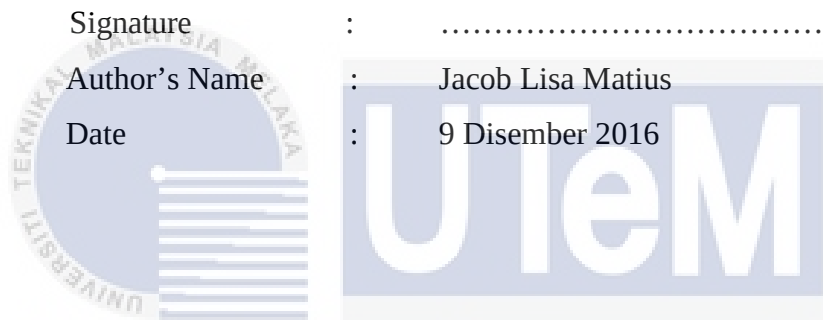
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APPROVAL

This report is submitted to the Faculty of Engineering Technology of UTeM as a partial fulfillment of the requirements for the degree of **Bachelor of Manufacturing Engineering Technology (Process And Technology) with Honours**. The member of the supervisory is as follow:



ABSTRAK

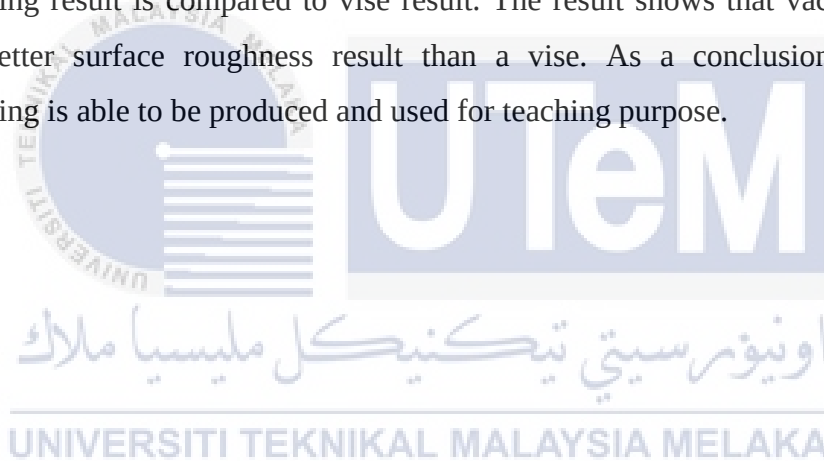
Mengapit bahan kerja dalam penggilingan biasanya menggunakan alat dan peranti pemegang seperti ragum untuk mengapit bahan kerja. Projek ini adalah untuk mencadangkan peranti pengapitan baru untuk proses memotong. Mesin yang digunakan dalam proses untuk menghasilkan produk ini adalah mesin penggilingan dan mesin gerudi. Selepas produk siap dihasilkan, satu ujian dilakukan pada pengapit vakum untuk menilai produk. Ujian ini adalah ujian kekasaran permukaan dan di mana hasil pengapit vakum dibandingkan dengan hasil ragum. Hasilnya menunjukkan bahawa pengapit vakum mempunyai hasil kekasaran permukaan yang lebih baik daripada ragum. Kesimpulannya, mengambil tindakan mengunci vakum ini mampu dihasilkan dan digunakan untuk tujuan mengajar.

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ABSTRACT

Clamping in milling usually use tools and holding devices such as vise to clamp workpiece. This project is to propose a new clamping device for cutting process. The machine used in the process to produce this product are milling machine and drilling machine. After product is finished, a testing is done on the vacuum clamping to evaluate the product. The testing are surface roughness testing and where vacuum clamping result is compared to vise result. The result shows that vacuum clamping has better surface roughness result than a vise. As a conclusion, the vacuum clamping is able to be produced and used for teaching purpose.



DEDICATION

I dedicate this thesis to my parents who have always been nearest to my heart and have been so close to me that I found them with me whenever I needed. It is their unconditional love that motivates me to get higher target. I also dedicate this thesis to my sisters(Ivy and Cherish) and brother (Darence) who are my nearest surrounders and have provided me with a strong love shield that always surround me and never let any sadness enter inside.



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CHAPTER 1

INTRODUCTION

1.1 Background

A clamp is a fastening device used to hold objects securely to prevent movement through the application of inward pressure. In demanding high speed cutting process, clamping is a key element. The workpiece that are being machined must be clamp securely and tightly to achieve precise and accurate machining results. Clamps provide two main purposes which are hold the workpiece against its locator and prevent movement of the workpiece. The primary cutting forces generated by operation should be resist by the locators.

Clamps functioning as to hold the position of the workpiece against the locators. Clamps should resist the secondary cutting force. When the cutting tools leaves the workpiece, secondary cutting forces is generated. In drilling for an example, in the axis of the drill, the primary forces is directed down and radially. Whereas the secondary forces are generated once the part tend to raise once the drill breaks through the alternative aspect of the half. The clamps need to be strong enough to secure the workpiece against the locators and also resist the secondary forces.

There are several types of clamp in the market. These clamps have different types of operation and different purpose. The first type of clamping is hand clamp. Hand clamp are hand operated tools, usually used for hold and positon workpiece while undergoing manufacturing or assembly. Hand clamp are used for many application such as door making, bookbinding, picture framing or as jigs in manufacturing process. Second is material handling clamp. Material handling clamps are used for holding heavy material as it being manipulated or lifted. This type of

clamping is usually used on cranes for lifting loads such as pipes and rails. They are also used in foundries and factory. The other types of clamps are hose clamp, cable clamp, pipe clamp and ground clamp.

For milling machine, there are two common vise that used for clamping workpiece which are universal angle milling vise and plain milling machine vise. For holding workpiece that has parallel sides, plain milling vise is used. While for universal angle vise, they are used when there are part that related in angle need to be machined.. There are a few limitation in using these vises such as cannot clamp workpiece with complex shape and no fix pressure acting on workpiece in holding the workpiece. So, this project is to develop a new clamping method which is vaccum clamping to overcome the limitation in these vises.



Figure 1.1 universal angle milling vise [retrieved from <http://www.toolzone.com/acatalog/11707.jpg>]



Figure 1.2 plain milling machine vise [retrieved from <http://www.use-enco.com/ProductImages/7003819-11.jpg>]

Vacuum clamping is one of the new clamping method in recent years. They are mostly used for clamp wood in woodworking. Vacuum clamping provide simple

machining so it will increase productivity and cost-saving. The advantage of using vacuum clamping is they will not cause any harm to the workpiece. Since vacuum clamping provides simple machining, no time-consuming labor is required. In a short time, vacuum clamping can clamp workpiece even when the workpiece does not have parallel side and various shapes. With all these advantages, vacuum clamp could be the best clamping method for milling machine.

1.2 Problem Statement

There are several setbacks in using vises in milling machine. Firstly is less adaptability to complex shapes of workpiece. As the vises only can hold workpiece with parallel side. Second, there is no fix force for clamping the workpiece using vises. Too much force acting on workpiece may damage the workpiece especially for soft material. Besides that, there are also safety issues in using the vises where cutting tool may collide with the vise. Colliding with the vise will cause damage to the cutting tools and also dangerous to the operator. Lastly, the clamping process using the vise takes much time. The clamping process alone takes too much time in whole milling cutting process operation.

1.3 Objective

The project objectives that have been determined are:

1. To design a new vacuum clamping method for milling machine
2. To choose suitable material for developing vacuum clamping
3. To develop a new vacuum clamping for milling machine
4. To evaluate the results based on the developed vacuum clamping

1.4 Project Scope

Scopes for this project is based on objectives that have stated and there are the several scopes that will be carrying out :

1. Design of the vaccum clamping is based on milling machine at laboratory and only for teaching purpose
2. Material that will be used for develop vacuum claming are aluminium and mild steel
3. Development of the vacuum clamping is using all machine that available at the factory
4. The result of surface roughness will be conducted to evaluate the result of vacuum clamping



CHAPTER 2

LITERATURE REVIEW

2.1 Introduction of machining process

Machining is a process where a piece of material is cut into a size and shape. There are three main principle in machining process which are milling, turning and drilling. Operation such as planing, boring, broaching, sawing and shaping fall into various categories.

Drilling is a process of producing round holes in a solid material or enlarging existing holes with the use of multi- tooth cutting tools called drills or drill bits(Marinov & Technology, n.d.). Enlarging an existing hole with multitooth cutting tools is also a drilling process. Various cutting tools are available for drilling, but the most common is the twist drill.

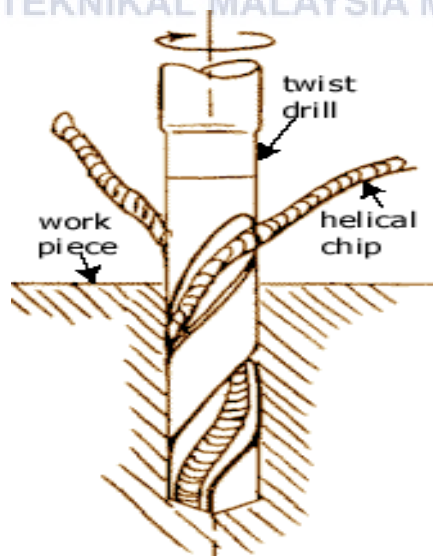


Figure 2.1 Drilling [retrieved from http://www.efunda.com/processes/machining/images/drill/drill_helical_chip_1.gif]

Turning is a type of machining, a material abstraction method, where rotational parts are created by removing the material. A turning machine or lathe is used in the turning process. Other components needed are cutting tool, fixture and workpiece. Secured to the fixture where it is secured to the turning machine, a workpiece is a material that allowed itself to spindle at a high speed. For the cutter, it is a cutting tool that also secured to the machine and usually a single point cutting tool. When the workpiece is rotating, the cutting tool will move in and feed the workpiece to produce the desired shape.

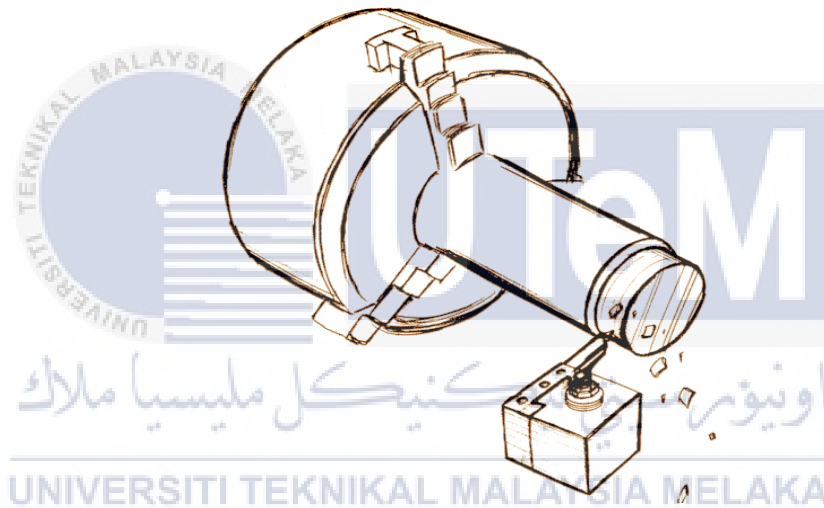


Figure 2.2 Turning[Reprinted from efunda, Retrieved from http://www.efunda.com/processes/machining/images/drill/drill_helical_chip_1.gif]

Milling is a machining process where a rotating cutting tool is used to remove material. From small part to big part, milling covers a wide variety of processes and has many different operations and machines. For machining parts to accurate desired shapes and sizes, a milling machine is commonly used in the industry.

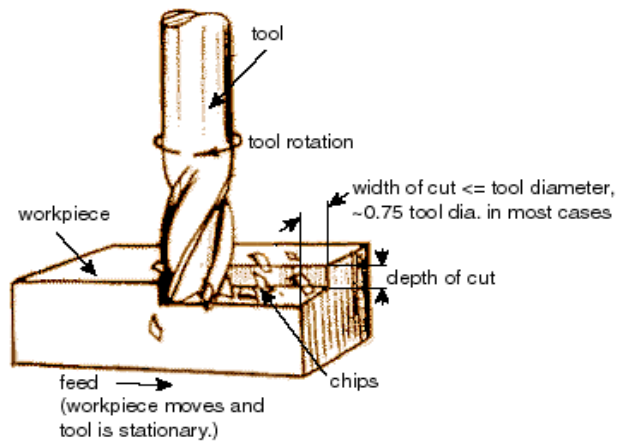


Figure 2.3 Milling [retrieved from http://www.efunda.com/processes/machining/images/mill/end_milling_2.gif]

2.1.1 Conventional machining process

Traditional machining process or otherwise called conventional machining as a usually utilizes the use of hard material to change the shape of the material. Using traditional machining process demand of energy and time and hence increments in expenses so in sometime, traditional machining is not suitable to use. Traditional machining additionally expenses as tool wear and the quality can be affect in the process. As the demand for hard alloy product is keep increasing due to technological advancement, more interest have been on the use of traditional machining. Traditional machining can be characterized as a procedure where mechanical energy is used.

Characteristics of contact machining process are :

1. Generally plainly visible chip development by shear deformation
2. Present of physical tool
3. Harder cutting tool material compare to the workpiece
4. Main energy is mechanical where utilize the cutting force to remove material
5. Workpiece and tool have direct contact between them
6. Low surface finish
7. Less tool life
8. Higher waste of material

9. Low capital expense
10. Manually to operate

The examples of traditional machining are milling, turning, boring, and drilling. These process consider as traditional machining as there are contact between cutting tool and workpiece in their machining process.

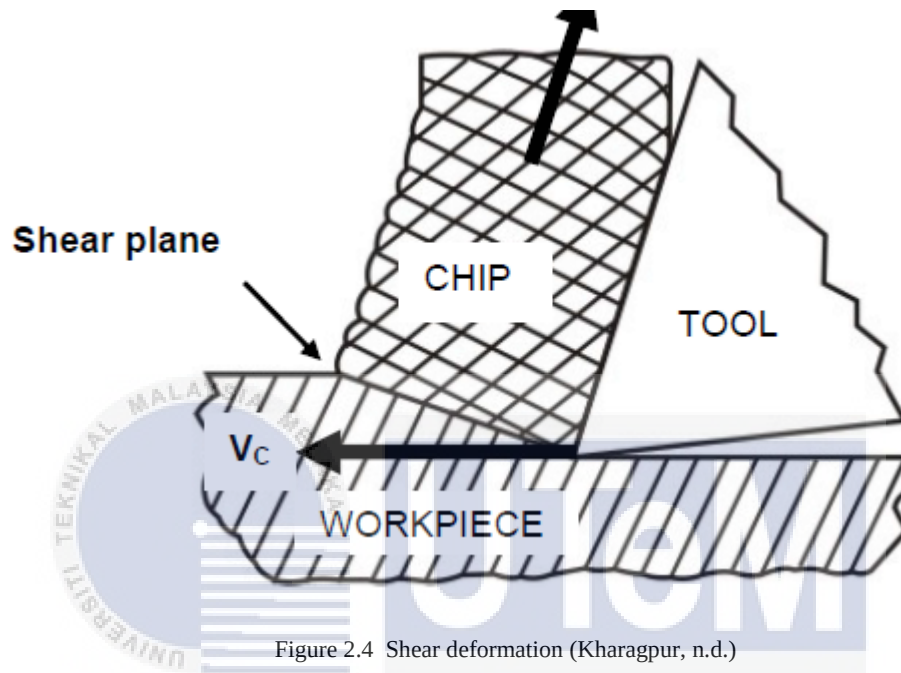


Figure 2.4 Shear deformation (Kharagpur, n.d.)

2.1.2 Advanced machining process

Over the past 10 years, traditional machining have been covered the requirement in the industries. But, new fascinating work materials and additionally complex parts and products put a lot of pressure to the traditional machining to produce the part . Due to that, advanced machining have been form for an improvement in the industries in producing parts with accuracy and economically. With advancement in the advanced forms, right now there are regularly the main choice and not an alternative option for routine procedures for certain specialized requirement.

Characterization of advanced processes categorised according to their type as follow:

- Mechanical Processes
 - Ultrasonic machining
 - Water jet machining
- Electrochemical Processes
 - Electrochemical grinding process
 - Electrochemical machining
 - Electro jet drilling
- Electro-Thermal Processes
 - Electro-discharge machining (EDM)

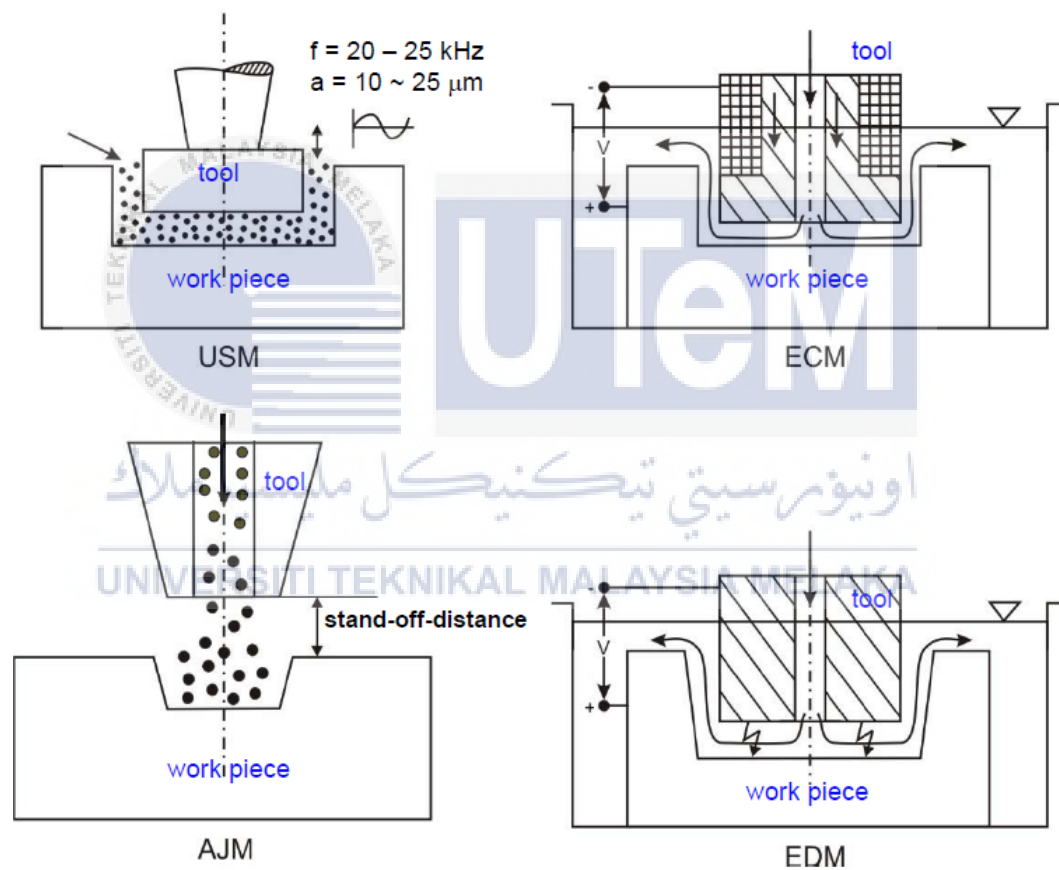


Figure 2.5 No physical contact between the tool and workpiece (Kharagpur, n.d.)

Characteristic of advanced machining are as follow:

1. Material removal can happen with or without formation of chips
2. There is usually no physical tool present
3. Does not depend on mechanical energy for material removal to take place
4. High surface finish and accuracy

5. Have high tool life
6. Skilled operator required

2.2 Milling process

Mainly used in the aerospace and automobile, milling process is a common process to use in material removal process . Processing machine is a standout amongst the most flexible ordinary machine instruments with an extensive variety of metal cutting capacity. Numerous convoluted operations, for example, indexing and straddle milling and so on can be completed on a milling machine. Secured in the milling machine and rotates at high speeds, the cutter is a cutting tool with sharp teeth. The rotating cutting tool will contact with material bit by bit to produced the desired parts shape and size.

Milling is commonly used to produce part that have complex feature such as pockets and gaps and also can machine three dimensional surface. Parts that fully produced by the milling process usually a limited quantity for example a custom design. Beside that milling process can also be used to produce art that used in other process for example producing a mold.

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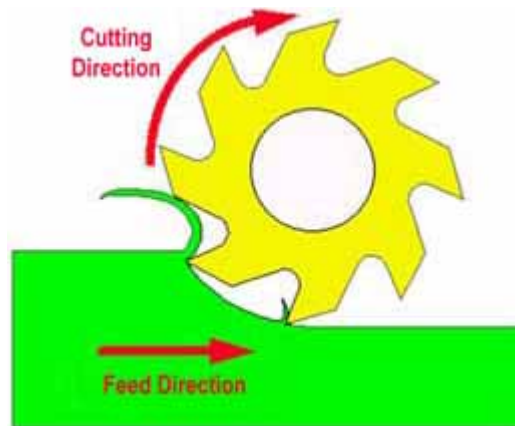


Figure 2.6 Milling process [retrieved from http://mmu.ic.polyu.edu.hk/handout/0103/03_f13.jpg]

2.2.1 Types of milling machine

The milling machine removes metal with a revolving cutting tool called a milling cutter (Od, 1988). The vast majority of the milling machine are built of section and knee structure and they are characterized into two principle sorts in particular horizontal milling machine and vertical milling machine. The name horizontal or vertical is given according to its shaft hub. Horizontal machines have two types which are plain horizontal and universal milling machine. The main difference between these two is the table of a universal milling machine can be set at a plot for helical processing.



Figure 2.7 Vertical Milling Machine

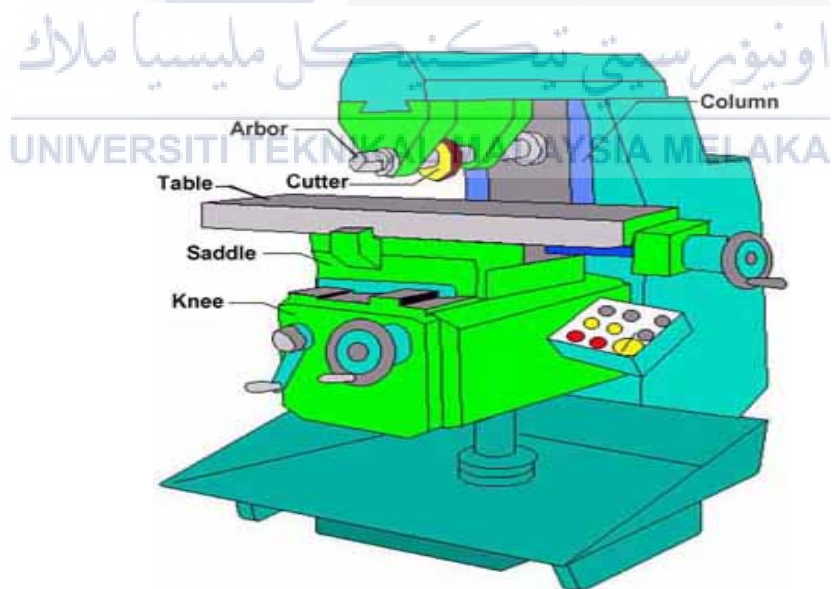


Figure 2.8 Horizontal Milling Machine [retrieved from http://mmu.ic.polyu.edu.hk/handout/0103/03_f2.jpg]

2.2.2 Cutting Tool in Milling Process

The tooling that is needed for milling is a sharp cutter which will be revolved by the spindle. The cutter could be a cylindrical tool with sharp teeth spaced round the exterior. The areas between the teeth area unit referred to as flutes and permit the material chips to maneuver faraway from the workpiece. The teeth is also straight on the facet of the cutter, however area unit a lot of unremarkably organized in a very helix. The angle reduces the load on the teeth by distributing the forces. Also, the amount of teeth on a cutter varies. a bigger range of teeth can give a more robust surface end. The cutters that may be used for milling operations area unit extremely various, so letting the formation of a spread of options. whereas these cutters different greatly in diameter, length, and by kind of the cut they will form, they conjointly disagree primarily based upon their orientation, whether or not they are used horizontally or vertically.

There are many types of cutting tool in milling for examples as follow:

- Plane (helical) mill

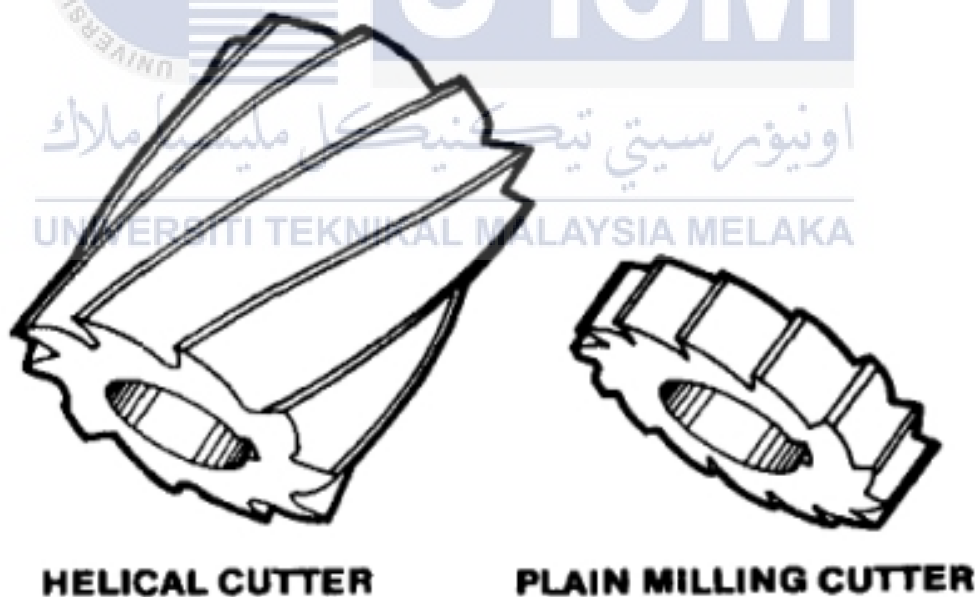


Figure 2.9 Plain milling cutter [retrieved from http://server2.smithy.com/media/jpg/machining%20handbook/Chapter_4/4-5.jpg]

- Form relieved mill



Figure 2.12 Double angle mill [retrieved from <http://2.bp.blogspot.com/-oek7XPYdDBs/U8hBpoS-vII/AAAAAAAAOEE/Erojb5TTTHQ/s1600/Angular-Cutter-milling.gif>]

While for vertical milling, the cutters have very different form. The cutter teeth only cover a bit of the tool and the remaining area is smooth surfaced known as shank. The shank is the area where it will be secure to the collet. Examples of cutting tool in vertical milling is listed below:

- Reamer
- Tap
- Face mill
- Ball end mill
- Drill
- End mill

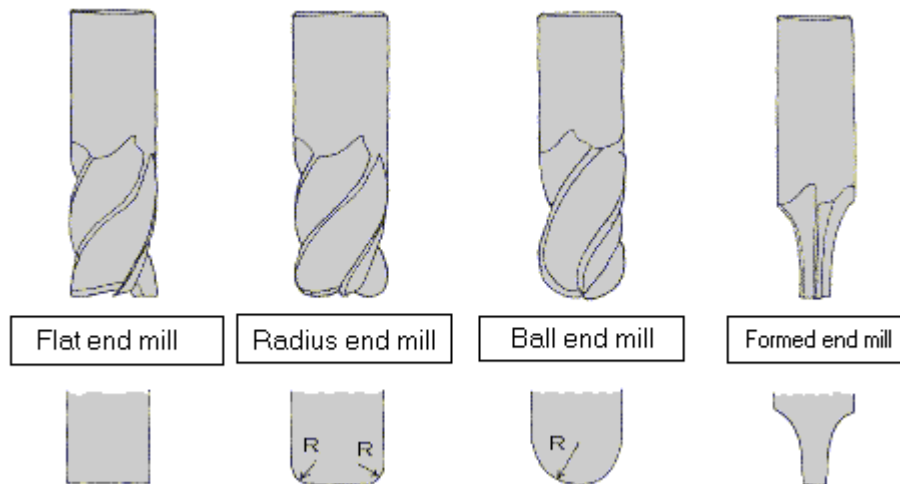


Figure 2.13 End mill (Marinov & Technology, n.d.)

2.3 Clamping method

The primary function of a jig and fixture is to locate the workpiece. Once placed, the workpiece should be controlled to stop movement throughout the process. Clamping is the process where to hold the workpiece securely. Each clamping device and their location on the workholder is chosen carefully to ensure they are working properly.

Clamps provide two main functions which are hold the piece of work against its locators and prevent the movement of the workpiece. Clamps should resist the secondary cutting force. When the cutting tool leaves the workpiece, secondary cutting forces are generated. In drilling for an example, in the axis of the drill, the primary forces are directed down and radially. Whereas the secondary forces are generated once the part tends to raise once the drill breaks through the alternative aspect of the half. The clamps need to be strong enough to secure the workpiece against the locators and also resist the secondary forces. (Hameed, 2003)

In figure below show the relationship between the locators and clamp. The locators are the solid jaw and vise body. While the moveable jaw acts as a clamp.

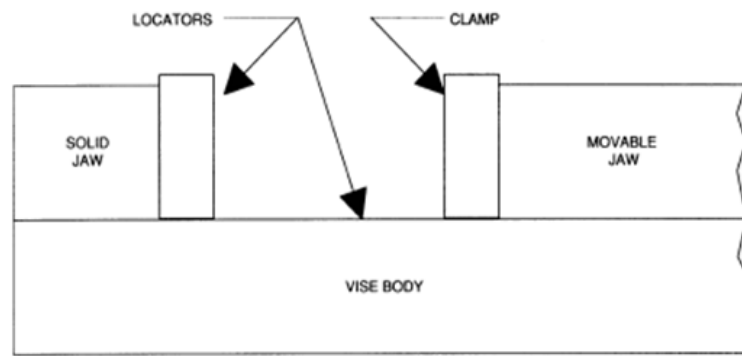


Figure 2.14 position of locating and clamp in a vise(Speed, n.d.)

To select a clamp, the next factor needed to be considered that is the stress and vibration expected in the process. In some operation, the vibration can loosen the workpiece from the workholding(Klotz, Gerstenmeyer, Zanger, & Schulze, 2014). We can add safety margin to estimate the force acting on the clamp.

Clamping the workpiece can damage the workpiece so we need to choose the correct clamping method. Damage to the workpiece can occur in different way where usually due too much clamping force acting on the workpiece. Common damage to the workpiece is marring and distortion

The clamping need to be fast to clamp and unclamp to increase the productivity of the overall process and also to time saving. When time can be saved, we can also save the cost from the labor time and also increase the productivity.

In milling machine process, there are four common clamping method that often used. They are vises, v-blocks, angles plates and mounting to the table. Nowadays, current techniques of conventional clamping are not a suitable method for the future since they present a number of drawbacks, such as reduced accuracy due to elastic deformation of the parts, less adaptability to complex shapes, high costs of specific tools for each operation, etc. (Cantano et al., 2015)

2.3.1 Milling machine vises

The most common workholding method in milling machine is the vise (Figure 2.15).



Figure 2.15 Plain milling machine vise (Speed, n.d.)

For high production uses, an air or hydraulically actuated vise may be used. These types of vises are fast. They also keep up reliable clamping pressures starting from one section to another. However, the vise is opened or closed using a handle on most manual type milling machines. (Od, 1988)

2.3.2 V-blocks

V-Blocks function as a support and hold round work for milling (Figure 2.14). There are many sizes of V-Blocks. V-Blocks are sometimes clamped to the table of the milling machine.

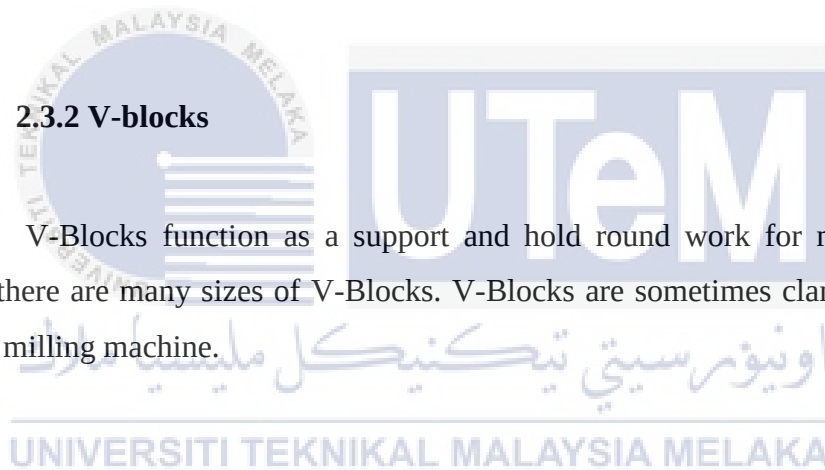




Figure 2.16 V-blocks (Speed, n.d.)



Figure 2.17 A V-Block used to clamping a round part. [retrieved from <https://engineerharry.files.wordpress.com/2012/02/t11.png?w=630>]

2.3.3 Angles plate

An angles plate is essentially a bit of cast iron or steel that has two level surfaces at right points to each other. The two closures of the angle plate are additionally level and at right angles to both of the two different surfaces. On some point plates there can be webbing between the two surfaces to add to the unbending nature of the surfaces. For this situation inside surfaces are frequently simply the rough surface of the original casting.

Most angles plates have on the two primary surfaces openings so either face can have a workpiece, other devices or the milling table connected to it. Some angles plates are made thicker so they are sufficiently rigid with no solidifying and need not bother with webs at the closures. This implies the inside surfaces can be machined precisely and level. It will be seen this is an extremely helpful facility particularly where space is restricted.

The fundamental motivation behind the angles plate is that it successfully turns one surface, for instance, a milling table, into another surface at right angles to the first. In the event that a workpiece is clamp to a angle plate, it viably turns it through 90°. At the point when a flattish workpiece is clamp to the milling table it is more often than not with the huge surface even. In this position it is not generally simple to machine the sides of the workpiece as may be required. Yet, in the event that we utilize an angles plate to turn it through 90° we can machine the sides without much of a stretch.

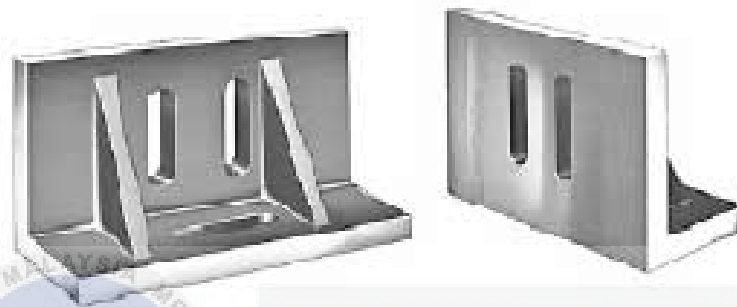


Figure 2.18 Angles plates [retrived from <http://archive.li/ru1r8/7be0de7bd02f10b24716f46a364b5a5e95fd0625.jpg>]

2.3.4 Mounting to the table

Workpiece also can be directly clamp to the table. These type of clamping method is used when the workpiece have rare shape or the size is too big.



Figure 2.19 workpiece is clamp directly to the table[retrived from <http://archive.li/ru1r8/13b11e7835d22f2e9cf81d28a965f183439a1181.jpg>]

As shown in the figure 2.19, the stop block is used to adjust the work and in addition keep the part from slipping. There are many clamps set that offered in the market (Figure 2.20).



Figure 2.20 Clamping sets [retrived from <http://archive.li/ru1r8/677196f6a417505c79f12edef86e406685280d9f.jpg>]

2.4 Vacuum

Vacuum is a region of space and time where all the components of the stress–energy tensor are zero. So the region is free from energy and momentum and also by consequence free from any physical fields and particles. vacuum means any volume containing less gas particles, atoms and molecules (a lower particle density and gas pressure), than there are in the surrounding outside atmosphere. Accordingly, vacuum is the gaseous environment at pressures below atmosphere (Marquardt, 1999).

2.4.1 Atmospheric air

During the operation , the vacuum system is always surrounded by the air. So it is a must to be familiar with the chemical and physical properties of the atmospheric air. Regarding the composition of the air, the following point needed to be noted:

- a). The water vapor contained noticeable all around, shifting as indicated by the moistness level, has vital influence while emptying a vacuum plant.
- b) The impressive measure of the idle gas argon ought to be considered in departure strategies utilizing sorption pumps .

2.4.2 Vacuum Pumps

To decrease the gas pressure, a vacuum pump is utilized. Subsequently consider the gas particles needed to be expelled from the volume. The classes of pump will be differentiated into two (Walecka, n.d.):

- a) Vacuum pumps where – gas are removed to the atmosphere through pumping (compression pumps)
- b) Vacuum pumps where- gas are removed through condense on the surface



Figure 2.21 Vacuum pump [retrieved from <http://www.labtekindia.com/measiring/Vacuum%20Pump.jpg>]

2.4.3 Vacuum Clamping

Vacuum clamping frameworks are utilized most importantly as a part of the wood, plastics and non-ferrous metals businesses for quick, basic machining (Screwing & Brochure, 2014). In vacuum clamping, under the workpiece, underpressure is generated. So there is a difference between the pressure on top of the workpiece and under the workpiece. The workpiece will be pressed against the vacuum devices. Vacuum clamping is not actually “sucked” as many would think but

pressed against the vacuum clamping. Meaning, a larger area of the workpiece will produce a better workholding.

2.5 Effect of cutting parameters

There are three important process parameters in the cutting process that are depth of cut, speed and feed. These parameters will affect the surface roughness of the workpiece. The surface roughness might also be affected by other factors such as condition of the cutting tool and also condition of the machine used, but the three parameters is the main parameters that need to be careful of.(Rao, Rao, & Srihari, 2013).

Feed rate has critical impact both on cutting power and also surface roughness. Depth of cut impacts cutting forces, however has an irrelevant impact on surface roughness. The cooperation of feed and depth of cut and the connection of all the three cutting parameters have huge impact on cutting forces, while, none of the collaboration impacts are having critical impact at surface roughness delivered

The cutting parameters affecting tool chatter are shown in Figure below in turning are:

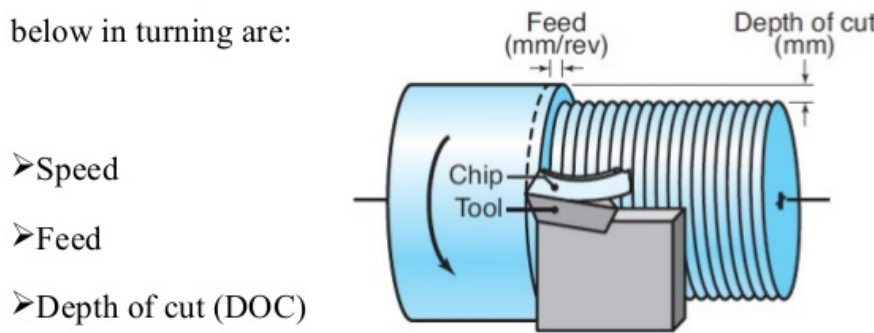


Figure 2.22 Cutting parameters [retrieved from <http://www.slideshare.net/devanshuy2/project-report-on-simulink-analysis-of-tool-chatter-vibration-on-lathe>]

2.5.1 Input

Speed in which the cutting tool passes the workpiece and remove material is known as the cutting speed. For better productivity, the cutting speed need to be higher. There is a suitable speed for each of type of material and tool combination where manufacturer usually provide for the guideline for the operators.

Spindle speed is derived from the formula $N = V / (\pi \times D)$, where V is the cutting speed and D is the diameter of the cutting (Rao et al., 2013). Depending on the operation, the D might be work diameter if the operation is turning and while it is tool diameter when the operation is drilling or milling.

How much the cutting tools dig into the workpiece in a single pass is known as depth of cut. The relative speed for the cutting tool to linearly pass the workpiece to removal the material is known as feed rate.

2.4.2 Surface roughness

The terms surface roughness and surface finish are utilized broadly as a part of industry and are by and large used to measure the smoothness of a surface

finsih. In 1947, the American Standard B46.1-1947 "Surface texture" characterized a large number of the ideas of surface metrology and wording which dominated past principles (Tseng, Konada, & Kwon, 2016). The pattern of the surface which different from the normal surface is known as surface texture. It may result from waviness, lay and flaws and may berepetitive or random. Real surface is that the real surface of associate object is that the peripheral skin that separates it from the encompassing medium. This surface invariably assimilates structural deviations that area unit classified as kind errors, waviness, and surface roughness. Roughness consists of the finer irregularities of the surface texture sometimes together with those irregularities that result from the inherent action of the assembly method. These are considered to incorporate cross food marks and different inconsistencies inside of the breaking points of the unpleasantness examining length

Alternatives for surface roughness estimation are basically delimited by the exactness required in the outcome. For instance, surface roughness could be surveyed by eye and touch, by contrasting a test with a standard specimen, however this is not an estimation: it is subjective. Touch affectability and visual determination restrict the viability of these evaluations to components that are a couple of microns high and wide, at as far as possible. Surface geology estimations, at an accuracy building level, are isolated for the most part into the size of the elements that are inspected.

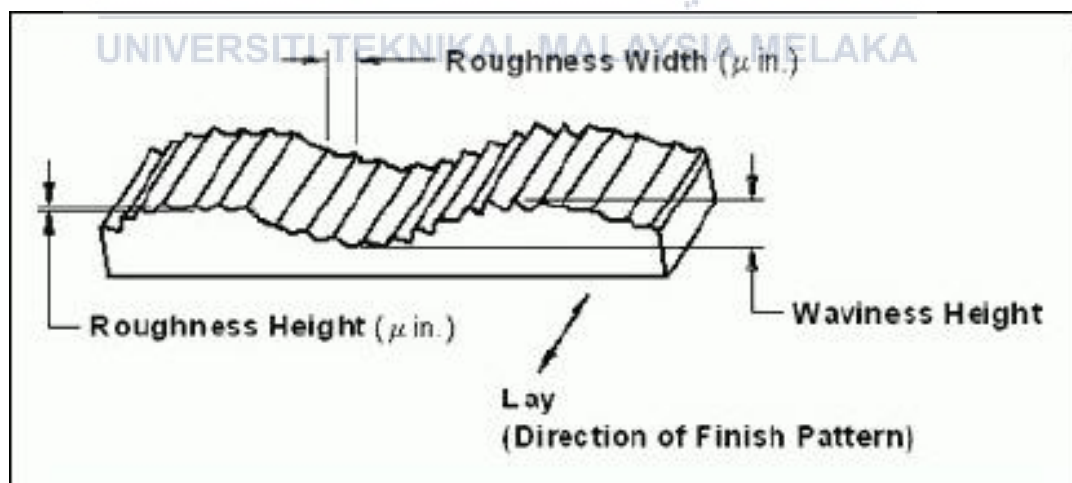


Figure 2.23 Surface roughness [retrieved from http://procnc.com/resources/newsletter/august_2010_-_surface_roughness/]

CHAPTER 3

METHODOLOGY

Introduction

This chapter discusses in detail about the process that been conducted to make the vacuum clamping and also experimental method that been conducted to test the product. In this chapter, it was divided into four part. First is design of vacuum clamping where this part explain on how the design of this product is produce. Second is material solution of design where the material selection to make the product. Third is developement of vacuum clamping where the process to make the vacuum clamping is explained in detail. Lastly the product will go through testing so evaluation can be make on the product. The overall process flow is shown in figure 3.1.

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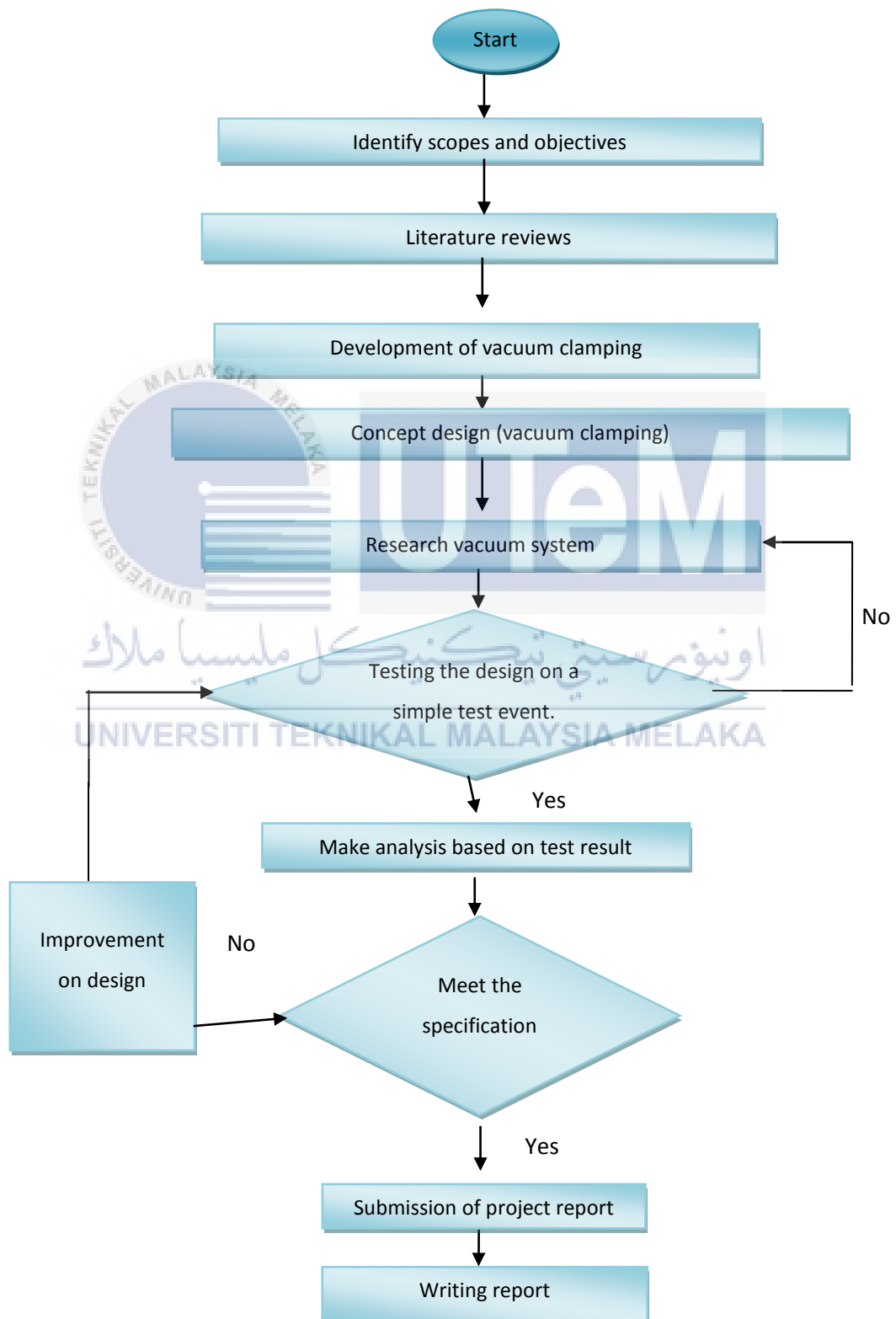


Figure 3.1 Project
flowchart



3.1 Design of vacuum clamping

3.1.1 Problem statement

Clamping system in milling usually uses vises to hold workpiece. Made from cast iron, vise is a rigid, strong and inexpensive clamping method. Beside milling machine, vise is also a popular choice for clamping method in other machine such as drill press and grinding machine. But there are several limitation on using the vise. The limitation are :

1. Vise only can clamp workpiece with parallel side.
2. Manually work, so there no fix clamping force
3. Safety issue where the cutting tool may collide with vise
4. Clamping process using vise can be taking much time



Figure 3.2 Workpiece with parallel side only can be clamp

3.1.2 Product Design

After the problem statement from the vise is collected, then the product design can be sketch. An online research is done first to know if there any other similar product on the market to ensure no any product is replicated. From the online research, there are several similar product but they are mostly used in woodworking. After research, a sketch is drawn after considering the suitable concepts and ideas. The product sketch is also drawn based on way to solve the problem in vises. The sketch then redraw using CATIA V5 software, a multi-platform computer-aided design (CAD)/computer-aided manufacturing (CAM)/computer-aided engineering (CAE) . The expected final product are shown as figure 3.3. Figure 3.3 is the overall product design that have been design using CATIA software.

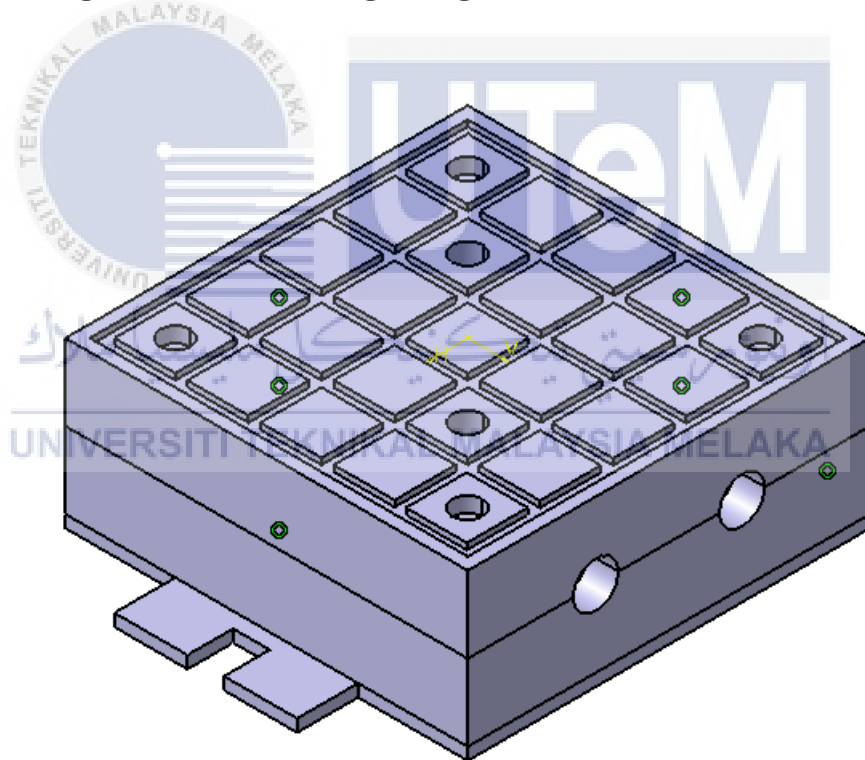


Figure 3.3 Vacuum clamping sketch using CATIA software

3.2 Material solution of design

Before the machining process for the vacuum clamping to be done, a quotation was made to know material and tool that needed in develop the vacuum clamping. After the quotation is complete, then the material and tool needed is ordered. The part needed is shown as in the table below

Table 3.1 List of part

Number.	Parts name	Expectation Size (mm)	Types of material	quantity
1	vacuum clamping	135x135x40	aluminium	2
2	base	132x132x5	Mild Steel	1
3	Electric vacuum pump	-	-	1
4	liquid seperator	-	-	1
5	sealing cord	4mm diameterx1000	rubber	1
6	eccentric stoper	4mm diameter	steel	2
7	pneumatic hose	M20x1000	rubber	1
8	screws	M4 x 50	Steel	4
9	suction filter	M4	-	2
10	ball valve	15mm diameter	PVC	1
11	cutting tool- end mill	Diameter 4	-	1
12	bolt and nut	M12	steel	2

3.3 Developement of vacuum clamping for milling machine

After all the material and tool is available, the project then proceed to machining. The machine that involves in the the machining process to produce the product is milling machine. For this project, only the vacuum clamping device go through the machining process while for the vacuum pump is ready made. The machining process are shown below :

Part 1:

The table shown in table 3.2 is about what machine, cutting tool and material that used to make this part.

Table 3.2 Machine, cutting tool and material used

Machine use	Cutting tool	Material
• Milling machine	• End mill • Face mill	Aluminium block

1. Firstly the raw material will be milling to the correct dimension (132x132x25)mm.
2. Then use end mill diameter 10mm to make a slot with a depth of 5mm.
3. Drill 4 holes using drill cutting tool (4mm diameter).
4. Thread the holes using tap tools.

Figure 3.4 is the design for part 1.

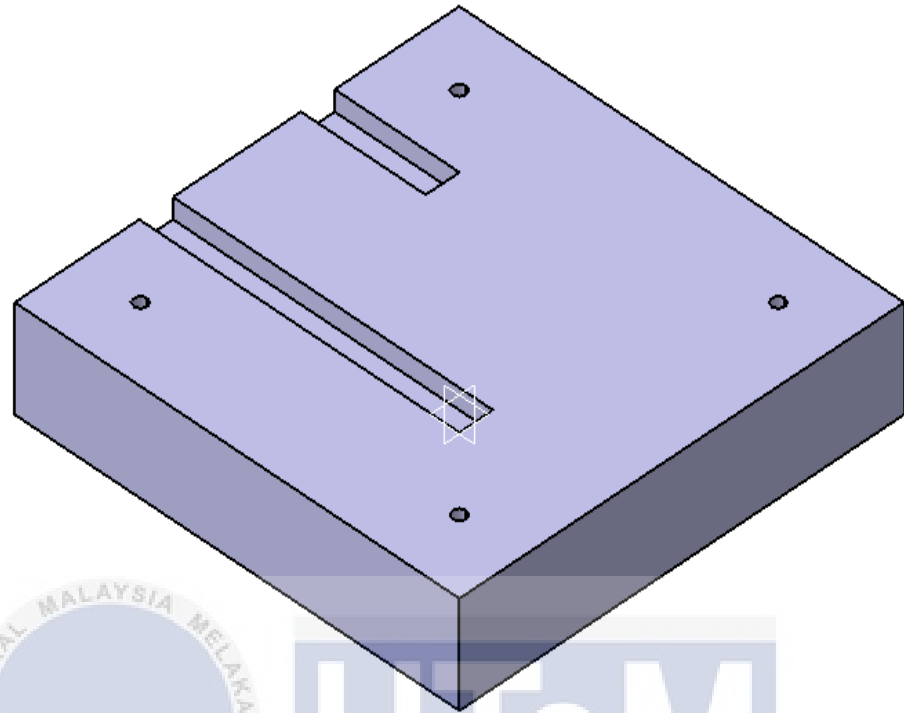


Figure 3.4 Part 1

Part 2:

The table shown in table 3.3 is about what machine, cutting tool and material that used to make this part.

Table 3.3 Machine, cutting tool and material used

Machine use	Cutting tool	Material
Milling machine	- End mill - Face mill	Aluminium block

1. Firstly the raw material is mill to the dimension (132x132x25)mm.
2. Then use end mill diameter 4mm to make slot on top of the workpiece with depth of 2mm.
3. Use a drilling cutting tool (10mm diameter) to make two hole in the surface of the workpiece
4. Then change the drill cutting tool to 4mm diameter and make another 4 holes.

5. Thread the holes using tap tools.
6. Use end mill diameter 10mm to make two slot on the bottom of the workpiece with depth of 5mm.

Figure 3.5 is the design for part 2.

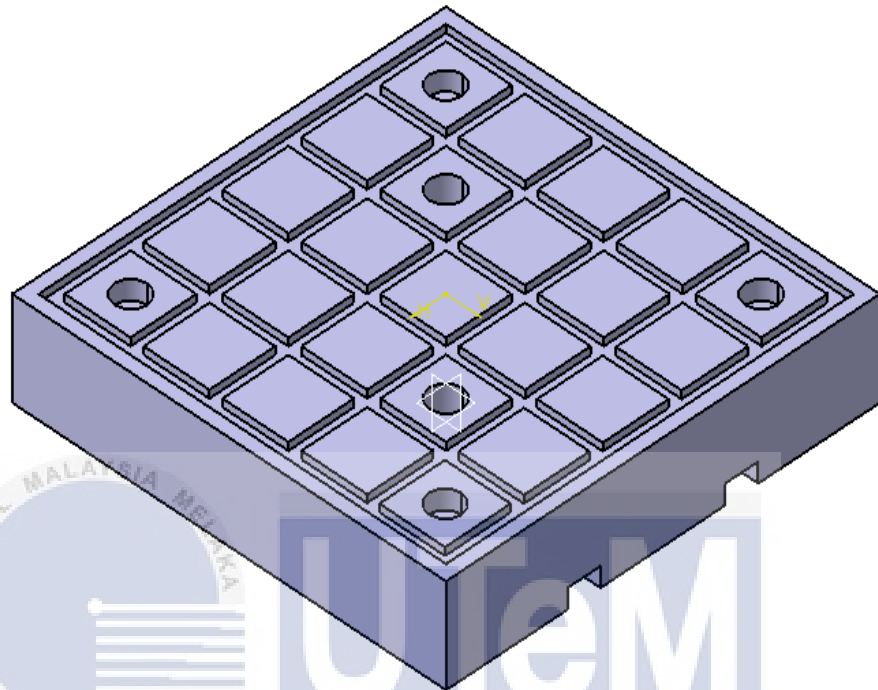


Figure 3.5 Part 2

Part 3 :

The table 3.4 shown below is about what machine, cutting tool and material that used to make this part.

Table 3.4 Machine, cutting tool and material used

Machine use	Cutting tool	Material
Milling machine	- End mill - Face mill	Mild steel plate

- 1) By using end mill cutting tool, cut the material to the above shape.
- 2) Drill 4 holes to the plate (4mm diameter).
- 3) Make thread to the holes by using tap tool.

Figure 3.5 is the design for part 3

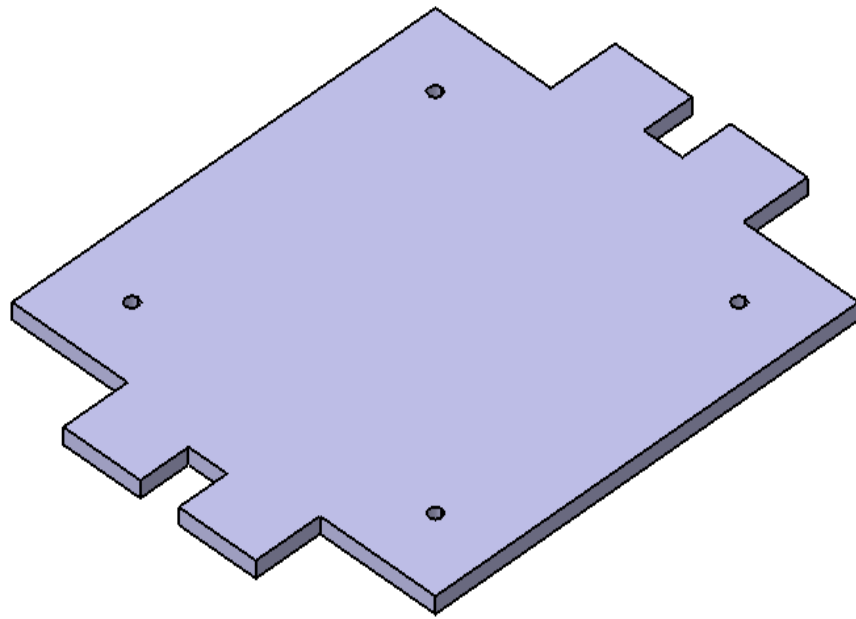
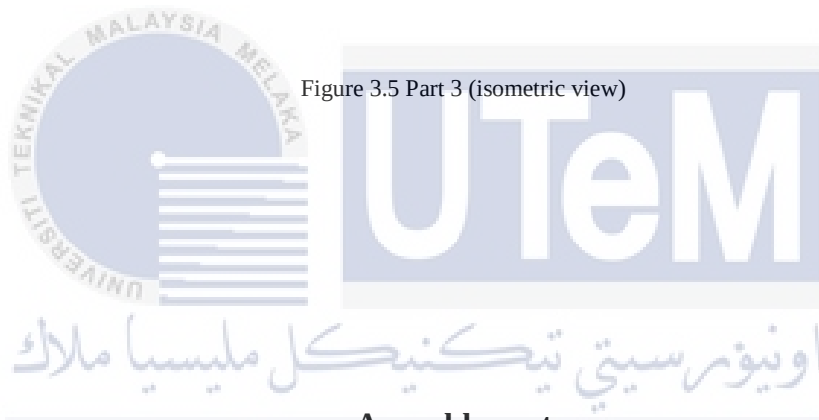


Figure 3.5 Part 3 (isometric view)



Assemble part :

The table 3.5 show below is about what machine, cutting tool and material that used to make this part.

Table 3.5 Machine, cutting tool and material used

Machine use	Cutting tool	Part needed	Component
Milling machine	Drill	Part 1	Screws
		Part 2	Ball valve

Below figure 3.6 show part 1 and part 2 is assembled

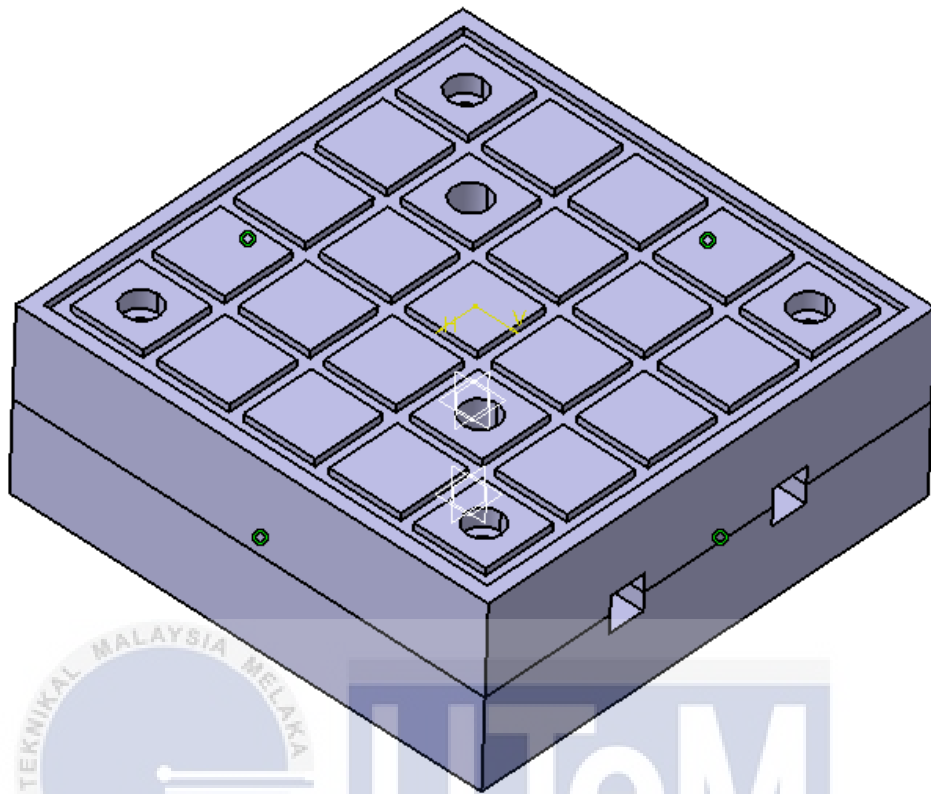


Figure 3.6 Part 1 and 2 is assembled

- 1) Assemble part 1 and part 2 using 4 screws(4 diameter) through the 4 holes as shown in figure 3.6.
- 2) Make holes size 15 diameter at the side of the product using drill cutting tool as shown in figure 3.7 below.
- 3) Make thread to the holes by using tap tool.
- 4) Assemble part 3 to the product bu using screws(4mm diameter) as shown in figure 3.7 below.

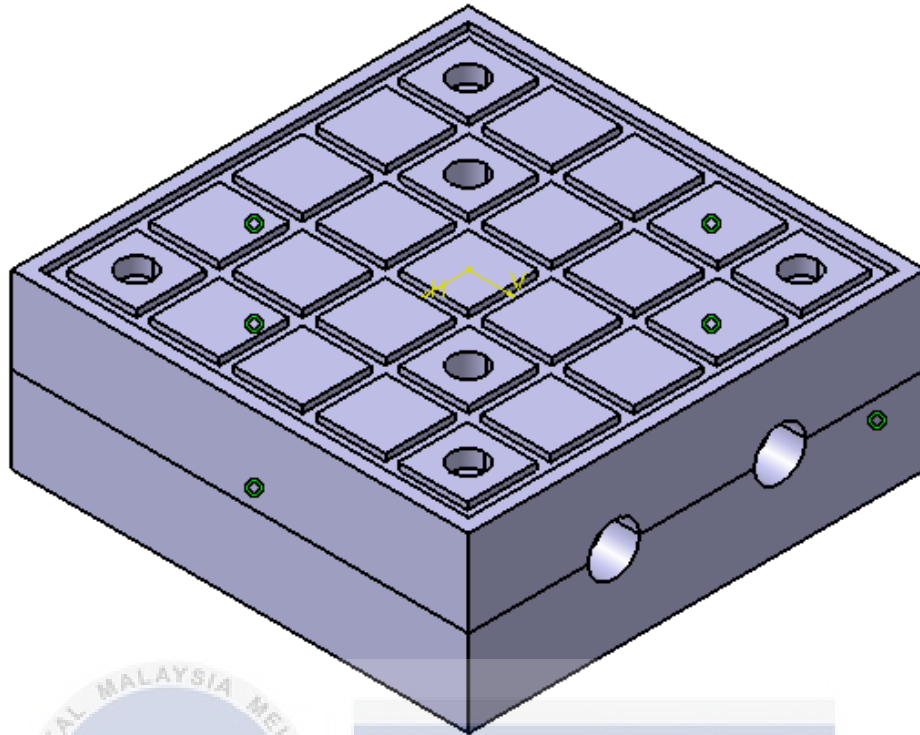


Figure 3.7 holes are drill at the side of the product

- 5) Insert two ball valves to the holes on the side of the product.

Assemble part

After all part has already go through machining process, the last step is to assemble all the part. Table 3.6 below show what component and part needed in the assembly.

Table 3.6

Machine use	Part needed	Component
Drilling machine	Part 1	Screws
	Part 2	
	Part 3	

1. Assemble part 1 and part 2 using four screws through the holes that already drilled and taped.
2. Assemble part 3 with the already assembled part 1 and part 2 using four screws through holes below part 2.

3. After all part already assembled attach the vacuum clamping to the milling table using bolt and nuts.
4. Vacuum pump then will be connect through to vacuum clamping using hose.

The finished product is shown as below figure

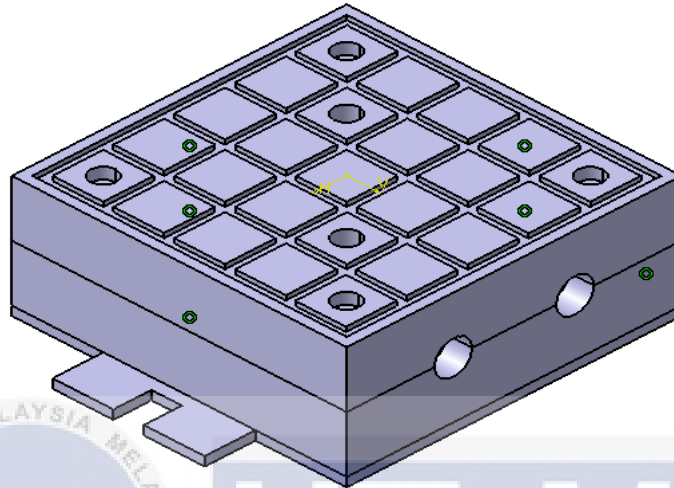


Figure 3.8 All part is assembled

3.4 Evaluation of the product

After the product is complete, two experiment is done to test the product. Experiment that are conduct are surface roughness testing and clamping time testing. Test is conducted using milling machine. Same size and material of workpiece is compared between using vise and vacuum clamping.

3.4.1 Surface roughness testing

To check if whether the vise or vacuum clamping can hold the workpiece better, surface roughness testing is done on the vacuum clamping. The experiment were carried out in a milling machine.. Face milling operations were performed with a face mill cutter. For each experiment new tool insert is used. All the experiments were carried out with new tool inserts. Each experiment was carried out for a cutting

length of 100 mm. The surface roughness parameter, arithmetic mean surface roughness of the the workpiece is checked out using microscope and the result is calculated and recorded. The result then will be compared to the current vise.



CHAPTER 4

RESULT & DISCUSSION

4.1 Introduction

This chapter represent analysis and interpretation of the data that obtained from this project. The developed vacuum clamping is evaluated from design aspect and also from its functionality. Surface roughness testing is done to evaluate the vacuum clamping whether it can clamp the workpiece

4.2 Finish Product

After go through all the machining process, the vacuum clamping is finally completed. But there are some changes that been made on the vacuum clamping during the machining process.



Figure 4.1 Finish Product



Figure 4.2 Part 1



Figure 4.3 Part 2

The changes that I have made are changing from aluminium to mild steel. This need to do as I have to cut the project cost as mild steel is much cheaper than aluminium. Beside that, there some changes in design for part 1. This is due to I find the original design is hard to machining as it require almost none tolerance. So changes in design have to be made. As shown in figure 4.4, the original design is change to design in figure 4.5. Two holes is added to each side of the part.

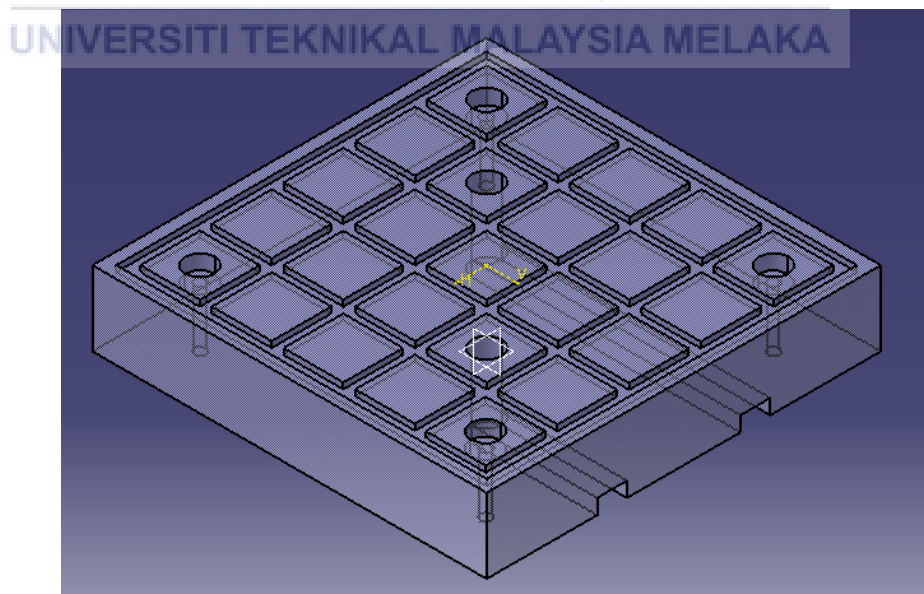


Figure 4.4 Part 1 original design

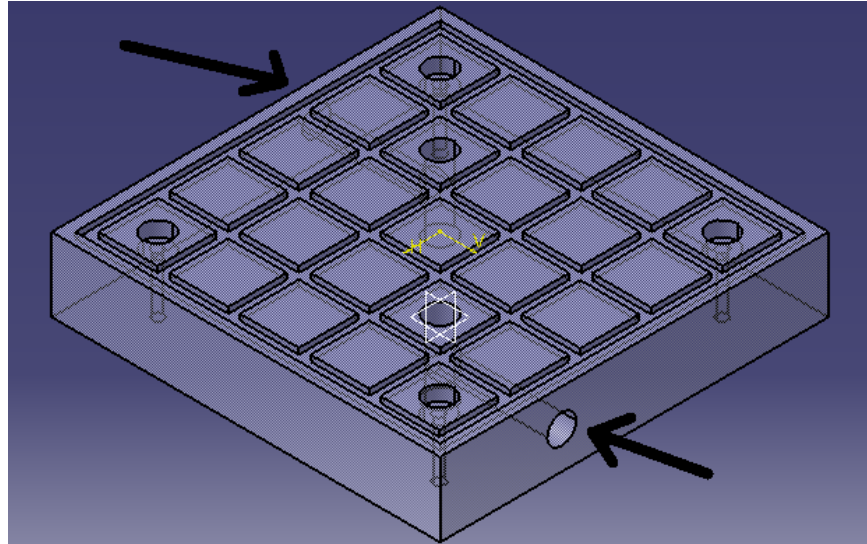


Figure 4.5 Part 1 design changes

As part 1 have changes in design, part 2 is removed completely from the project as it is not needed after changes in design for part 1.

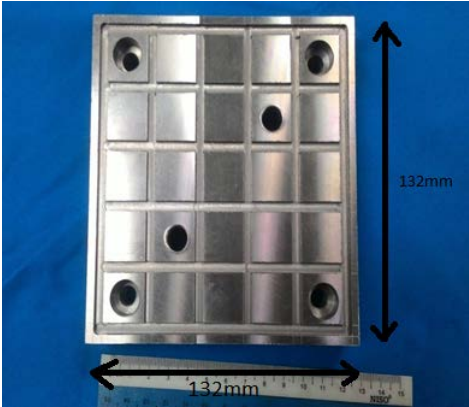
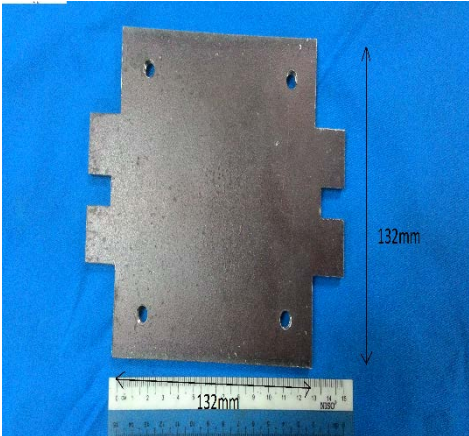


Figure 4.6 Part 2 that removed

4.1.1 Machining process

In this project, the whole machining process is using milling machine. The detail of machining process is as shown in the table 4.1 below.

Table 4.1 Machining process

Part	Tool and process
Part 1 	1) The workpiece is cut using face mill to get the square dimension. 2) Using 4mm end mill, the workpiece is cut to get the grid line shape with 2mm depth. 3) The 4 holes on each corner is drill using 8mm drill tool . 4) Using 10mm end mill, counter bore is cut on each of the 4 holes. 5) 2 holes near the centre is drill using 10mm drill. 6) Another 2 holes drilled on the side part using 10mm drill tool. 7) The 2 holes on the side part is tapped using thread tapper.
Part 2 	1) Using 10mm end mill cutting tool, the workpiece is cut to get the shape and dimension. 2) The 4 holes is drilled using 8mm drill tool. 3) Thread is tapped on the 4 holes using thread tapper

4.1.2 Part Assembly

1. Part 1 and part 2 is assemble using 4 screws.
2. The assembled parts then attach to the milling table using bolts and nuts as shown in figure 4.7.

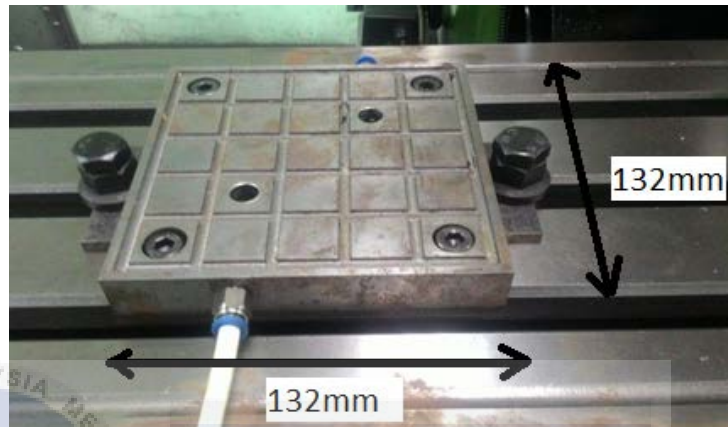


Figure 4.7 Vacuum clamping attached to milling table

3. The device then connected to vacuum pump using pneumatic hose as shown in figure 4.8.



Figure 4.8 Vacuum clamping connected to vacuum pump

4. A sealing cord is placed on the vacuum clamping according to the size of the workpiece as shown in figure 4.9.

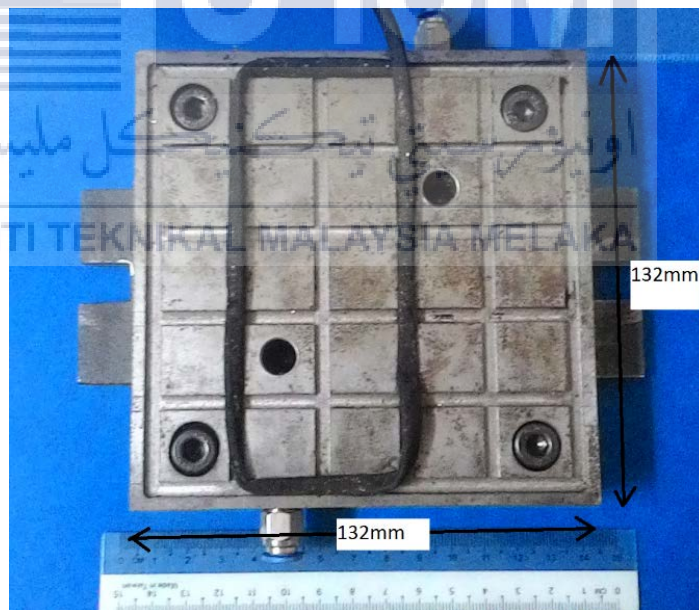


Figure 4.9 Sealing cord place on top of vacuum clamping

5. The workpiece is placed on the vacuum clamping and vacuum pump is turned on to complete the clamping process as shown in figure 4.10.

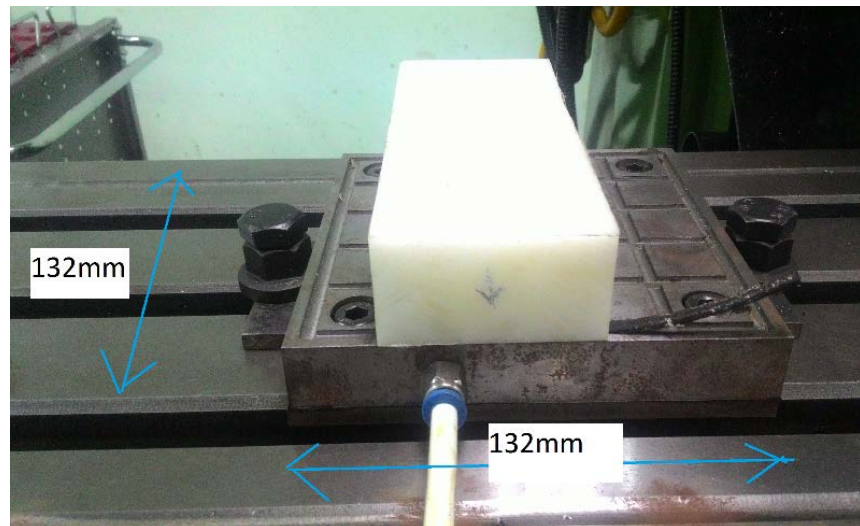
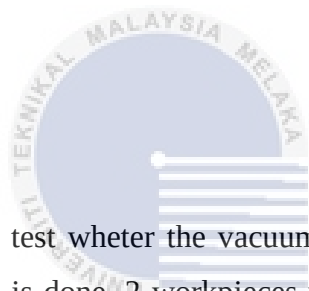


Figure 4.10



4.3 Surface Roughness

To test whether the vacuum clamping can function properly, a surface roughness testing is done. 2 workpieces which are aluminium and delrin are milled by using face mill. The dimension of the aluminium is 91mm x 61mm x 18mm while for the delrin the dimension is 170mm x 59mm x 31mm.

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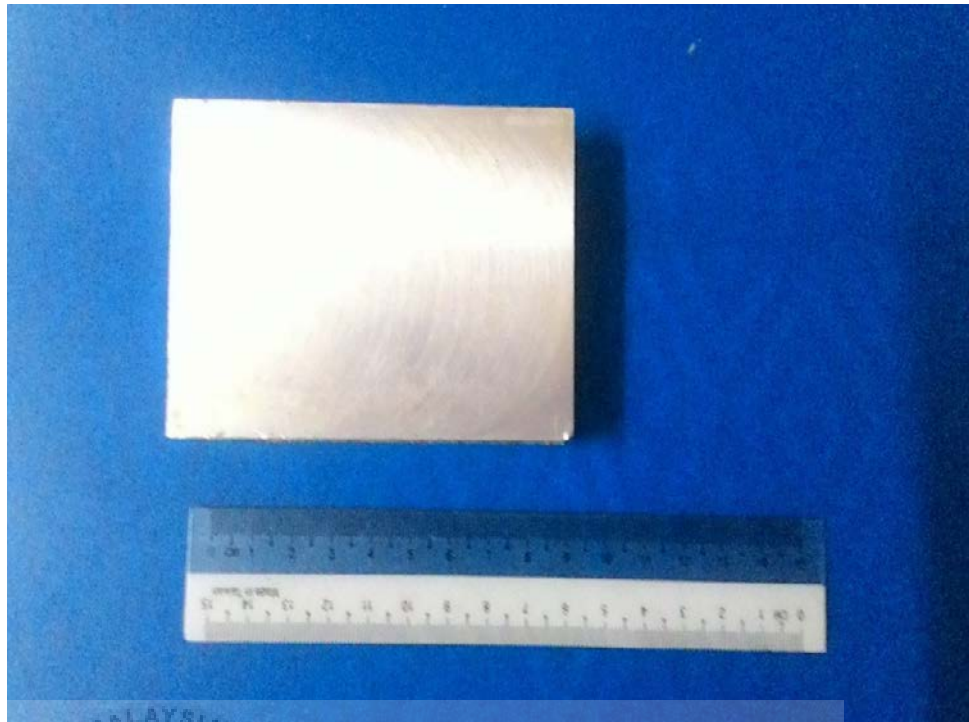


Figure 4.11 Aluminium workpiece



Figure 4.12 Delrin workpiece

Each workpiece go through the milling twice, once is clamp using conventional vise and later using vacuum clamping. The workpiece then was tested on its surface roughness using Portable Surface Roughness Tester, SJ-401. The data obtained from the tester is printed and tabulated.

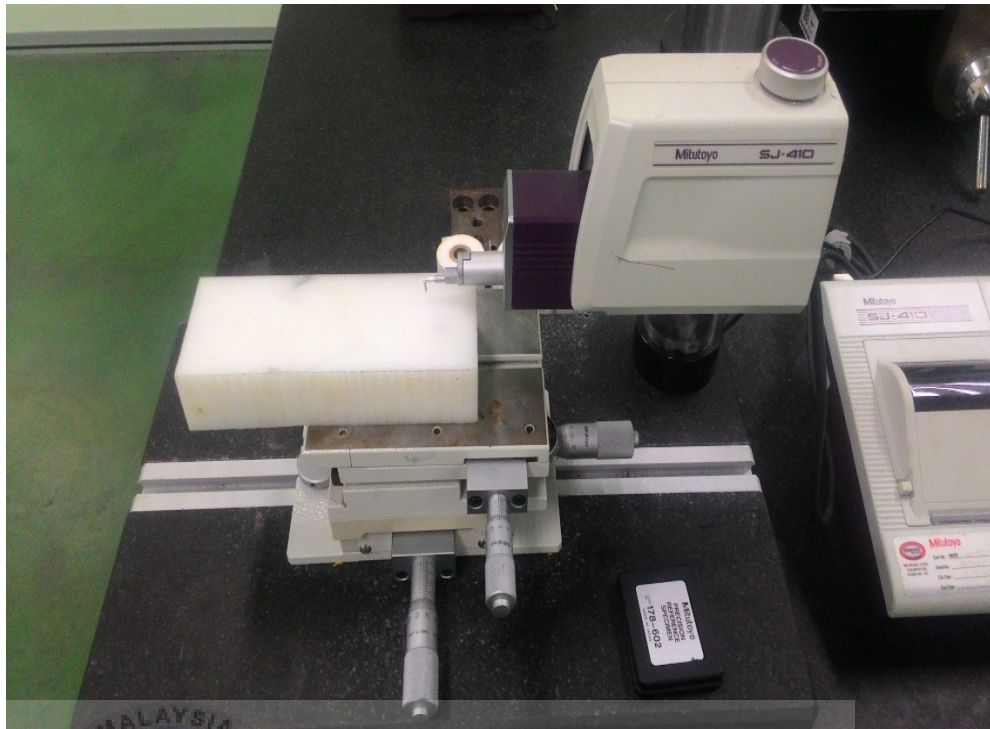


Figure 4.13 Portable Surface Roughness Tester, SJ-401

The workpiece was cut using milling machine and the cutting parameter used is shown in table 4.1.

Table 4.2 Cutting parameter

Test number	Cutting parameter values			material	Clamping method
	Spindle speed (RPM)	Feed (mm/min)	Depth of cut (mm)		
1	600	0.15	0.1	Aluminium	Conventional vise
2	600	0.15	0.1	Aluminium	Vacuum clamping
3	700	0.15	0.1	Delrin	Conventional vise
4	700	0.15	0.1	Delrin	Vacuum clamping

4.3.1 Surface roughness on aluminium

7 reading is taken for each surface of the aluminium workpiece. The obtained arithmetic mean value, Ra are as shown in the table 4.2.

Table 4.3

Reading number	Arithmetic mean value, Ra	
	Conventional vise	Vacuum clamping
1	1.232	0.552
2	1.194	0.595
3	1.157	0.851
4	1.204	0.775
5	1.198	0.672
6	1.218	0.611
7	1.129	0.708
Average	1.190	0.680

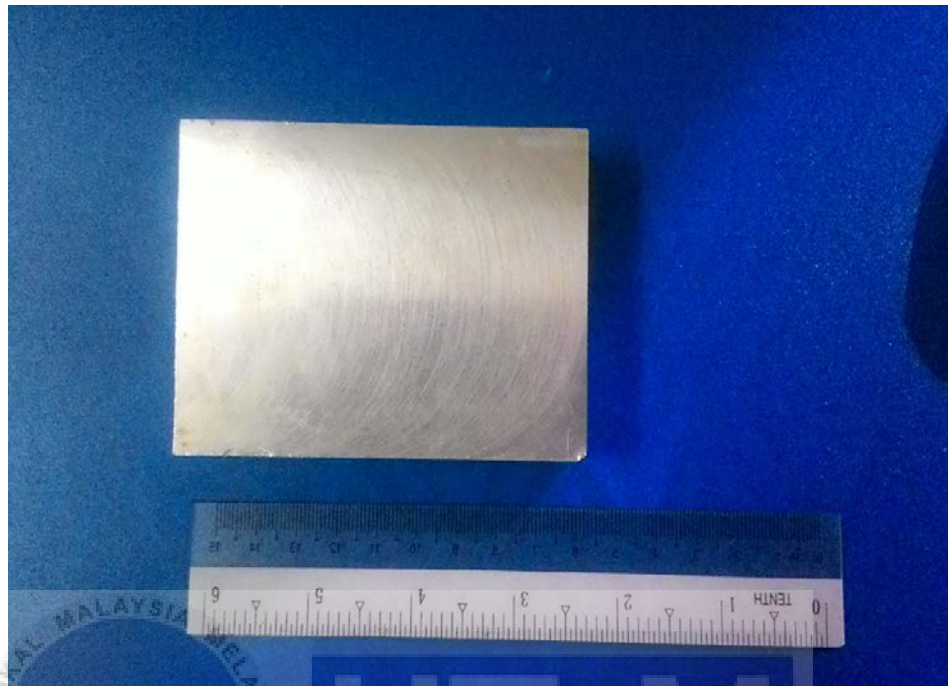


Figure 4.14 Aluminium clamped using conventional vise



Figure 4.15 Aluminium clamped using vacuum clamping



Figure 4.16 Surface roughness testing on aluminium workpiece

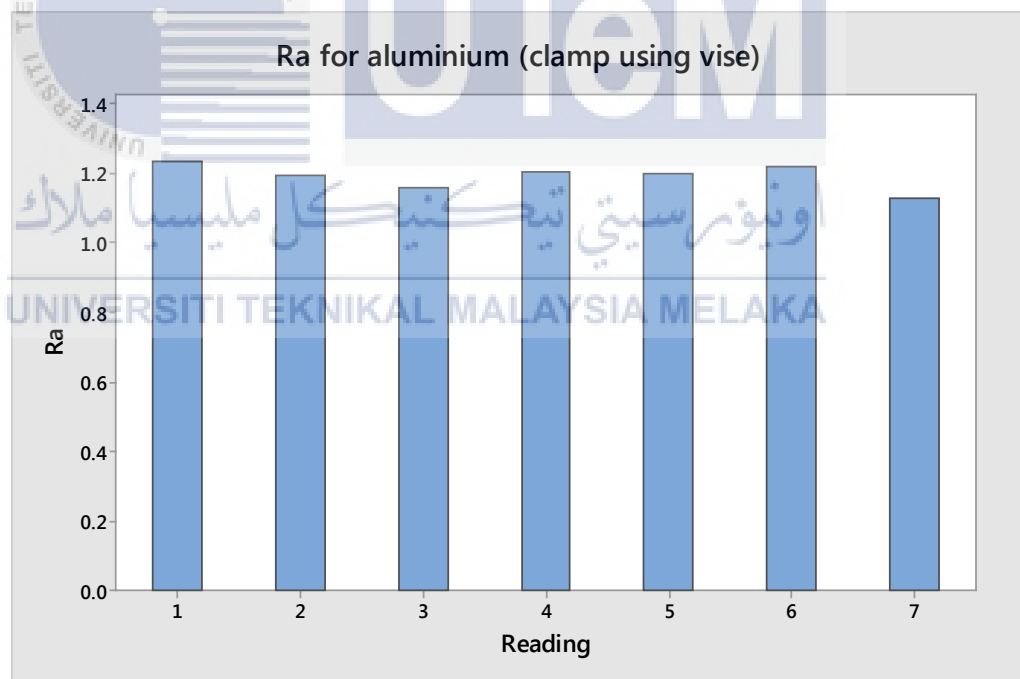


Figure 4.17 Surface roughness bar graph for aluminium clamped using vise

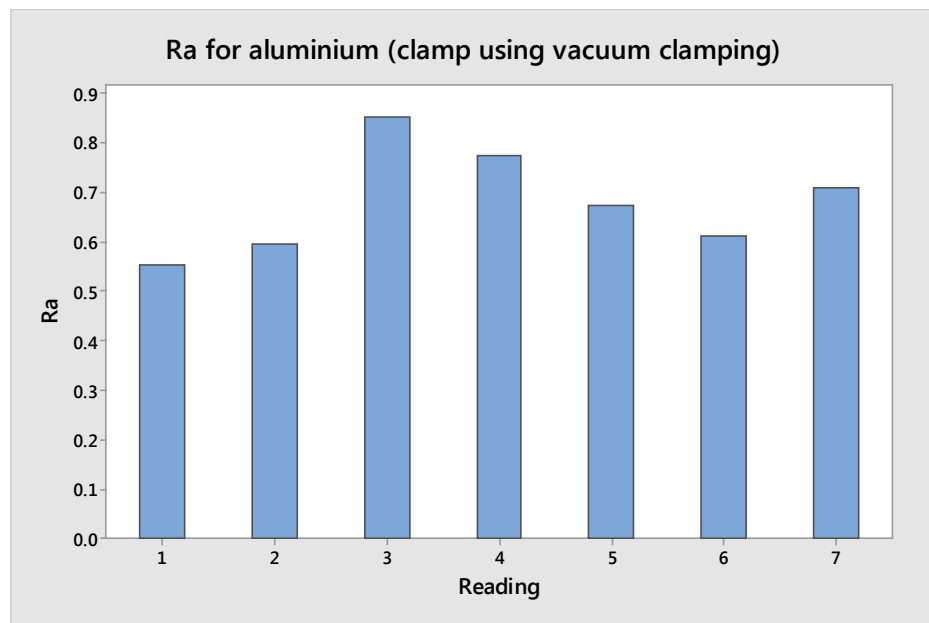


Figure 4.18 Surface roughness bar graph clamped using vacuum clamping

From the table , the average arithmetic mean value, Ra for aluminium clamped using vise is 1.190 micrometer. While for aluminium clamped using vacuum clamping, the average arithmetic mean value is 0.680 micrometer as shown in table . That the surface roughness of aluminium clamped using vacuum clamping is lower than surface roughness of aluminium that clamped using conventional vise, this prove that there is less vibration on the workpiece clamped using vacuum clamping during the milling process.

4.3.2 Surface roughness on delrin

Same as the test cut that I done on aluminium, this time the workpiece is change to delrin. Delrin is much softer material compare to aluminium. The parameter used such as spindle speed, feed rate and depth of cut is same for cut on conventional vise and vacuum clamping. The arithmetic mean value, Ra for delrin clamped using vise is shown in table 4.3.

Table 4.4

Reading number	Arithmetic mean value, Ra	
	Conventional vise	Vacuum clamping
1	2.031	1.245
2	2.023	1.358
3	1.874	1.243
4	1.863	1.357
5	1.882	1.018
6	2.008	0.936
7	1.923	0.920
Average	1.943	1.154

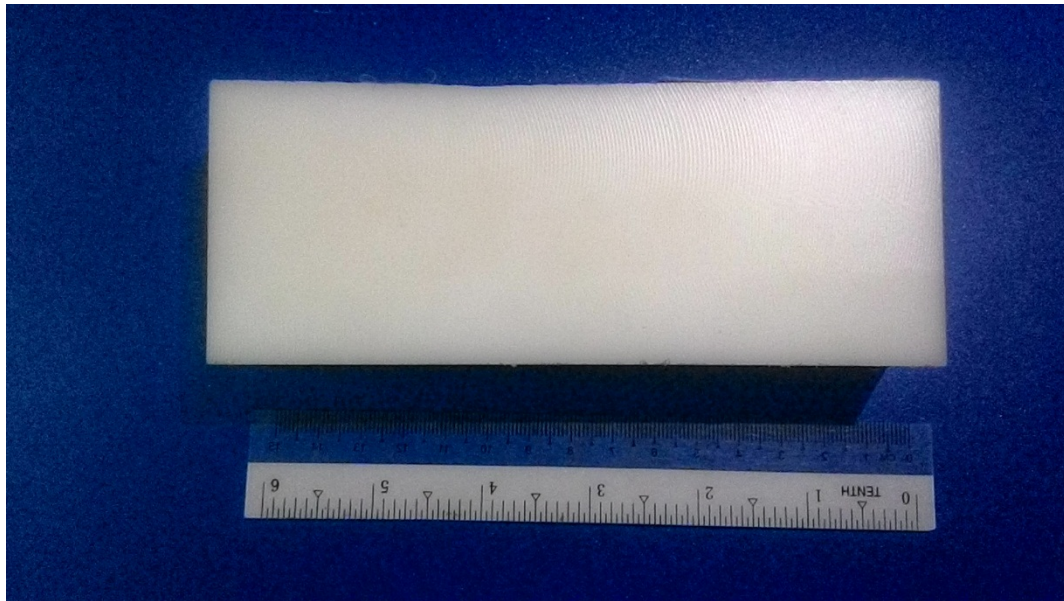


Figure 4.19 Delrin clamped using conventional vise



Figure 4.20 Delrin clamped using vacuum clamping

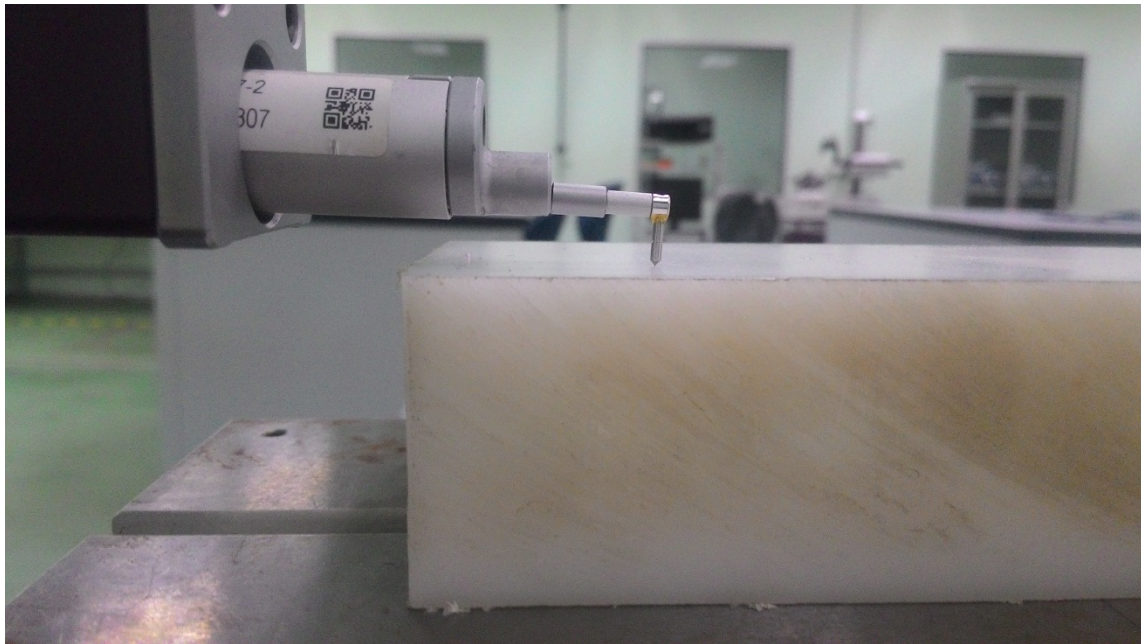


Figure 4.21 Surface roughness testing on delrin workpiece

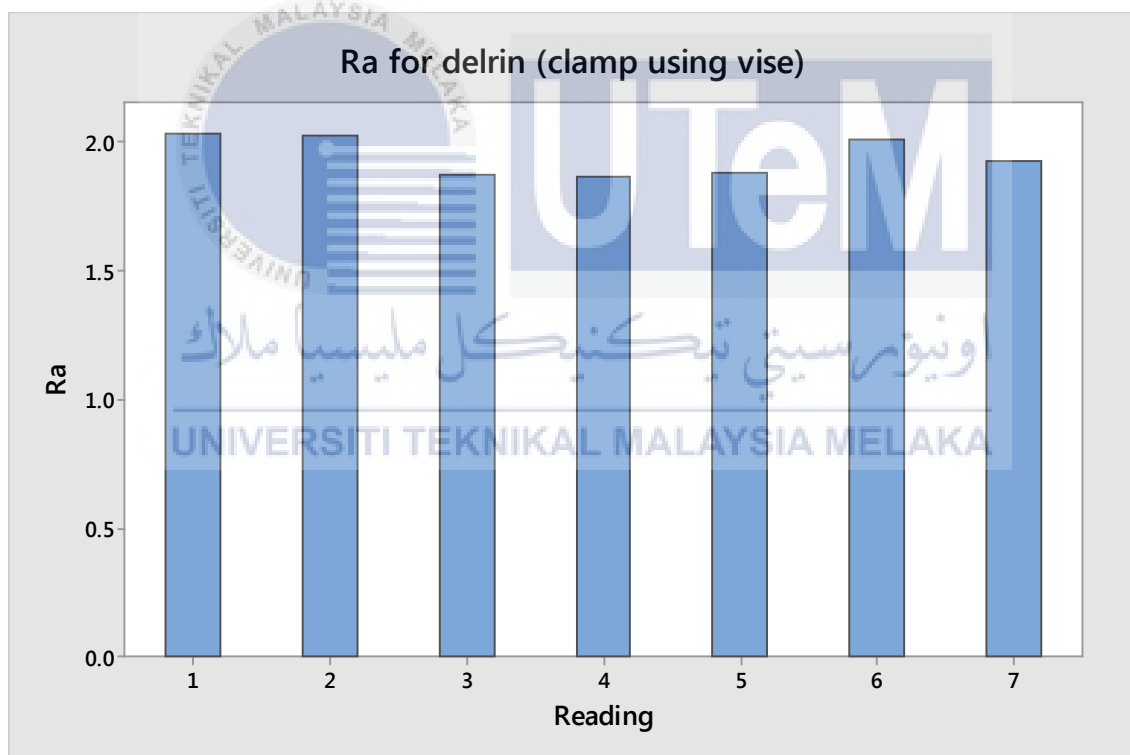


Figure 4.22 Surface roughness bar graph for delrin clamped using vise

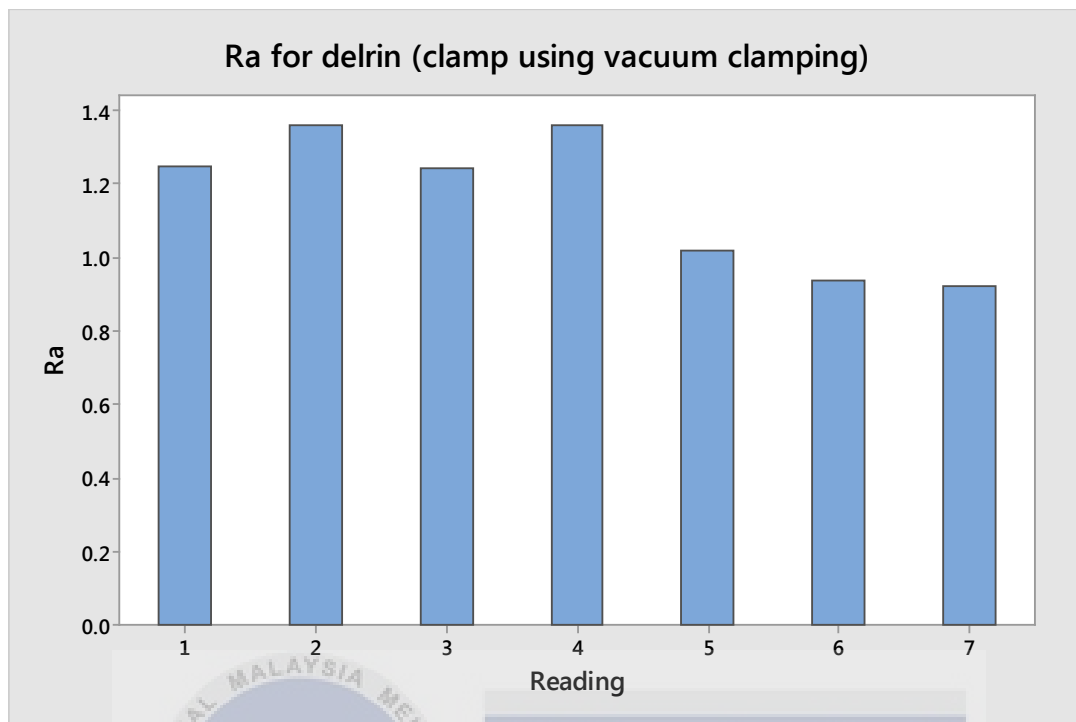


Figure 4.23 Surface roughness bar graph for delrin clamped using vacuum clamping

As shown in table 4.3, the average arithmetic mean value, Ra for delrin clamped using conventional vise is 1.943 micrometer. While for delrin clamped using vacuum clamping, the average arithmetic mean value is 1.154 micrometer. That the surface roughness of aluminium clamped using vacuum clamping is lower than surface roughness of delrin that clamped using conventional vise, this prove that there is less vibration on the workpiece clamped using vacuum clamping during the milling process.

4.4 Vacuum Workholding

The clamping force on a component is proportional to the surface area. The formula for vacuum clamping force are:

$$F \text{ (N)} = P(\text{bar}) \times A \text{ (m}^2\text{)}$$

where F is the force, bar is the vacuum suction pressure and A is the surface area for the workpiece. So the clamping force that able to generate from the vacuum clamping is depend on the vacuum pump suction force and also the surface area of the workpiece. The vacuum pump that used in this project is single-staged vacuum pump VE115N with 0.47 bar suction force. The vacuum pump suction force is fix so the clamping force generate is depend on the surface area of the workpiece.

The minimum surface area of the workpiece that the vacuum clamping can clamp is 0.784m². Using the formula, the minimum clamping force generate will be 0.368 kN. The maximum surface area of the workpiece that the vacuum clamping can clamp is 15.625m². Using the formula, the maximum clamping force will be 7.344 kN.

CHAPTER 5

CONCLUSION AND FUTURE WORK

This chapter summarizes the thesis, discusses its findings and contributions, points out limitations of the current work, and also outlines directions for future research. The chapter is divided into three sections. Section 5.1. is a summary of the thesis. Section 5.2. present the limitation from this project. Section 5.3. discusses the future work, and finally Section 5.4. is on about the implication.



The project was set out to develop a vacuum clamping that able to clamp workpiece and overcome the limitation in conventional vise. The whole project in developing is carried out using milling machine. The material used for the vacuum clamping are mild steel. Some changes have to done from the previous planning such as aluminium change to mild steel to cut the project cost. Beside that a bit of changes in the design also have been made as it is easier for machine the part. From the changes in design, part 2 is removed from the initial planning. After the vacuum clamping have been developed, a test is done where a workpiece is clamp using the vacuum clamping and cut the workpiece using face mill. The type of material of the workpiece use is aluminium. Next, same test also been done but this time the workpiece is clamp using the conventional vise. The test then repeated, using delrin as the workpiece. The workpieces then was checked on its surface roughness using Portable Surface Roughness Tester, SJ-401.

The result of the surface roughness show that the workpiece that been clamp using vacuum clamping have lower Arithmetic mean value, Ra compare to the surface of the workpiece that been clamp using conventional vise. That the surface roughness of workpiece clamped using vacuum clamping is lower than surface roughness of aluminium that clamped using conventional vise, this prove that there is less vibration on the workpiece clamped using vacuum clamping during the milling process.

. From this result we can say that the vacuum clamping is reliable and able to achieve the objective in clamping workpiece for the milling machine.

5.2 Limitation

Although this research was carefully prepared, I am still aware of its limitations and shortcomings. The limitations for this projects are listed below :

- Time factor
 - As there is only about 14 weeks to developed and also run the product for testing, there are not much testing that able to do with the vacuum clamping. To know more on the product ability and limitation, more testing need to be done.
- Product cost
 - In developing this product, the cost is RM400, which consists of the material, parts, vaccum pump, and also tools. To produce better vacuum clamping, more money is needed. The material for this product have to be change from aluminium to stainless steel to cut the project cost. Low powered vaccum pump is used in this project as its the chepeast vacuum pump available.

5.3 Future Research

While this project have been able to produce a functioning vacuum clamping and the result of surface roughness is showing positive result, there are a few future research that can be done to the vacuum clamping. The suggestions are listed and discussed below:

1. Type of material

- For this project, the material have to be changed from aluminium to mild steel to cut the cost. Comparing the aluminium and mild steel, aluminium is much better option as aluminium is lighter, does not rust and easier to machine. For future research it will be better to use aluminium.

2. Vacuum pump

- For a vacuum clamping, vacuum pump is very critical equipment for the vacuum clamping to functioning. In this project, I use a 2CFM vacuum pump with only $\frac{1}{4}$ horse power. For future work, it is better to use a vacuum pump with more horse power as it can produce more vacuum suction force and hence can clamp workpiece better.

3. Testing on the vacuum clamping

- In this project, I just did 1 testing to check whether the vacuum clamping is working properly. In the test I cut the workpiece using face mill. The workpieces are aluminium and delrin. Future researcher can use end mill instead of face mill to cut the workpiece. Beside that, future researcher can use more variety of other material such as mild steel and brass.

5.4 Implication

In this part, the implication of this project is discussed and explained. The implication is divided in two part which is implication for theory and implaction practice.

5.4.1 Implication for Theory

This project can give students knowledge on how to use vacuum clamping and how does it works. Student will be disclosed that there is more clamping method beside of using conventional vise. This study also can give exposure to the student on how vacuum energy wokrs theoritically.

5.4.2 Implication for practice

As vacuum clamping have its own advantage compare to conventional vise, there will be more implication toward the manufacturing process in the milling process. Firstly, more variety of design can be make in the future projects as vacuum clamping can clamp workpiece where vise can only clamp workpiece with parallel side only. Students is limited their project design considering their workpiece later cannot be clamp using vise to be machine. With using vacuum clamping, they are not limited to the workpiece with parallel side only. Second, time to clamp will be reduce as clamping using vacuum clamping is faster comparing to the conventional vise. This will save the overall machining process in using milling machine. Third, in term of safety, vacuum clamping is safer than cinventional vise. This will overall reduced the chance on any accident to happen during using the milling machine. Lastly, better product finish can be produce. As shown in the result, the surface finish of the workpiece is better when using the vacuum clamping comparing to the workpiece clamped using conventional vise.

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APPENDICES

Appendix A: Result of surface roughness testing on aluminium (clamped using conventional vise)

Appendix B: Result of surface roughness testing on aluminium (clamped using vacuum clamping)

Appendix C : Result of surface roughness testing on aluminium (clamped using conventional vise)

Appendix D: Result of surface roughness testing on delrin (clamped using vacuum clamping)



APPENDIX A

Date
Time

17/11/2016
12:17:15

Eval. Cond.

Standard	ISO1997
Profile	R
Filter	GAUSS
Ac	0.8mm
As	2.5um
N	5
Pre/Post	ON
Del. Wave	OFF
Tol. Judge	Mean
Prof. Comp.	OFF
Mean Line	OFF

Calc. Result

Ra	1.232	um
Rq	1.427	um
Rz	5.682	um

RProfile

x2K

x50

V-scale	5.00	um/cm
H-scale	200.00	um/cm

Eval. Cond.

Standard	ISO1997
Profile	R
Filter	GAUSS
Ac	0.8mm
As	2.5um
N	5
Pre/Post	ON
Del. Wave	OFF
Tol. Judge	Mean
Prof. Comp.	OFF
Mean Line	OFF

Calc. Result

Ra	1.194	um
Rq	1.370	um
Rz	5.005	um

RProfile

x5K

x50

V-scale	2.00	um/cm
H-scale	200.00	um/cm

Eval. Cond.

Standard	ISO1997
Profile	R
Filter	GAUSS
Ac	0.8mm
As	2.5um
N	5
Pre/Post	ON
Del. Wave	OFF
Tol. Judge	Mean
Prof. Comp.	OFF
Mean Line	OFF

Calc. Result

Ra	1.157	um
Rq	1.319	um
Rz	4.683	um

RProfile

x5K

x50

V-scale	2.00	um/cm
H-scale	200.00	um/cm

APPENDIX B

Standard R ISO1997
Profile GAUSS
Filter
Ac 0.8mm
As 2.5um
N 5
Pre/Post ON
Del. Wave OFF
Tol. Judge Mean
Prof. Comp. OFF
Mean Line OFF

Calc. Result

Ra	1.204	um
Rq	1.371	um
Rz	5.408	um

RProfile

x5K

x50

Eval. Cond.
Standard R ISO1997
Profile GAUSS
Filter
Ac 0.8mm
As 2.5um
N 5
Pre/Post ON
Del. Wave OFF
Tol. Judge Mean
Prof. Comp. OFF
Mean Line OFF

Calc. Result

Ra	1.198	um
Rq	1.398	um
Rz	5.458	um

RProfile

x2K

x50

Eval. Cond.
Standard R ISO1997
Profile GAUSS
Filter
Ac 0.8mm
As 2.5um
N 5
Pre/Post ON
Del. Wave OFF
Tol. Judge Mean
Prof. Comp. OFF
Mean Line OFF

Calc. Result

Ra	1.218	um
Rq	1.425	um
Rz	5.672	um

RProfile

x5K

x50

V-scale 2.00 um/cm

Eval. Cond.
Standard R ISO1997
Profile GAUSS
Filter
Ac 0.8mm
As 2.5um
N 5
Pre/Post ON
Del. Wave OFF
Tol. Judge Mean
Prof. Comp. OFF
Mean Line OFF

Calc. Result

Ra	0.552	um
Rq	0.707	um
Rz	4.194	um

RProfile

Eval. Cond.
Standard R ISO1997
Profile GAUSS
Filter
Ac 0.8mm
As 2.5um
N 5
Pre/Post ON
Del. Wave OFF
Tol. Judge Mean
Prof. Comp. OFF
Mean Line OFF

Calc. Result

Ra	0.595	um
Rq	0.727	um
Rz	3.739	um

RProfile

Eval. Cond.
Standard R ISO1997
Profile GAUSS
Filter
Ac 0.8mm
As 2.5um
N 5
Pre/Post ON
Del. Wave OFF
Tol. Judge Mean
Prof. Comp. OFF
Mean Line OFF

Calc. Result

Ra	0.851	um
Rq	1.084	um
Rz	4.923	um

RProfile

Eval. Cond.
Standard R ISO1997
Profile GAUSS
Filter
Ac 0.8mm
As 2.5um
N 5
Pre/Post ON
Del. Wave OFF
Tol. Judge Mean
Prof. Comp. OFF
Mean Line OFF

Calc. Result

Ra	0.708	um
Rq	0.928	um
Rz	5.306	um

Eval. Cond.
Standard R ISO1997
Profile GAUSS
Filter
Ac 0.8mm
As 2.5um
N 5
Pre/Post ON
Del. Wave OFF
Tol. Judge Mean
Prof. Comp. OFF
Mean Line OFF

Calc. Result

Ra	0.672	um
Rq	0.844	um
Rz	4.440	um

66

RProfile

x5K

x50

V-scale 2.00 um/cm
H-scale 200.00 um/cm

Eval. Cond.
Standard R ISO1997
Profile GAUSS
Filter
Ac 0.8mm
As 2.5um
N 5
Pre/Post ON
Del. Wave OFF
Tol. Judge Mean
Prof. Comp. OFF
Mean Line OFF

Calc. Result

Ra	0.611	um
Rq	0.753	um
Rz	4.156	um



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APPENDIX C

Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	2.031	µm
Rq	2.389	µm
Rz	9.435	µm
RProfile		
	x2K	
	x50	
V-scale	5.00	µm/cm
H-scale	200.00	µm/cm

Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	2.023	µm
Rq	2.421	µm
Rz	9.456	µm
RProfile		
	x2K	
	x50	
V-scale	5.00	µm/cm
H-scale	200.00	µm/cm

Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	1.874	µm
Rq	2.219	µm
Rz	8.973	µm
RProfile		
	x2K	
	x50	
V-scale	5.00	µm/cm
H-scale	200.00	µm/cm

3 Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	2.023	µm
Rq	2.421	µm
Rz	9.456	µm
RProfile		
		
x2K		
x50		
V-scale	5.00	µm/cm
H-scale	200.00	µm/cm

A Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	1.874	µm
Rq	2.219	µm
Rz	8.973	µm
RProfile		
		
x2K		
x50		
V-scale	5.00	µm/cm
H-scale	200.00	µm/cm

APPENDIX D

Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	1.863	µm
Rq	2.185	µm
Rz	8.243	µm
RProfile		
	x2K	
	x50	
V-scale	5.00	µm/cm

Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	1.613	µm
Rq	1.938	µm
Rz	8.118	µm
RProfile		
	x2K	
	x50	
V-scale	5.00	µm/cm

Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	2.008	µm
Rq	2.427	µm
Rz	9.641	µm
RProfile		
	x2K	
	x50	
V-scale	5.00	µm/cm

Eval. Cond.	
Standard	ISO1997
Profile	R
Filter	GAUSS
Ac	0.8mm
As	2.5µm
N	5
Pre/Post	ON
Del. Wave	OFF
Tol. Judge	Mean
Prof. Comp.	OFF
Mean Line	OFF

Calc. Result		
Ra	1.613	µm
Rq	1.938	µm
Rz	8.118	µm

RProfile		
	x2K	
	x50	
V-scale	5.00	µm/cm

Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	2.008	µm
Rq	2.427	µm
Rz	9.641	µm
RProfile		
	x2K	
	x50	
V-scale	5.00	µm/cm

A Eval. Cond.	
Standard	ISO1997
Profile	R
Filter	GAUSS
Ac	0.8mm
As	2.5µm
N	5
Pre/Post	ON
Del. Wave	OFF
Tol. Judge	Mean
Prof. Comp.	OFF
Mean Line	OFF
Calc. Result	
Ra	1.245 µm
Rq	1.480 µm
Rz	6.326 µm
RProfile	

A Eval. Cond.	
Standard	ISO1997
Profile	R
Filter	GAUSS
Ac	0.8mm
As	2.5µm
N	5
Pre/Post	ON
Del. Wave	OFF
Tol. Judge	Mean
Prof. Comp.	OFF
Mean Line	OFF
Calc. Result	
Ra	1.358 µm
Rq	1.594 µm
Rz	6.670 µm
RProfile	

A Eval. Cond.	
Standard	ISO1997
Profile	R
Filter	GAUSS
Ac	0.8mm
As	2.5µm
N	5
Pre/Post	ON
Del. Wave	OFF
Tol. Judge	Mean
Prof. Comp.	OFF
Mean Line	OFF
Calc. Result	
Ra	1.243 µm
Rq	1.481 µm
Rz	6.095 µm
RProfile	

A Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5um	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	1.358	um
Rq	1.594	um
Rz	6.670	um
RProfile		

Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	1.243	µm
Rq	1.481	µm
Rz	6.095	µm
RProfile		

A Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	0.920	µm
Rq	1.181	µm
Rz	5.735	µm
RProfile		
x2K		
x50		
V-scale	5.00	µm/cm
H-scale	200.00	µm/cm

A Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	1.018	µm
Rq	1.271	µm
Rz	6.298	µm
68		
RProfile		
x2K		
x50		
V-scale	5.00	µm/cm
H-scale	200.00	µm/cm

A Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	0.936	µm
Rq	1.174	µm
Rz	5.679	µm
RProfile		
x2K		
x50		
V-scale	5.00	µm/cm
H-scale	200.00	µm/cm

Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	1.018	µm
Rq	1.271	µm
Rz	6.298	µm
68		
RProfile		
x2K		
x50		
V-scale	5.00	µm/cm
H-scale	200.00	µm/cm

A Eval. Cond.		
Standard	ISO1997	
Profile	R	
Filter	GAUSS	
Ac	0.8mm	
As	2.5µm	
N	5	
Pre/Post	ON	
Del. Wave	OFF	
Tol. Judge	Mean	
Prof. Comp.	OFF	
Mean Line	OFF	
Calc. Result		
Ra	0.936	um
Rq	1.174	um
Rz	5.679	um
RProfile		
		
x2K		
x50		
V-scale	5.00	um/cm
H-scale	200.00	um/cm

