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EFFECT OF CHIP FORMATION ON TOOL WEAR IN MACHINING OF TITANIUM

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I certify that the project entitled “Effect of Chip Formation on Tool Wear in Machining of Titanium” is written by Lee Ka Hung. I have examined the final copy of this project and in my opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering.

Examiner: DR. AHAMD RAZLAN YUSOFF Signature

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Report submitted in partial fulfilment of the
requirements for the award of the degree of
Bachelor of Mechanical Engineering

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SUPERVISOR’S DECLARATION

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

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STUDENT’S DECLARATION

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

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DEDICATION

Specially dedicated to my beloved family and friends.

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First and the foremost, I would like to express my gratitude to my supervisor Mrs. Daw Thet Thet Mon that had guided me throughout this study from the beginning until the end. Besides, she had given me invaluable advices that empower my spirit and passion toward the job and the tolerance of my silly mistakes. I would like to take this chance to thank her for the support and encouragement whenever I faced any problems while completing this study. I am very thankful for the time that she had been spent with me for the study and correcting my mistakes even though she had a busy working schedule.

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ABSTRACT

Nowadays, titanium has become an important material mainly used in engineering application because of its excellent mechanical and physical property, for example, aircraft, aero-engines, biomedical devices and components in chemical processing equipments. However, the machining of titanium is getting tougher as tool wear is a common phenomenon happened during machining operations due to the frictions and forces produced when the cutting tool is in contact with the workpiece. The kind of chips produced from the machining operation may contribute to certain tool wear and cause the cutting tool life to be lowered. So, it is necessary to find out the optimum machining parameters that produce certain chip structure formations with lowest tool wear rate. Therefore, this project gives an investigation on the effect of chip formation on tool wear in machining of Titanium. The experiments will be carried out using a Computer Numerically Controlled machine (CNC). Different value of cutting speeds and feed rates are selected in order to study and observe the kind of chip formed. The cutting speed selected in the experiment are 90, 120 and 150 m/min, while the feed rates range from 0.05 to 0.15 mm/min. Apart from that, the depth of cut is kept constant at 0.5 mm. The diameter and length of titanium used in this study are 25 mm and 200 mm respectively. The chips collected from all these machining parameters will be taken to several chip preparation processes and then examined using optical microscope. Lastly, these data will be tabulated into graphical form as to clearly show the relationship between the variables and tool wear. The result shows that the shear layer thickness of the chip is the significant parameter that influences the tool wear relatively. The higher the shear layer thickness, the lower the tool wears, and vice versa. From the experiments, the shear layer thickness is proved as affected by the cutting speed and feed rate significantly. The lowest tool wear (crater and flank wear are 7.8921 μm and 1.2162 μm respectively) was determined at shear layer thickness of 0.0123 μm, which machined with cutting speeds of 162.4264 m/min and feed rate of 0.1 mm/rev.

ABSTRAK

Pada masa kini, titanium telah menjadi bahan yang penting digunakan terutamanya dalam aplikasi teknikal disebabkan oleh cirri-ciri mekanikal dan fizikal. Namun, pemesinan titanium menjadi semakin mencabar di mana kerosakan alat memotong merupakan fenomena umum yang terjadi semasa operasi pemesinan. Kerosakan ini disebabkan oleh tekanan dan daya yang dihasilkan semasa alat ini di kenakan dengan permukaan objek. Jenis cip yang dihasilkan daripada operasi pemesinan ini boleh mempengaruhi kerosakan alat memotong dan ini boleh menurunkan tempoh hayat alat memotong tersebut. Oleh sebab itu, projek ini memberikan penyelidikan tentang pengaruh cip struktur terhadap kerosakan alat memotong bagi pemesinan titanium. Eksperimen ini akan diljalankan dengan menggunakan mesin Computer Numerically Controlled (CNC). Nilai kelajuan memotong dan kadar kemasukan objek yang berbeza akan digunakan untuk mengkaji jenis cip yang terbentuk. Kelajuan memotong yang dipilih adalah 90, 120 dan 150 m/min, manakala kadar kemasukan objek adalah di antara 0.05-0.15 mm/min. Selain itu, kedalaman potong dipertahankan malar sebanyak 0.5 mm. Diameter dan panjang titanium yang digunakan dalam kajian ini adalah 25 mm x 200 mm. Cip yang dikumpulkan dari semua parameter pemesinan akan dibawa ke beberapa proses penyediaan dan kemudian memerihati dengan menggunakan mikroskop optik. Akhir sekali, data ini akan ditabulasikan dalam bentuk grafik untuk jelas menunjukkan hubungan antara pembolehubah berserta dengan analisasi. Keputusan eksperimen menunjukkan bahawa ketebalan lapisan memotong merupakan satu pembolehubah yang signifikan menpengaruhi kerosakan alat memotong. Semakin kurang ketebalan lapisan memotong, semakin rendah kerosakan alat momotong, dan sebaliknya. Daripada eksperimen, ketebalan lapisan memotong ini terbukti bahawa dipengaruhi kuat oleh kelajuan memotong dan kadar kemasukan objek. Nilai kerosakan alat memotong yang paling rendah ditentukan pada ketebalan lapisan memotong sebanyak 0.0123 μm, di mana kelajuan memotong dan kadar kemasukan objek adalah 162.4264 m/minit dan 0.10 mm/pusingan.

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f	Feed rate
V	Cutting speed
p	Significant value

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
BUE	Build Up Edge
CNC	Computer Numerically Controlled

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Titanium is an important material used in a wide variety of product forms in this modern engineering world. Nevertheless, titanium and its alloys are extremely difficult to machine materials owing to several inherent properties of the metal. For instances, it has low thermal conductivity and tends to react chemically with many cutting tool materials at tool operation temperatures. Low thermal conductivity increases the temperature at the cutting edge of the tool. As this rate, on machining, the workpiece may be deformed and produce chips that different in microstructure which give effects to the tool wear. In this study, we focus on the effect of chip structure formation on tool wear in machining titanium.

1.2 PROJECT BACKGROUND

Nowadays, there are many products made from titanium in this modern industry due to its excellent properties like high strength, toughness and low mass. According to Suisman (2005), titanium is 30% stronger than steel but is nearly 50% lighter and it is 60% heavier than aluminium but twice as strong. Titanium is also nonmagnetic and possesses good heat transfer properties. It has the ability to passivate, thereby giving it a corrosion resistance to acid. Besides, the main properties such as high strength, low density, and excellent corrosion resistance have make titanium attractive for a variety of application. Examples include aircraft (high strength in combination with low density), aero-engines (high strength, low density and good creep resistance up to about 550^{o}c), biomedical devices (corrosion resistance and high strength) and components in chemical processing equipment (corrosion resistance).

In many titanium applications machining, it is necessary to identify the type of wear that could happen with respect to the kind of chip microstructure produced in order to increase the tool life. There are two main reasons for investigating the effect of chip structural formation on tool wear. First, the results obtained provide quantitative data to explain functional behaviors of the machined-material and second, the findings can be used as a means for process control, as well as for improving machinability of Titanium.

1.3 PROBLEM STATEMENT

Tool wear is an important parameter that must be controlled and minimized in order to increase tool life in any machining process. However, the low thermal characteristics of titanium usually produce a poor chip formation due to the heat generated cannot be conducted to environment. In this case, the cutting temperature will also increase rapidly. Moreover, the low elastic modulus of titanium property has increased more vibration during machining. Combining all these factors, titanium are said difficult to machine and produce unusual chip formation that affects the tool wears. When the tool wear is high, the tool life will be lowered and thus the replacement of new cutting tool is become quicker as compared to low tool wear. In this case, the machining cost will be increased. However, the inter-relationship between the chip structure deformation and tool wear has not been well understood and need to be investigated in this study.

1.4 PROJECT OBJECTIVE

The objectives of this project are (1) to investigate the effect of chip formation on tool wear in machining of Titanium; (2) to determine the machinery parameters that affect chip formation; and (3) to investigate the relationship between chip formation and tool wear.

1.5 SCOPE OF THE PROJECT

This study mainly focuses on machining of titanium, which will be carried out in a CNC turning center. The experiment procedures will be designed by the Design of Experiment (DOE) method using STATISTICA software. It will rearrange the order of turning operation in different cutting speeds and feed rates in order to minimize the error. Machining parameters selected in this study, cutting speeds and feed rates will be varied up to few levels. Constant depth of cut is chosen based on the literature and finding. The cutting speed range from 77.5736, 90, 120, 150 and 162.4264 m/min whereas the feed rates used in the experiment are 0.029289, 0.05, 0.10, 0.15 and 0.170711 mm/min. The chips will be collected from each machining parameter in turning process and undergo several chip specimen preparation process such as hot mounting, grinding, polishing and etching.

Next, the chips microstructure was observed by using optical microscope and integrated software. All the experimented data will be collected for further analysis. Finally, a tool wear curve was developed with respect to chip microstructure from the results obtained by using Excel workbook.

1.6 ORGANIZATION OF THESIS

This study is delegated into five chapters. In the first chapter, the introduction of the project title is discussed and the problem statements, objectives, scope of project are reviewed in order to list out the tasks and act as a guideline for this study.

In the second chapter, it consists of detailed literature review of machining titanium and tool wear. At the beginning of this chapter, some of the basic information about the titanium is discussed. Next, the operation of CNC turning is reviewed together with cutting tools, cutting fluids and turning parameters which play an important role in determining the machining efficiency and result. Moreover, this chapter continues with chip formation study and tool wears which is inter-related with the project research. Lastly, the related previous research about this study is briefly discussed.

Next chapter consists of the methodology which is used to conduct the whole research experiment from the starting until the study is completed. Starting of this chapter, an overall project flow chart is designed in order to act as guideline for task sequences. In addition, the information about the materials used to complete the study is briefly discussed.

In the forth chapter, the results obtained from the experiment will be discussed. Several graphs will be made to preview the relationship between the chip formation and tool wear, which is resulting from different machining parameters, namely cutting speed and feed rate. At the end of this chapter, some of the sources of errors that affect the experiment outcomes are briefly discussed.

The final chapter consists of the conclusions of the study together with the project summary, project findings and further recommendations to improve the study in the future.

1.7 CONCLUSION

In Chapter 1, the project background, problem statement, objectives and scope of the project related to the boundary of my study was presented to avoid any unwanted deviation from the project title. This chapter was thereby acted as guidelines for the whole project. The relationship between chip structure formation and tool wear, machining parameters that influence chip formation and tool wear relationship were determined at the end of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter discussed about the literature review of the chip microstructure on tool wear in machining of titanium. Starting of this review, titanium machining from aspects of machining parameters, cutting tool, cutting fluid, chip formation and tool wear are briefly discussed. Next, an overviews of the previous study related to this title is discussed.

2.2 TITANIUM MACHINABILITY

Titanium is a chemical element with the symbol Ti and atomic number 22. Commonly, it has a strong, lustrous, corrosion-resistant metallic element with low density, which covered in silver color. In most of the application, titanium can be alloyed with many elements to produce strong and lightweight property such as vanadium, aluminium, iron and so on. The specific weight of titanium is about two thirds that of steel and about 60% higher than aluminium. In term of tensile and sheet stiffness, titanium has fall between steel and aluminium. Moreover, its Young's Modulus and ultimate strength are ranging from 100-110GPa and 300MPa respectively. The mechanical properties of pure titanium can be shown in the Appendix A.

In any machining operation, titanium has a tendency to gall, and its chips can weld to the cutting edges of the tool and this will lead to tool wear begins. In addition, the titanium's low modulus of elasticity can caused slender workpieces to deflect more than steel. In consequence, this will arise to cutting problems like chatter, tool contact and holding tolerances, which greatly affect the workpiece surface finish and tool wear.

However, it is often to produce an unusual chip microstructure with titanium due to the nature of the metal and generation of high temperature during machining process. Lastly, the tool wear and tool life depend greatly on the kind of chip microstructure formation which is influenced by the machining parameters.

2.3 MACHINING: COMPUTER NUMERICALLY CONTROLLED (CNC) TURNING PROCESS

Turning is best describes as a material removal process, which is used to create rotational part by cutting away unwanted part of material. Basically, the workpiece is secured to fixture, which is attached to the turning machine and allows rotating at high speed. Next, the cutting tool feeds into the rotating workpiece and cuts away the unwanted portion of material in the form of small chips to create the desired shape. Turning can be performed either manually or by computer through numerical controlled programming. A typical CNC machine is shown in Figure 2.1.

Figure 2.1: Computer Numerically Controlled (CNC) machine.

In the CNC turning process, a piece of material is rotated on the lathe and a cutting tool is traversed along two axis of motion, either transversely or longitudinally. The lathe holds the workpiece in cylindrical shape between two rigid supports (a.k.a chuck) that revolves about the centre line of the lathe. The spindle carrying the work is rotated whilst a cutting tool, which is supported in a tool post, is made to travel in a certain direction depending on the type of surface required. For example, a cylindrical surface is shaped when the tool moves parallel to the axis of the motion. The whole process is continued until the required depth and dimension is achieved. According to one's needs and specification, turning can also be done from inside-to-outside or vice versa.

Figure 2.2 shows the schematic diagram of typical turning process. The spindle or rotation speed, which enables control of tool motion, can be adjusted using a computer programming. Turning tool moves in one direction which is call feed direction. Parts that are too large to balance and cause difficulty in rotating around one center point, can be worked on a machining center featuring a U axis. The turning length is about 1000 mm between centers and has a drive power and speed range up to 46 kW and 3000 revolution per minute respectively.

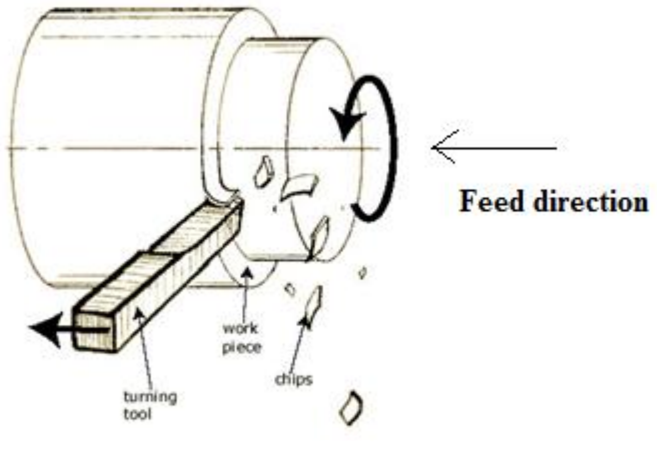


Figure 2.2: Schematic diagram of typical turning process.

According to the diagram above, it is necessary to identify the appropriate spindle rotational speed before running the turning process. Different materials would have different allowable cutting speed range. The relationship between surface speeds so called cutting speed and spindle rotational speed can be best described as:

$$V=\pi DN \tag{1}$$

Where,

V= Cutting speed, (m/min)
D= Diameter of bar (m)
N= Spindle rotational speed (RPM)

The cutting tool is used until the required depth and dimension is achieved. Turning can be on both side, inside or outside as per the need and specifications. The rotation occurs at the turning center that enables control of tool motion through computer programs that use numeric data.

CNC turning process allows the materials to be cut into various shapes ranging from plain surface, taper ends, contour and filter to radius profiles as well as threaded surfaces. These cut and turned metal pieces are then used to create shafts, rods, hubs, bushes, pulley and etc. CNC turning machines are able to deliver components at a faster production rate with optimum manufacturing accuracy.

2.4 TURNING PARAMETER

In turning process, the speed and motion of the cutting tool is specified through several parameters. These parameters are selected for each operation based upon the workpiece material, tool size, and tool material. These parameters are important because it will directly affecting the output and also the performance of work. So, the turning parameters that can affect the process are shown in the Table 2.1.

Table 2.1: Parameter in turning process.

Parameter	Definition
Cutting speed	The speed of the workpiece surface relative to the edge of the cutting tool during a cut, measured in surface feet per minute (SFM).
Feed rate	The speed of the cutting tool relative to the workpiece as the tool makes a cut, measured in millimeter per revolution (RPM).
Spindle speed	The rotational speed of the workpiece in revolution per minute (RPM). The spindle speed is equal to the cutting speed divided by the circumference of the workpiece where the cut is being made.
Axial depth of cut	The depth of the tool along the axis of the workpiece as it makes a cut, as in a facing operation.
Radial depth of cut	The depth of the tool along the radius of the workpiece as it makes a cut, as in a turning or boring operation. A large radial depth of cut will require low feed rate, or else it will result in a high load on the tool and reduce the tool life.

2.5 CUTTING TOOLS

Cutting tool is one of the most important components in the machining process, in which its performance determines the efficiency of the operation. In particular, consideration should be given not only to the selection of the cutting tool material but also to the cutting tool angles required to machine titanium properly.

Generally, the properties possessed by each of these materials are different and the application of each depends on the material being machined and the condition of the machine. Different material property would require different cutting tool to shape it into desire dimension. Generally, these tool bits should possess the following properties:

i) They should be hard
ii) They should be wear-resistant
iii) They should be capable of maintaining a "red hardness" during the machining operation

(Note*: Red hardness is the ability of a cutting tool material to maintain a sharp cutting edge even when it turns red because of the high heat produced at the work-tool interface during the cutting operation.*)

iv) They should be able to withstand shock during the cutting operation
v) They should be shaped so that the edge can penetrate the work

(Note: *The shape is determined by the cutting-tool material, the material being cut and the angle of keenness.)*

Until recently, tool materials have been shifted from common high-speed steel and carbide to advanced carbides coated with various coatings for better toughness, hardness and heat resistant properties. Cutting tool geometries are standardized according to ISO designation. Major geometric information for a cutting is shape, rake angle, clearance angle, included angle and approaching angle. Figure 2.3 shows some disposable turning inserts of various geometries.

Figure 2.3: Various turning inserts.

In turning process, rake angle plays an important role in producing a high quality output, mostly focus to the kind of chip formation. The rake angle is the angle formed by the leading edge and the radius of the file. If the angle formed by the leading edge and the surface to be cut is obtuse, the rake angle is said to be positive or cutting. If the angle formed by the leading edge and the surface to be cut is acute, the rake angle is said to be negative or scraping. However, the rake angle may not be the same as the cutting angle. Clearance angle is another parameter that should be taken into account during turning machining operation.

The clearance angle refers to the angle of the cutting edge with respect to the face of the cutter. This angle allows for chip clearance, determines how find the cutting edge is and selected based on material properties. Commonly, the clearance angle ensures only the cutting edge of the tool contacts the workpiece and the back, or heel, of the tool does not rub the finished surface in order to prevent the tool does not degrade the surface finish and consuming extra power. Figure 2.4 below illustrates the rake and clearance in a cutting operation.

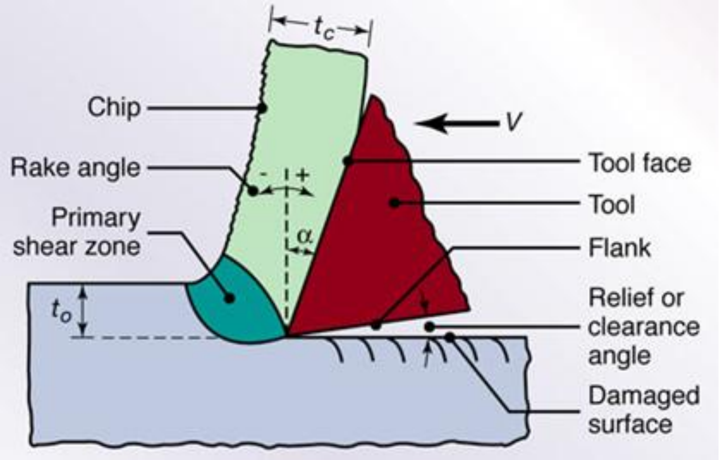


Figure 2.4: Schematic diagram of cutting process.

2.6 CUTTING FLUIDS

There is a wide variety of cutting fluids available today. Many new coolants have been developed to meet the needs of new materials, cutting tools and coating on cutting tools. The goal of machining operations is to improve productivity and at the same time reduce costs. This can be accomplished by machining at the highest practical speed while maintaining practical tool life, reducing scrap, and producing parts with the desired surface quality. Proper selection and use of cutting fluids can thus help to achieve all of these aims.

During machining almost all of the energy expended in cutting is transformed into heat. Deformation of the metal create chip, and the friction of the chip sliding across the cutting tool produces heat. Therefore, the primary function of cutting fluids is to cool the cutting tools, workpiece and chip, so that friction at the sliding contact can be reduced and prevent the welding or adhesion on the contact edges that causes a built-up edge on the cutting tool or insert. In addition, cutting fluids also help to prevent rust and corrosion and flush chip away from the material machining surface. Reducing cutting-tool temperature is important since a small reduction in temperature will greatly extend cutting tool life (Tuholski, 1993). Figure 2.5 below illustrates the ejection direction of the cutting fluid.

Figure 2.5: Ejection direction of the cutting fluid.

2.7 CHIP FORMATION

Formation of chips is a common process for every machining operation. The nature of which differs from operation to operation, properties of workpiece material and the machining parameters. Chips are formed due to the cutting tool, which is harder and more wear resistant than the workpiece and the force and power to overcome the resistance of the work material. The chip is formed by the deformation of the metal called shearing process. Generally, there are four main types of chips (S.Kalpajian, 2003).

2.7.1 Continuous Chip

For this kind of chips formation, the pressure of the workpiece is built until the material fails by slipping along the plane. The inside on the chip displays steps produced by the intermittent slip. The chip has its elements bonded together in the form of long coils and formed by the continuous plastic deformation of material without fracture ahead of the cutting edge of the tool. Commonly, the deformation takes place along primary shear zone or narrow shear zone. Continuous chips are not always desirable, particularly in automated machine tools, where tend to get tangled around the tool.

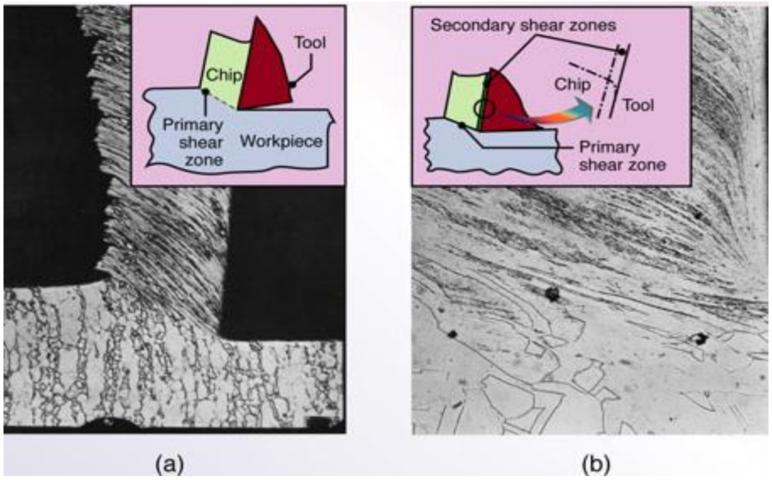


Figure 2.6: Chip produced in orthogonal cutting (a) continuous chip with narrow, straight, and primary shear zone; (b) continuous chip with secondary shear zone at the chip-tool interface.

2.7.2 Continuous Chip Build-up-Edge (BUE)

This kind of chips is almost same to that of continuous type, but the difference is that the chip is not as smooth as the previous one. This type of chip is associated with poor surface finish but protects the cutting edge from wear due to movement of chips and the action of heat causing the increase in tool life. This kind of chip formation can be reduced by decreasing the depth of cut, increasing the rake angle, using sharp tool and effective cutting fluid.

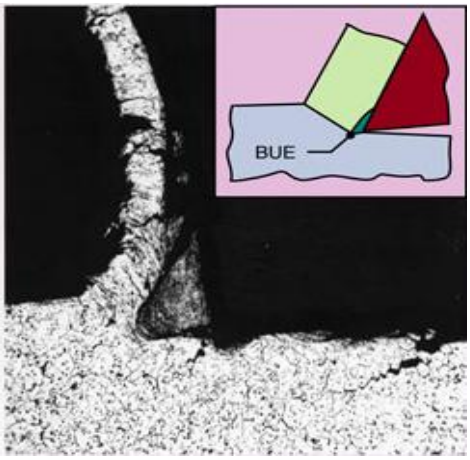


Figure 2.7: Built-up-edge formation; *Source*: After M.C. Shaw, P.K. Wright, and S. Kalpakjian.

2.7.3 Discontinuous Chip

These chips are small segments, which adhere loosely to each other. The chips are formed when the amount of deformation to which chips undergo is limited by repeated fracturing. Generally, these chips occur when machining hard brittle material such as cast iron. Brittle failure take place along the shear plane before any tangible plastic flow occurs. Besides, discontinuous chips will form in brittle materials at low rake angles or large depth of cut. Figure 2.8 illustrates the discontinuous chip with its microstructure.

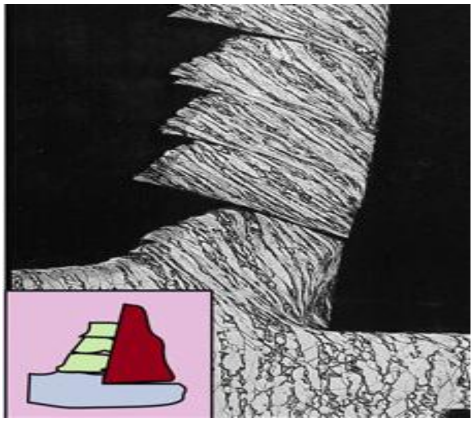


Figure 2.8: Discontinuous chip formation. *Source*: After M.C. Shaw, P.K. Wright, and S. Kalpakjian.

2.7.4 Serrated Chip

The chips are formed in semi continuous in which it possesses a saw-tooth appearance that is produced by a alternating high shear strain followed by low shear strain. This chip is most closely associated with certain difficult-to-machine metals such as titanium alloys, austenitic stainless steels and nickel-base super alloys when machined with high cutting speeds.

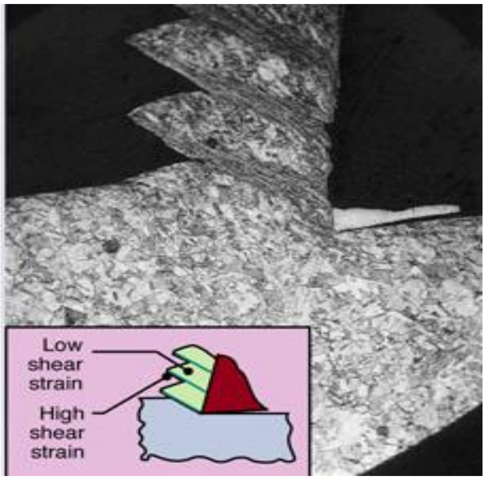


Figure 2.9: Serrated and segmented chip formation. *Source*: After M.C. Shaw, P.K. Wright, and S. Kalpakjian.

2.8 STATISTICAL APPROACH

In this study, STATISTICA experimental design software was used for designing and conducting the experiment as well as analyzing data. To achieve these, certain steps need to be followed throughout the experiment. Montgomery (2001) listed the guidelines to be followed in designing and analyzing an experiment.

2.8.1 Statement of the problem

As mentioned in Chapter 1, before designing an experiment, it is necessary to understand the problems and develop ideas about the objectives of the whole study. This step is crucial for the beginning and for the outcomes of the entire experiment.

2.8.2 Choice of factors levels and range

Considering the factors that have major effects on the process performance or outcome is the first part of this step. These factors can be either controllable, uncontrollable, or noise factors. In controlled factors, the level of the factor can be set and manipulated by the experimenter. In uncontrollable factors, there is no setting for the levels of the factor. It can be measured by not controlled. In this case, the measured values of the levels of the factor can be recorded and treated as a covariate in the analysis. In noise factors, the factor varies naturally and uncontrolled but can be controlled for the purpose of the experiment. In such cases, the experimenter aims to find out levels of controlled factors that will minimize the variation that is introduced into system by noise factor. This kind of problem is often called as robust design problem. In selecting the levels for the factors, process knowledge is the key element that is a combination of practical experience and theoretical understanding.

2.8.3 Selecting a response variable

In selecting a response variable, the experimenter should be confident that such measure really provides information about the process that is under study. Often, rather than just the response variable itself, the average or the standard deviation can be used as a response variable. There can be more than one response variable and the ability to accurately and repeatedly measure the response variables is crucial.

2.8.4 Choice of experimental design

This step is determining the size of the experiment, the number of replications whether to use blocking, randomize and select the order of the runs. All of these elements can directly affect the effectiveness of the experiment.

2.8.5 Performing the experiment

While running the experiment all the processes should be monitored carefully and closely, and everything should be carried out as planned. All the conditions are kept same for the entire study. Here, a condition refers to the set up of the machine or measurement equipment, room temperature and operator. Any changes in those conditions might have a significant impact on data collection.

2.8.6 Statistical analysis of the data

After completing the first five steps successfully, the obtained results should not be too difficult to be analyzed. The proper and effective use of statistical techniques in experimentation requires that the experimenter keep the following steps in mind (Montgomery, 2001).

a. Use non-statistical knowledge that is not a substitute for thinking.
b. Keep the design and analysis as simple as possible.
c. Experiments should be repeatable.

2.9 SHEARING MECHANISM

In any kind of metal machining process, shearing is the common process involved by removing the unwanted portion of the workpiece into desired dimension. At the same time, chips are produced with certain shape and characteristic depending on the machining parameters. During the shearing process, there are two thin zones of intense plastic deformation are concerned and analyzed, as shown in Figure 2.10.

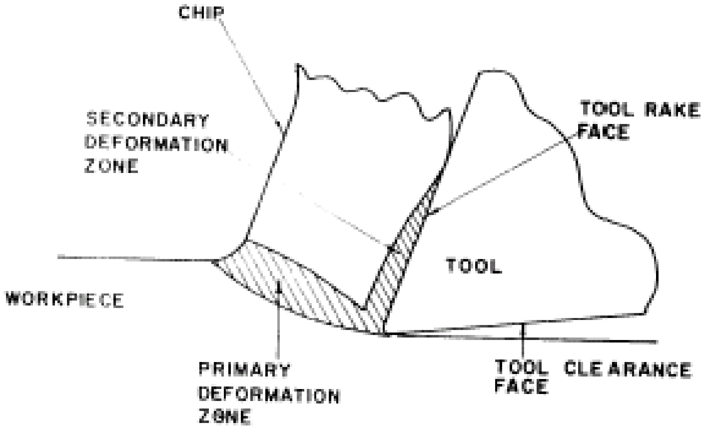


Figure 2.10: Primary and secondary shear deformation zone.

The primary deformation/shear zone was arising as the chip is initially sheared from workpiece being machined. It is a primarily examination of phenomena associated with the creation and formation of chips, with the effect of the components of cutting force-the state of strain deformation, the location of the angle of the shear level, chip compression, the temperature field, chip shape, chip formation and separation, the effect of the components of cutting force

The secondary deformation/shear zone was arising from frictional interaction between chip and tool. It is primarily an examination of phenomena associated with friction and cutting wedge wear, and also with the generation of heat and temperature-the location of the grain angle, the contact length of the cutting edge and the face plate, friction stress and scab creation (BUE), friction, the generation of heat and temperature, the mechanism of tool wear).

According to Olayinka Oladele Awopetu (2008), the shear zone, during the process of turning titanium and its alloys, is not constant. It sometimes appears and sometimes disappears. This means that not all parts of the segmented chip passes through the shear zone. The shear zone, when present, is resuced and even sometimes could not be called a shear but a “shear line” (shear plane) and passes through the boundaries of the microstructure blocks since they tend to be the weakest parts of the structures. However, shear line sometimes passes through the microstructure blocks if it can be turned or if it has a defect.

2.10 TOOL WEAR

Tool wear can be best describes as the gradual failure of cutting tools due to regular operation. As a tool wears, a crater forms on cutting tool surface. The shape of this crater conforms to the shape of the curled chip, and thus the presence of a chip breaker will affect the wear process. Theoretically, tool wear is greatly reduced when adhesion occurs between the tool and the chips, preventing relative sliding at tool-chip interface. In this case, we will be more concentrated on the effect of cutting speed and feed rate in order to investigate the type of chip microstructure formed related to the tool wear of titanium in turning operation.

Generally, there are two major types of wear found during cutting operation; they are crater wear and flank wear (S.Kalpajian, 2003). Typically, crater wear occurs on the rake face of the tool. It is essentially the erosion of an area parallel to the cutting edge. This erosion process takes place as the chip being cut, rubs the top face of the tool. Under very high-speed cutting conditions and when machining tough materials, crater wear can be the factor which determines the life of the tool. However, when tools are used under economical conditions, the edge wear and not the crater wear is more commonly the controlling factor in the life of the tool. Crater wear is caused mainly by diffusion and adhesion.

Flank wear occurs on the clearance face of the tool and is mainly caused by the rubbing of the newly machined workpiece surface on the contact area of the tool edge. This type of wear occurs on all tools while cutting any type of work material. Flank wear begins along the lead cutting edge and generally moves downward, away from the cutting edge. The edge wear is also commonly known as the wear land. During the initial and steady phase, the root cause is due to abrasion, whereas during third stage, it is by diffusion. Figure 2.11 shows the type of wears happen on a cutting tool.

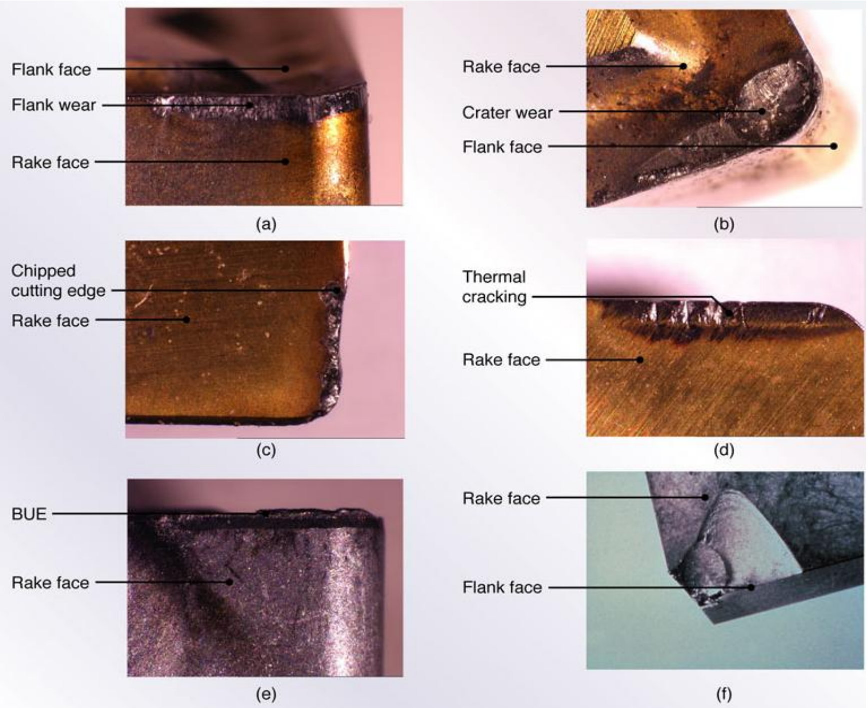


Figure 2.11: Types of wear on a turning tool: (a) flank wear; (b) crater wear; (c) chipped cutting edge; (d) thermal cracking on rake face; (e) built-up edge; (f) catastrophic failure. *Source*: Courtesy of Kennametal, Inc.

A tool that no longer performs the desired functions is said to have failed and hence reached the end of its useful life. At such end point the tool is not necessarily unable to cut the workpiece but is merely unsatisfactory for the purpose required. The tool may be re-sharpened and used again.

2.11 WEAR MECHANISM

Practically, the four basic wear mechanisms are abrasion, adhesion, diffusion and oxidation. By identifying and understand the type of wear mechanism happen in a tool operation, we could be able to find out a suitable prevention method to eliminate the kind of wears could happen. Thus, the tool life can be increased (S.Kalpajian, 2003).

2.11.1 Abrasion

Abrasion occurs due to the hard inclusions in the workpiece microstructure plow into the tool face and flank surface, abrasion wear predominates at relatively low cutting temperature. The abrasion resistance of a tool material is proportional to its hardness.

2.11.2 Adhesion

Adhesion is caused by formation and subsequent destruction of minute welded junctions, adhesion wear is commonly observed as built-up edge (BUE) on the top face of the tool. This BUE may eventually disengage from the tool, causing a crater like wear. Adhesion can also occur when minute particles of the tool surface are instantaneously welded to the chip surface at the tool chip interface and carried away with the chip.

2.11.3 Diffusion

When a metal is sliding contact with another metal and the temperature at their interface is high, conditions may become right for the alloying atoms from the harder metal to diffuse into the softer matrix; thereby increasing the latter’s hardness and abrasiveness. On the other hand atoms from the softer metals may also diffuse into harder metal, this weakening the surface layer of the latter to such an extent that particles on it are dislodged and are carried away by flowing chip material. Because of high temperatures and pressures in diffusion wear, micro transfer on an atomic scare takes place. The rate of diffusion increases exponentially with increases in temperature.

2.11.4 Oxidation

At elevated temperature, the oxidation of the tool material can cause high tool wear rates. The oxides that are formed are easily carried away, leading to increased wear.

2.12 PREVIOUS RESEARCH

From the past, there are many researches has been done regarding the effect of chip microstructure on tool wear. Overall, the suggested titanium machining conditions are with low cutting speeds and high feed rate. This is because these machining conditions have been proved from many practical experiments that could minimize the tool wear and extend the cutting tool life. Following are the some similar studies discussed and done by previous researchers.

R.Komanduri (1981) in the journal titled “Some clarifications on the mechanics of chip formation when machining titanium alloys” studied about various aspects related to the mechanism of titanium chip formation based on machining studies on titanium work material at various speeds. He found that the machining of titanium alloys is classical case of distinct gross inhomogeneous plastic deformation involving periodic upsetting and intense shear localization in a narrow band. Instability in the chip formation process has resulted in a serrated or cyclic chip. In addition, he urged that the high tool-chip interface temperatures and high chemical reactivity of titanium in machining with almost any tool material are responsible for the rapid tool wear.

D.Lee (1985) in the journal titled “The effect of cutting speed on chip formation under orthogonal machining” studied that the cutting speeds greatly influences on the chip formation process. He observed that the chips formed were highly segmented and discontinuous with numerous edge cracks, when the titanium was cut at low speeds. However, the chips showed no sign of discontinuity, with nearly smooth surface on a macroscopic scale, when the titanium was cut at high speeds. The chips formed with low cutting speeds is desired because when low cutting speeds is used, the tool tip temperature generated is much lower than high cutting speeds and this temperature will affects the tool wear and tool life as well.

A.R.Machado and J.Wallbank (1990) in journal titled “Machining of titanium and its alloys” had studied about titanium machining problems, chip formations, tool wear and wear mechanisms. They found that titanium chips are very thin and serrated with consequently an unusually small contact area with the tool. Besides, it has a high coefficient of friction between the chip and the tool face and this causes high stresses generated on the top of the cutting tool. Combining all these facts has caused rapid tool wear.

Gerard Poulachon and Alphonse L.Moison (2000) in the journal titled “Hard turning: Chip formation mechanisms and metallurgical aspects” had found that feed rate is one of the parameter that influences the chip morphology. The chips are flow chips until the feed rate is equal to 0.15mm/rev: above this rate, they become discontinuous, and at very high feed rates they are reduced to powder. They observed that the length of the chip increases with the value if the feed rate, while it is practically independent of the value of the cutting speeds. The maximum value of the chip thickness is equal to the feed up to cutting speed equal to 130m/min. Therefore, the maximum chip thickness is practically equal to the feed.

P.D.Hartung (2008) in journal titled “Tool wear in titanium machining” had urged that the tool wear is greatly reduced when adhesion occurs between the tool and the chip, preventing relative sliding at the tool-chip interface, and this adhesion is promoted by chemical reaction at the interface. Besides, the wear rate of tool materials which maintain a stable reaction layer is limited by the diffusion flux of tool material through the layer.

2.13 CONCLUSION

This chapter covers the introduction about titanium, the operation of Computer Numerically Controlled (CNC) machine, cutting tool and some theory about turning process, STATISTICA software and tool wear mechanism and lastly, few of previous research related to this project is briefly discussed.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

Current chapter discusses methodology of the project with the focus on investigating the effect of chip microstructure on tool wear in machining titanium. Relevant data was collected for further research analysis in Chapter 4.

3.2 METHODOLOGY FLOW CHART

The methodology flow chart is a visual representation of the sequence of a project. A completed flowchart organizes the topic and strategies done to ensure smooth working flow of project. Figure 3.1 illustrates a simple flow chart that shows the flow processes of this project. As shown below, the first was step was literature review on the research topic to ensure better understanding on the research topic. It was followed by experimental design using STATISTICA software to build out a complete experiment procedure. Next, machining work was performed using a CNC machine. During the experiment, the chip microstructure was observed and recorded using an optical microscope. The data collected from the chip microstructure will be interpreted accordingly. The final step involved comparison and analysis of the results obtained from machining processes.

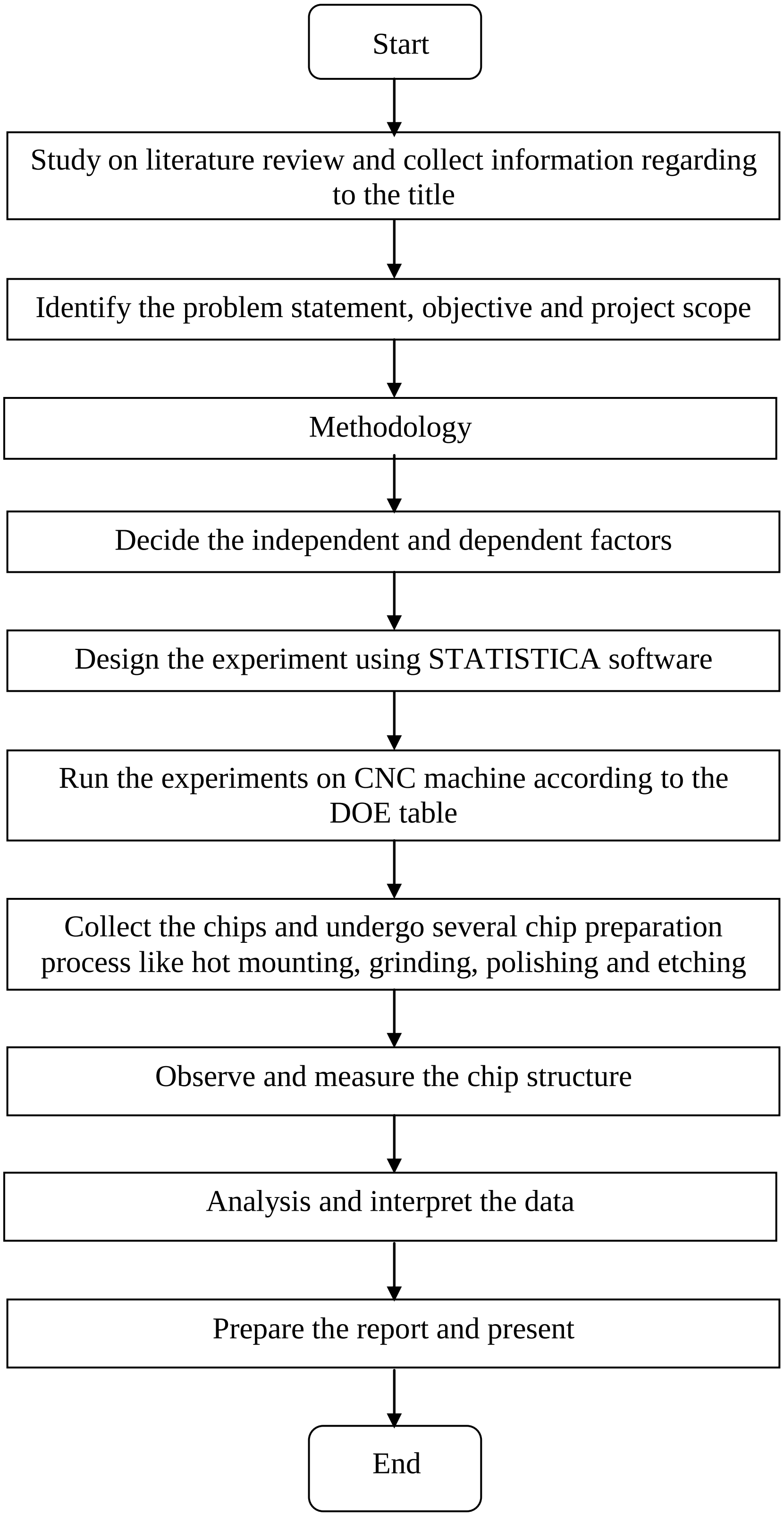


Figure 3.1: Overview of methodology

3.3 LITERATURE STUDY

First and for most, more literature studies were done on various sources such as research journal, books and online articles in order to develop a better understanding on the project. The scope was mainly on the effect of chip microstructure on tool wear in machining titanium which was the key research topic for this project.

3.4 WORKPIECE MATERIAL

The work piece material used in the experiments was titanium of 25 mm in diameter and 200 mm in length which shown in Figure 3.2. The composition and mechanical properties of the tested material are shown in Table 3.1 and Table 3.2 respectively. Before the experiment, a thin layer of 0.20 mm thickness will be removed from the superficial surface to eliminate any surface defect.

Figure 3.2: Pure titanium, Grade 2.

Table 3.1: Composition of commercial pure titanium.

Chemical Composition (weight %) , Maximum values unless range is shown										
O	N	C	H	Fe	Al	V	Ni	Mo	Others	Residual
0.25	0.03	0.08	0.015	0.3						0.4

Table 3.2: Mechanical properties of the commercial pure titanium.

Mechanical properties at room temperature		
	Minimum Values	**Typical Values**
Yield Strength	275 MPa	350-450 MPa
Ultimate Strength	345 MPa	485 MPa
Elongation in 50 mm, A5	20%	28%
Reduction in Area	30%	55%
Hardness		160-200 HV
Modulus of Elasticity		103 GPa
Charpy V-Notch Impact		40-82 J

3.5 DIAMOND CUTTING TOOL

Cutting tool is one of the most important tools in machining processes. Many efforts in term of time and money have been developed in order to improve the cutting tools. Among the developed cutting tools, diamond cutting tools have been increasingly popular in making precision parts. Diamond possesses unique mechanical and elastic properties due to its very strong chemical bonding of the structure. Its hardness and thermal conductivity are higher than those of any other known materials. Figure 3.3 below shows the triangular diamond insert and tool holder.

Figure 3.3: Insert and tool holder.

3.6 CHIP-SPECIMEN PREPARATION

This chip-specimen preparation is an important process, in which the chips will be mounted into a round specimen before proceed to next step, which is the microstructure observation. During this chip-specimen preparation, there are four processes included; they are hot mounting, grinding, polishing and lastly etching. So, the set of processes will be repeated for 20 times for different chip parameters. Figure 3.4 illustrates the procedure of chip-specimen preparation process.

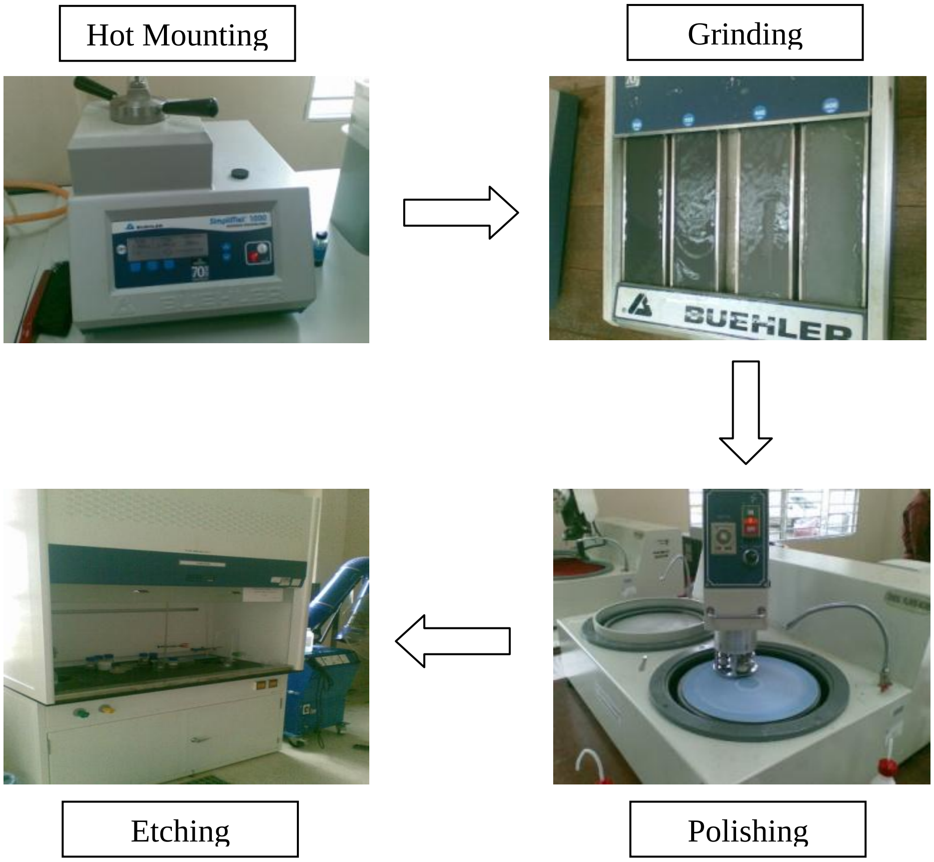


Figure 3.4: Chip-specimen preparation processes.

3.6.1 Hot Mounting

This is the first process of the chip-specimen preparation process, in which the chips will be mounted into a hard round specimen for the ease of analysis. First, the chips have to be placed in well vertically form inside the mounting machine as to check the chip thickness. After that, the powder material called Buehler Phenocure will be poured inside to mix with the chips. The volume of powder being mixed is one and a half scope of the spoon provided. Next, run the mounting process and wait for about 15 minutes for the mounting process complete. At last, a round hard specimen will be produced.

3.6.2 Grinding

After the chip-specimen is produced, it will be taken for next process, called grinding. The purpose of grinding is to remove the unwanted surface from the chips after mounting with the powders. Firstly, the specimen will be grinded with sand paper of grain size of 400 first and then 600. Each grinding will be carried out about 20 seconds manually with hand and the specimen surface has to be checked frequently. This is because the thickness of the chips is quite small and over grinding may remove the chips thickness and microstructure as well. Repeat the grinding process until the chips surface can be seen completely. After that, the specimen will be undergoing for polishing process.

3.6.3 Polishing

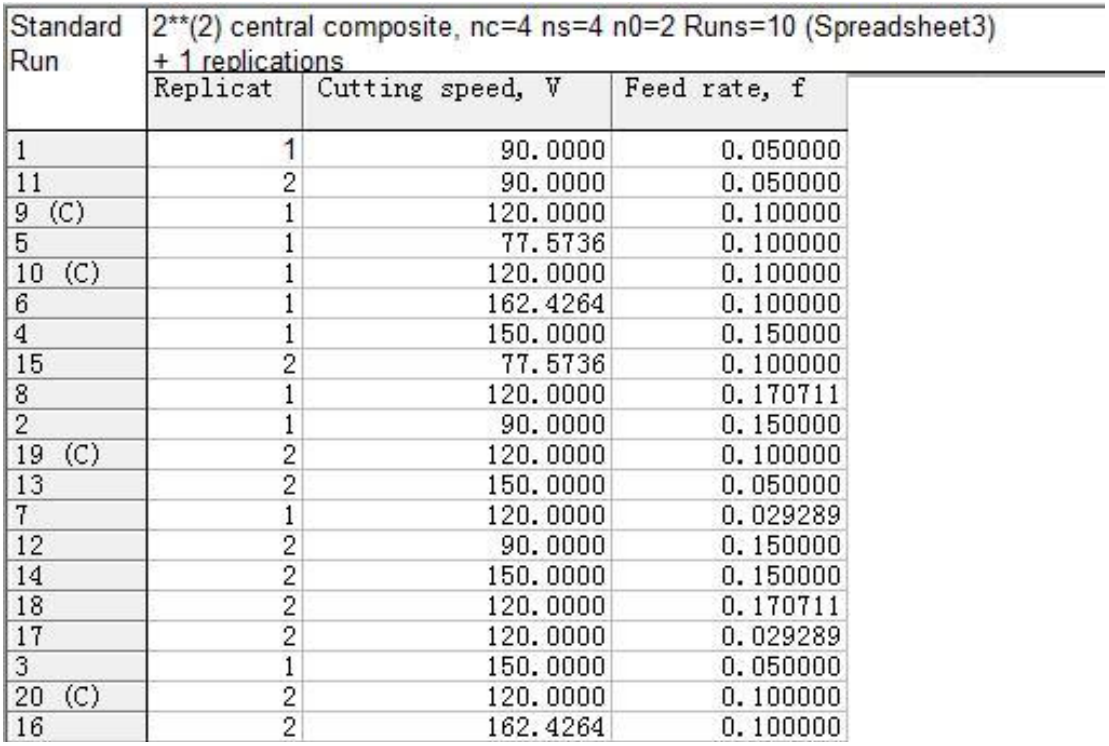
The main function of polishing is to polish the chip surface, in where the scratches in the chips will be removed and a smooth surface is formed. In this stage, the specimen will be polished with two solutions, 1μm and 6μm. The specimen will be polished with 6μm solution first and then continue with 1μm solution. Each polishing will take about 30 seconds. The RPM of the polish machine is 250. Repeat the polishing until a smooth surface with no scratches is formed. Next, the specimen will be taken for etching process.

3.6.4 Etching

This is the last process of the chip-specimen preparation process, in which the polished chip surface will be etched with an etchant solution. The etchant solution consists of hydrofluoric acid, nitric acid and water. The main purpose of etching is to remove the unwanted particles on the chip surface before observe with optical microscope. Firstly, the etchant is poured into a beaker. Next, the specimen is gripped using a grasper and immerse the chip surface into the etchant beaker. Shake the specimen for two seconds when immersing with the etchant and then wash the immersed surface with high volume of water. After that, the chip surface will be dried by using dryer. At last, the specimen can be well observed under optical microscope for further analysis.

3.7 EXPERIMENTAL DESIGN (DOE) USING STATISTICA

Three cutting parameters, namely cutting speed V (m/min) and feed rate F (mm/rev) were considered as factors (independent variables). In this study, the depth of cut is remained constant, 0.5 mm. Figure 3.5 shows the experiment data designed in STATISTICA. Total set of 20 experiments were carried out. The type of experimental design analyses used was central composite and non-factorial response surface designs, with one replication.



Standard Run	2**(2) central composite, nc=4 ns=4 n0=2 Runs=10 (Spreadsheet3) + 1 replications		
	Replicat	Cutting speed, V	Feed rate, f
1	1	90.0000	0.050000
11	2	90.0000	0.050000
9 (C)	1	120.0000	0.100000
5	1	77.5736	0.100000
10 (C)	1	120.0000	0.100000
6	1	162.4264	0.100000
4	1	150.0000	0.150000
15	2	77.5736	0.100000
8	1	120.0000	0.170711
2	1	90.0000	0.150000
19 (C)	2	120.0000	0.100000
13	2	150.0000	0.050000
7	1	120.0000	0.029289
12	2	90.0000	0.150000
14	2	150.0000	0.150000
18	2	120.0000	0.170711
17	2	120.0000	0.029289
3	1	150.0000	0.050000
20 (C)	2	120.0000	0.100000
16	2	162.4264	0.100000

Figure 3.5: STATISTICA table with various parameters.

3.8 DATA ANALYSIS

At this stage, analysis of variance, known as ANOVA, is a technique used to investigate which of the parameters significantly affect the measured (dependent variable). In this study, the measured variable was tool wear. The P-value in the ANOVA was used to determine the level of significant of the parameters on dependent variable. The indication of significant level is shown as below.

a) $P < 0.05$: Control factor has a strong effect.
b) $P > 0.05$: Control factor effect is insignificant.

3.9 CHIP OBSERVATION

During the machining test, an optical microscope was used to observe the chip structure after the chip has undergoes several chip-specimen preparation processes. First, the well prepared chip-specimen was placed on the clips stage, and the suitable objective lenses power was selected to observe the chip microstructure accordingly. The fine focus and coarse focus were adjusted until us able to clearly observe the microstructure of the chip. Then, the chip microstructure will be clearly projected on the computer screen and this chip structure will be saved in JPEG picture format for further analysis. Figure 3.6 shows the measuring equipment used, an optical microscope.

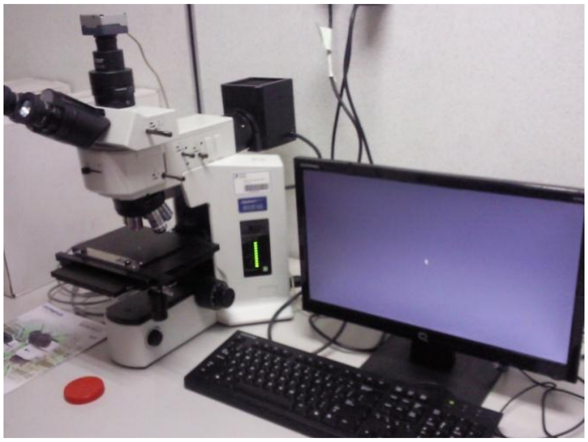


Figure 3.6: An optical microscope equipped with computer.

3.10 MEASURING CHIP STRUCTURE

Measuring of chip microstructure will be conducted using the measuring equipment above. The chip thickness and length of the deformation zone inside the chip microstructure will be determined for different set of parameters according to the experiment design. The measurements were made three times for each experiment. The average results were taken for the analysis.

3.11 DATA INTERPRETATION

Analysis of tool wear and chip effect were taken after each experiment was completed. A tool wear curve was built according to the results obtained and justifies the relationship between the chip structure and tool wear.

3.12 CONCLUSION

n this project, turning process of titanium was performed under various cutting speeds and feed rate. Optical microscope and computer software is an excellent tool that used to observe the chip microstructure distribution and measure the deformation zone. The data obtained was compared using the same machining parameters. These data was then plotted into few graphs and compared with those documented findings. These results was further interpreted and reported in Chapter 4.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

This chapter is mainly discuss about the results obtained throughout the experimental research on the cutting parameter effects of chip formation and tool wear in machining titanium determined using optical microscope and software after a period of machining process.

4.2 STATISTICAL ANALYSIS

In this section, the obtained results like the measurement of chip thickness, shear layer thickness and tool wears were tabulated into a table according to the run of design of experiment. These data were then used to perform the Statistical analysis in order to the find the relationship between dependent and independent variables. There are total run of 20 experiments with center points. The results are shown in Table 4.1.

Table 4.1: Results obtained from the experiments according to DOE.

Run of Experiment	Cutting Speed, V (m/min)	Feed Rate, *f* (mm/rev)	Chip thickness, (mm)	Thickness variation, (mm)	Shear Layer Thickness, (µm)
1	90.0000	0.0500	0.0357	0.0143	0.0300
2	90.0000	0.1500	0.1249	0.0251	0.0307
3	150.0000	0.0500	0.0362	0.0138	0.0162
4	150.0000	0.1500	0.1260	0.0240	0.0154
5	77.5736	0.1000	0.0805	0.0195	0.0350
6	162.4264	0.1000	0.0813	0.0187	0.0121
7	120.0000	0.0293	0.0205	0.0088	0.0227
8	120.0000	0.1707	0.1423	0.0284	0.0209
9	120.0000	0.1000	0.0806	0.0194	0.0207
10	120.0000	0.1000	0.0812	0.0188	0.0213
11	90.0000	0.0500	0.0345	0.0155	0.0292
12	90.0000	0.1500	0.1251	0.0249	0.0296
13	150.0000	0.0500	0.0355	0.0145	0.0149
14	150.0000	0.1500	0.1268	0.0232	0.0138
15	77.5736	0.1000	0.0799	0.0201	0.0343
16	162.4264	0.1000	0.0809	0.0191	0.0123
17	120.0000	0.0293	0.0218	0.0075	0.0227
18	120.0000	0.1707	0.1413	0.0294	0.0205
19	120.0000	0.1000	0.0827	0.0173	0.0203
20	120.0000	0.1000	0.0814	0.0186	0.0214

Figure 4.1 and Figure 4.2 show the sample pictures of chips collected from the experiment. Both pictures below shown the chips structure clearly with identified thickness and shear deformation zone, observed with 10x magnification optical microscope.

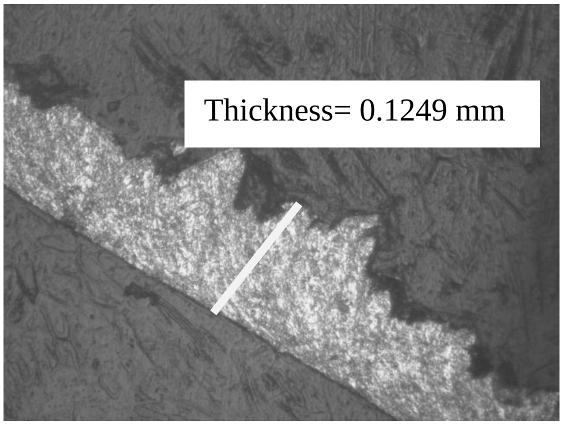


Figure 4.1: Sample chip produced with 90 m/min cutting speeds and 0.15 mm/rev feed rate.

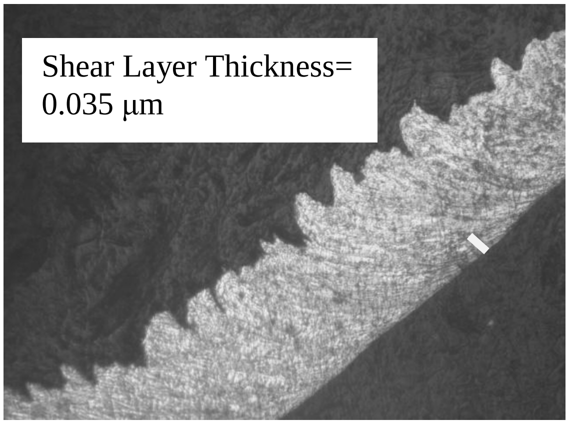


Figure 4.2: Sample chip produced with 77.5736 m/min cutting speeds and 0.10 mm/rev feed rate.

From the sample pictures above, there was a saw tooth features formed in the chips as it is a common feature found in the machining on titanium and its alloys. The measuring of chip thickness was shown in Figure 4.1, in which the chip thickness was proved as approximate as the feed rate. However, the chip thickness was found as not the same as feed rate practically due to certain factors like saw tooth formation and high shear deformation at chip tool interface. These factors might contribute to the thickness variation between the theory and experimental results.

Figure 4.2 shows a clear shear deformation pattern in the chips as the workpiece was machined with certain cutting speeds and feed rate. This shear layer thickness was formed when there was a friction generated between cutting tool and workpiece. The higher the friction, the higher the shear layer thickness, and vice versa. Commonly, the lower shear layer thickness was desired as it affects the tool wear directly.

4.2.1 EFFECT OF CUTTING SPEED AND FEED RATE ON CHIP THICKNESS VARIATION

Cutting speed and feed rate are two independent variables that chose to investigate the effects on tool wear. But before this, the analysis of the effect of cutting speed and feed rate n chip thickness variation is performed first.

4.2.1.1 ANALYSIS OF VARIANCE (ANOVA)

ANOVA analysis generated by STATISTICA was used to determine the significant parameters that influencing the turning machining process on tool wear. The model used for the all ANOVA analysis was linear/quadratic main effects in 2 ways interaction. Two independent variables, cutting speed and feed rate, are firstly used to investigate the effect on chip thickness and shear layer thickness. Next, these data will be used to investigate the effect on the dependent variables, tool wear. A relation between the effects of chip thickness and shear layer thickness on tool wear will be made, as to find out the best machining parameters that produced the chip structure with lowest tool wear.

A general null hypothesis was stated at first followed by analysis to check whether the hypotheses were accepted or not. P-value at 0.05 levels was selected for testing the significance of the main effects and two-level interaction effects.

The first analysis done was the normal probability plot. This is a graphical technique for assessing whether or not a set of data is approximately normally distributed. The data are plotted against a theoretical normal distribution in such a way that the points should form a straight line. Departures from this straight line indicate departures from normality. Figure 4.3 shows the normal probability plot of expected normal value versus residual value.

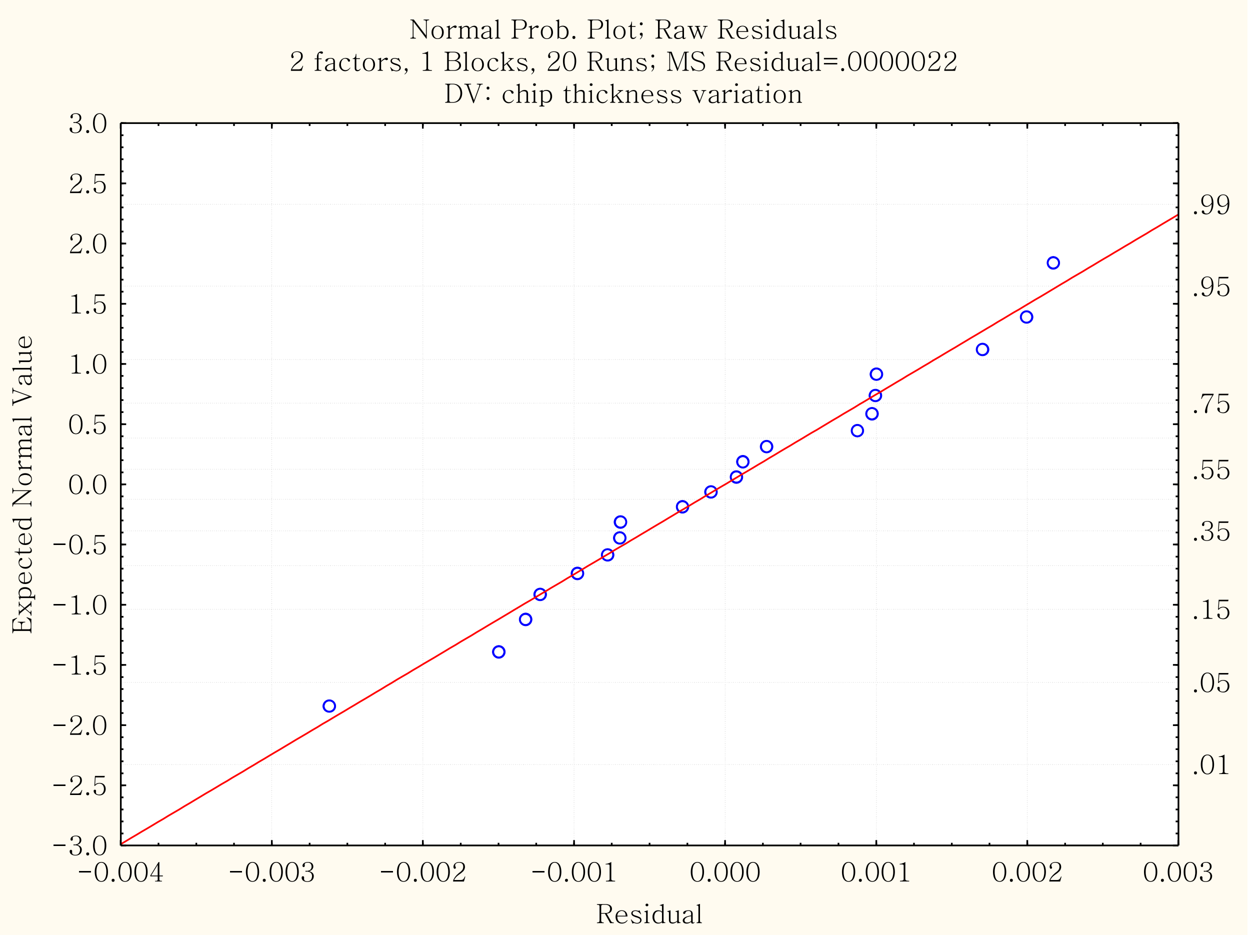
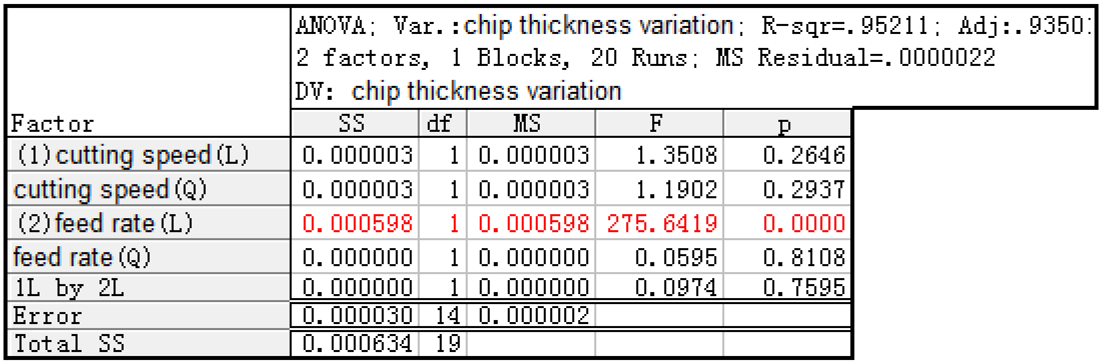


Figure 4.3: Normal probability plot: Expected normal value versus residual value of chip thickness variation analysis.

From the graph above, it shows that the data does not exhibit any particular bias in any part of the data. The spread of points was around the fitted line, which means the data collected was less deviated from the normal plot and can be used for further analysis. Figure 4.3 shows the residual values are normally distributed when the values of expected normal is more than -1.0 since the values are fall within the fitted line in the plot. However, the expected normal values less than -1.0 can be considered as outliers because the points were deviated from the normal plot.

The second analysis was done between the effect of cutting speed and feed rate on chip thickness. A null hypothesis was expressed as the effects of cutting speed and feed rate on the chip thickness variation do not significantly differ from zero. The ANOVA analysis result was shown in Table 4.2.

Table 4.2: ANOVA analysis of effect of cutting speed and feed rate on chip thickness.



ANOVA; Var.:chip thickness variation; R-sqr=.95211; Adj:.9350
2 factors, 1 Blocks, 20 Runs; MS Residual=.0000022
DV: chip thickness variation

Factor	SS	df	MS	F	p
(1)cutting speed(L)	0.000003	1	0.000003	1.3508	0.2646
cutting speed(Q)	0.000003	1	0.000003	1.1902	0.2937
(2)feed rate(L)	0.000598	1	0.000598	275.6419	0.0000
feed rate(Q)	0.000000	1	0.000000	0.0595	0.8108
1L by 2L	0.000000	1	0.000000	0.0974	0.7595
Error	0.000030	14	0.000002		
Total SS	0.000634	19			

Based on the ANOVA analysis result above, it was observed that feed rate, with P-value equal to 0, is the significant parameter that affects the chip thickness variation. The F-ratio for feed rate was recorded as 275.6419. Thus the null hypothesis was rejected. Theoretically, it was proved that the chip thickness was approximately equal to feed rate (A.Daymi, 2000). However, the measured chip thickness was not exactly the same as feed rate due to some factors, and feed rate was proved as one of the factors that contribute to the thickness deviation.

However, for the cutting speed, the analyzed P-value was equal to 0.2646, which is higher than 0.05. Thus, the null hypothesis (i.e. there is no linear relationship between chip thickness variation and cutting speed) is accepted. Therefore, a conclusion was made that cutting speed has only slight effect on chip thickness. The F-ratio for the cutting speed was 1.3508.

Next, a graph of predicted values versus observed values were plotted in order to investigate the spreading of the data with respect to the predicted values. The data could not be used if there were a large deviation between the predict values and observed values, and vice versa. Therefore, the observed values must be fitted with the predicted values. Figure 4.4 illustrated the graph result of predicted values versus observed values.

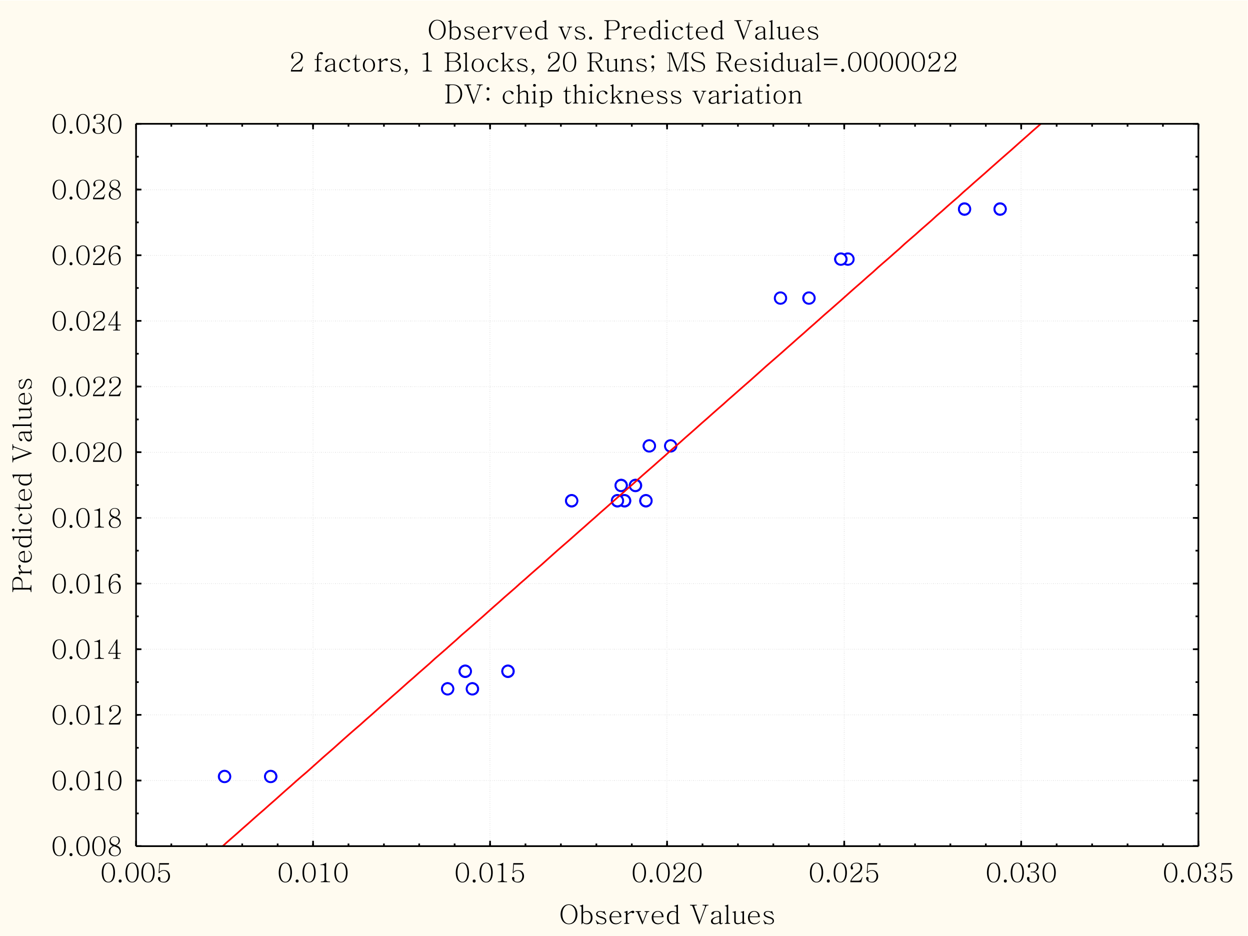


Figure 4.4: Graph of predicted values versus observed values for analysis of chip thickness variation.

According to the graph above, the observed values were concluded as approximate as the predicted values. However, the spread of the points around the fitted line is somewhat uneven. Since the deviation of the observed values and predicted values are small, thus the data is acceptable.

After that, the relationship between the chip thickness variation and feed rate, as well as chip thickness variation and cutting speed were plotted, as shown in Figure 4.5 and Figure 4.6 show respectively.

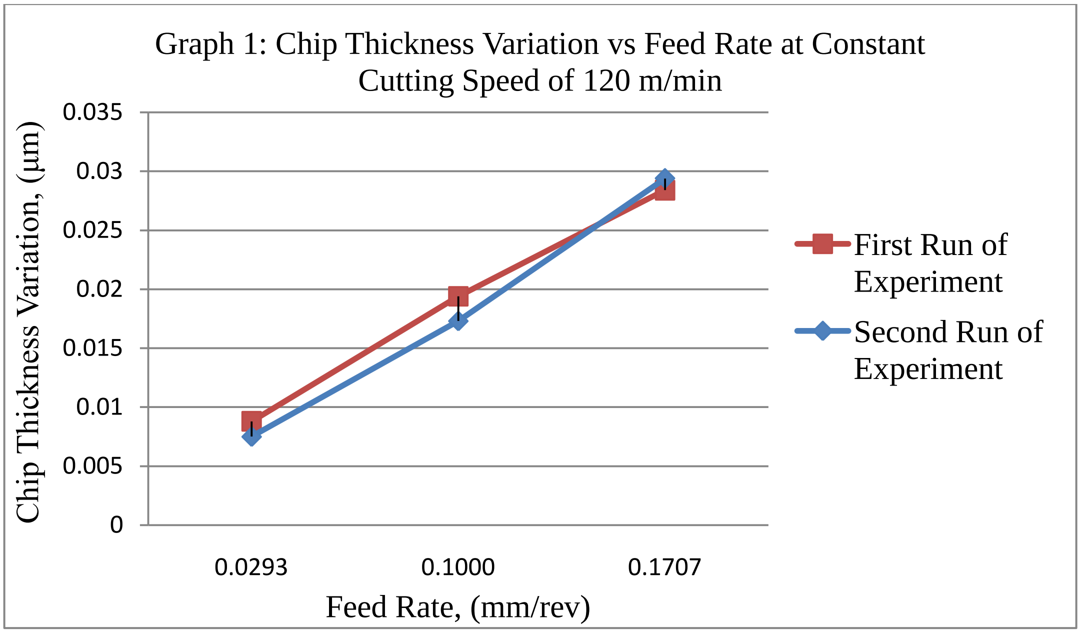


Figure 4.5: Graph of chip thickness variation versus feed rate.

According to the Figure 4.5, it shows that the chip thickness variation is directly proportional to feed rate, which means the chip thickness variation is increased as the feed rate increases, and vice versa. The lowest chip thickness variation was recorded as 0.0075 mm when the feed rate was 0.0293 mm/rev. Whereas, the highest chip thickness variation measured was 0.0294 mm when the feed rate was 0.1707 mm/rev.

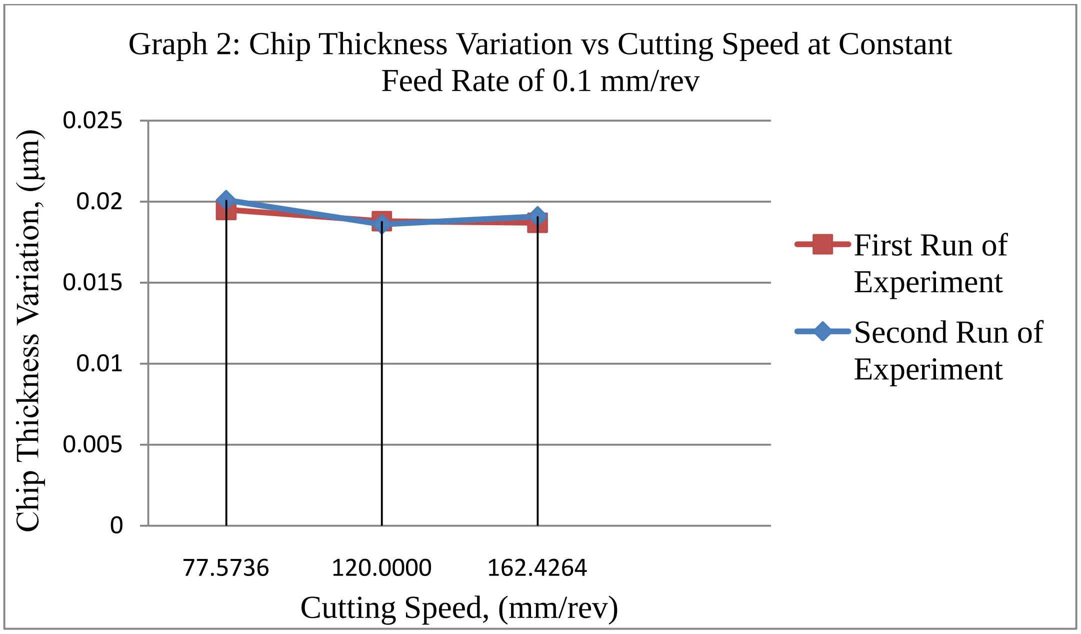


Figure 4.6: Graph of chip thickness variation versus cutting speed.

Based on the graph above, it found that the graph pattern was behaved like a straight line, which means there is no linear relationship between the chip thickness variation and cutting speed. Thus, it proved that cutting speed was not a significant parameter that affects the chip thickness variation.

4.2.2 EFFECT OF CUTTING SPEED AND FEED RATE ON SHEAR LAYER THICKNESS

In this section, the analyses of the effect of cutting speed and feed rate on shear layer thickness are performed and discussed. Firstly, the normal probability plot was conducted using the ANOVA analysis and the result was shown in Figure 4.7.

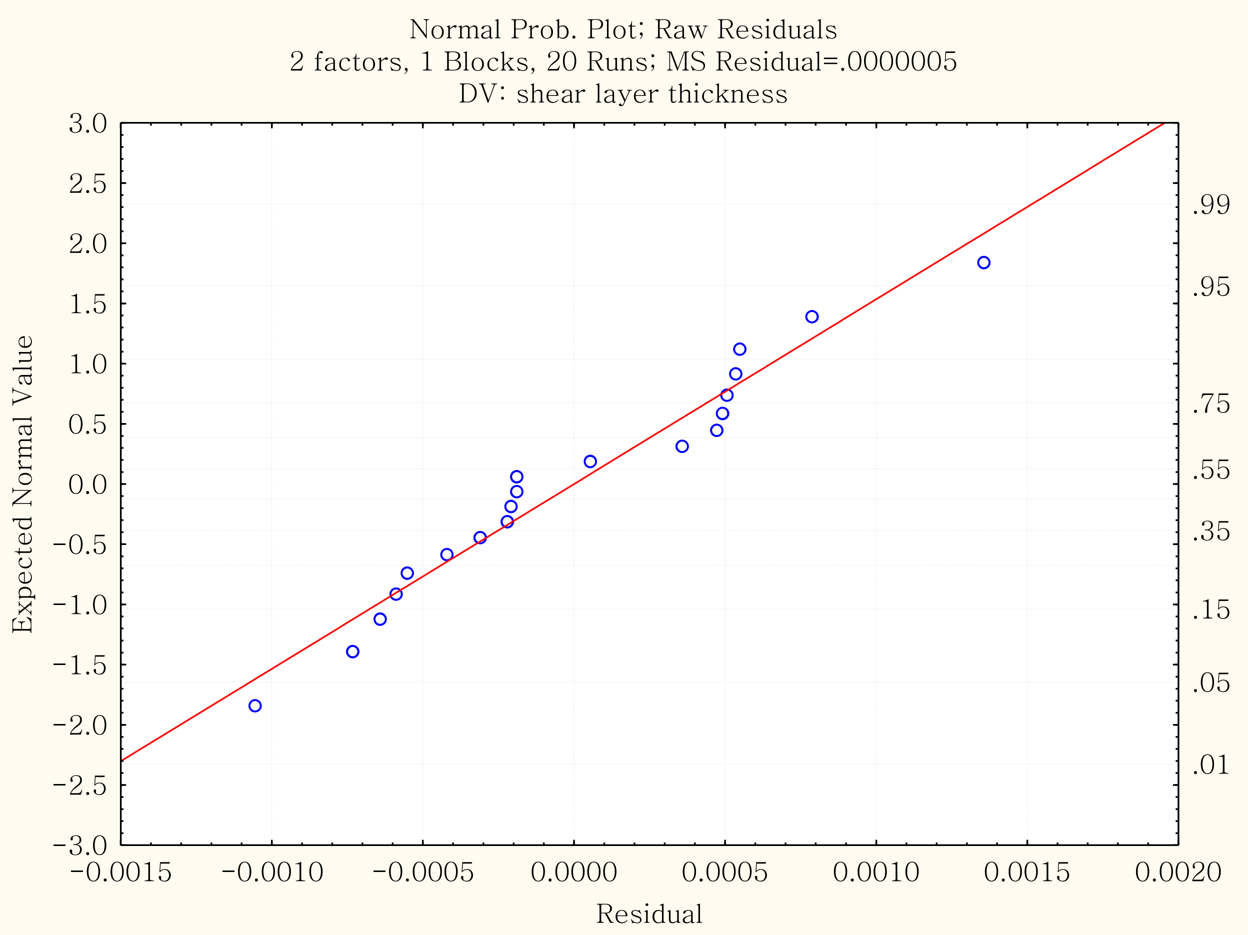
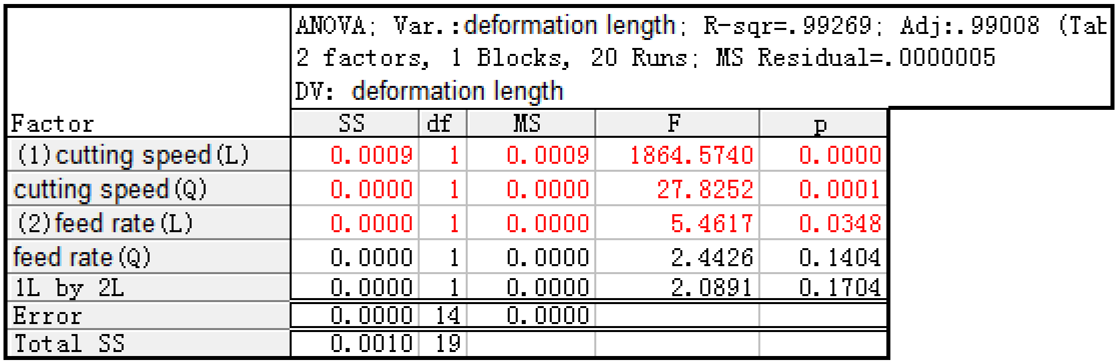


Figure 4.7: Normal probability plot: Expected normal value versus residual value of shear layer thickness analysis.

From the graph above, it shows that the spread of the points were uneven, in which not all the points were fall into the fitted line. However, the points were said near and approach to the straight line with less deviation. Therefore, the data collected from the experiment was considered normal distribution and acceptable for further analysis.

Next, the second ANOVA analysis was performed to determine the significant effect of cutting speed and feed rate on shear layer thickness. A null hypothesis was expresses as there is no linear relation between the cutting speed and feed rate on shear layer thickness. The analysis result was shown in Table 4.3.

Table 4.3: ANOVA analysis of effect of cutting speed and feed rate on shear layer thickness.



ANOVA; Var.:deformation length; R-sqr=.99269; Adj:.99008 (Tat
2 factors, 1 Blocks, 20 Runs; MS Residual=.0000005
DV: deformation length

Factor	SS	df	MS	F	p
(1)cutting speed(L)	0.0009	1	0.0009	1864.5740	0.0000
cutting speed(Q)	0.0000	1	0.0000	27.8252	0.0001
(2)feed rate(L)	0.0000	1	0.0000	5.4617	0.0348
feed rate(Q)	0.0000	1	0.0000	2.4426	0.1404
1L by 2L	0.0000	1	0.0000	2.0891	0.1704
Error	0.0000	14	0.0000		
Total SS	0.0010	19			

According to the analysis result above, the analyzed P-value for cutting speed and feed rate are 0 and 0.0348 respectively. In other word, cutting speed and feed rate are two significant parameters that affect the thickness of shear layer in chip. Thus, the null hypothesis was rejected.

Since it was proved there was a linear relationship between the variables, thus a graph of predicted value versus observed value was plotted in order to find out the spreading of the collected data relative to the predicted values.

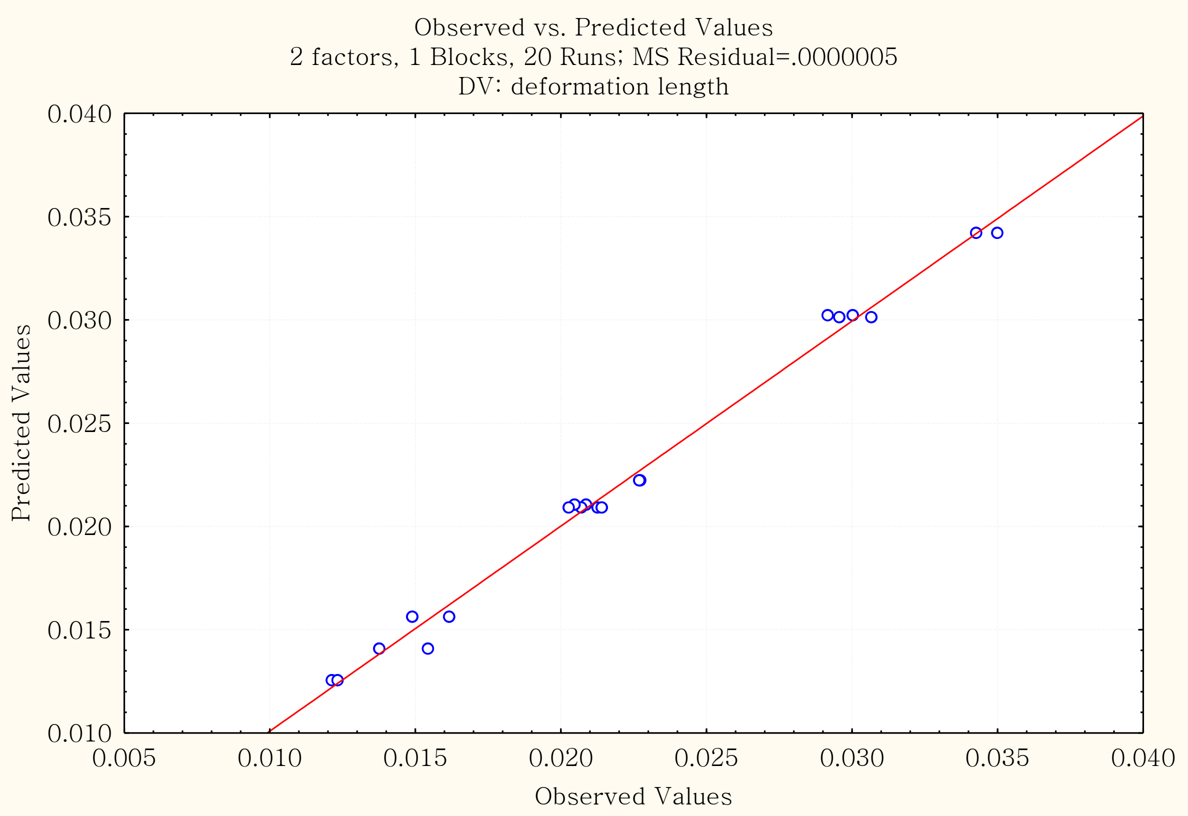


Figure 4.8: Graph of predicted values versus observed values for the shear layer thickness analysis.

The Figure 4.8 shows the result of a plotted graph between the predicted values and observed value for the shear layer thickness analysis. Based on the graph, it shows that the observed values were fitted to the predicted values with small deviation. Thus, these data are acceptable and can be used for the further analysis, which is the relationship between the shear layer thickness and tool wear.

The relationships between chips shear layer thickness and cutting speed, as well as shear layer thickness versus feed rate are shown in Figure 4.9 and Figure 4.10 respectively. The cutting speed and feed rate used in the study were varied over a range of 77.5736 m/min to 162.4264 m/min and 0.0293 mm/rev to 0.1707 mm/rev, respectively.

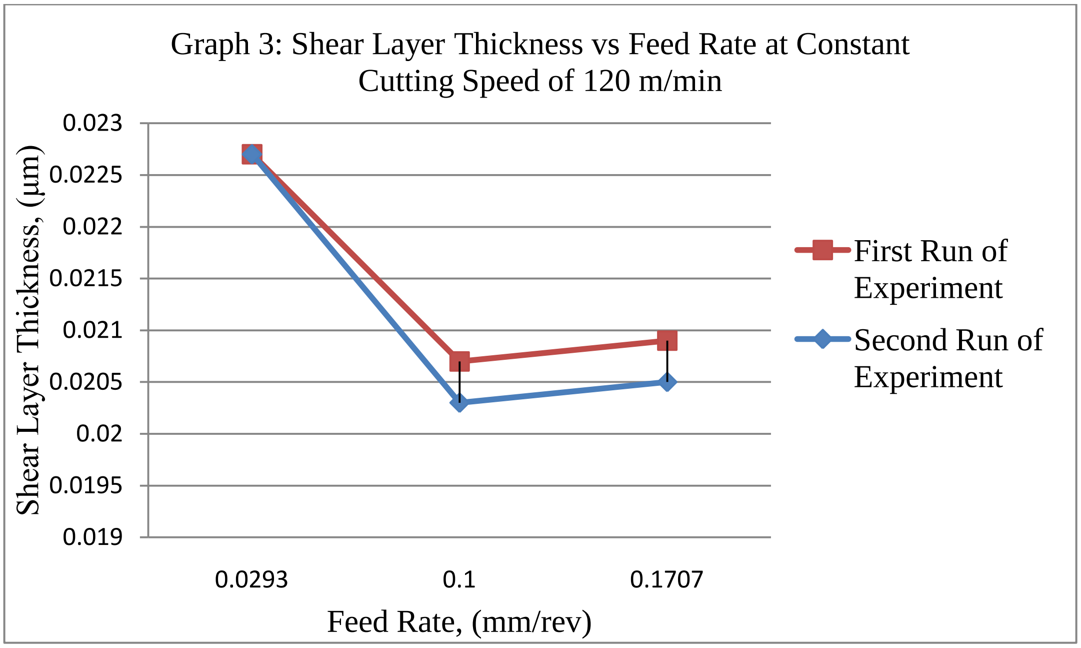


Figure 4.9: Graph of shear layer thickness versus feed rate.

Referring to the graph 3, it shows that the graph pattern distribution was not even. The values of shear layer thickness were inversely proportional to feed rate, when the feed rate was between 0.0293 mm/rev to 0.1 mm/rev. After that, the graph shows a positive linear relationship between the shear layer thicknesses and feed rate, when the feed rate was over 0.1 mm/rev. Therefore, the lowest shear layer thickness was recorded at feed rate of 0.1 mm/rev.

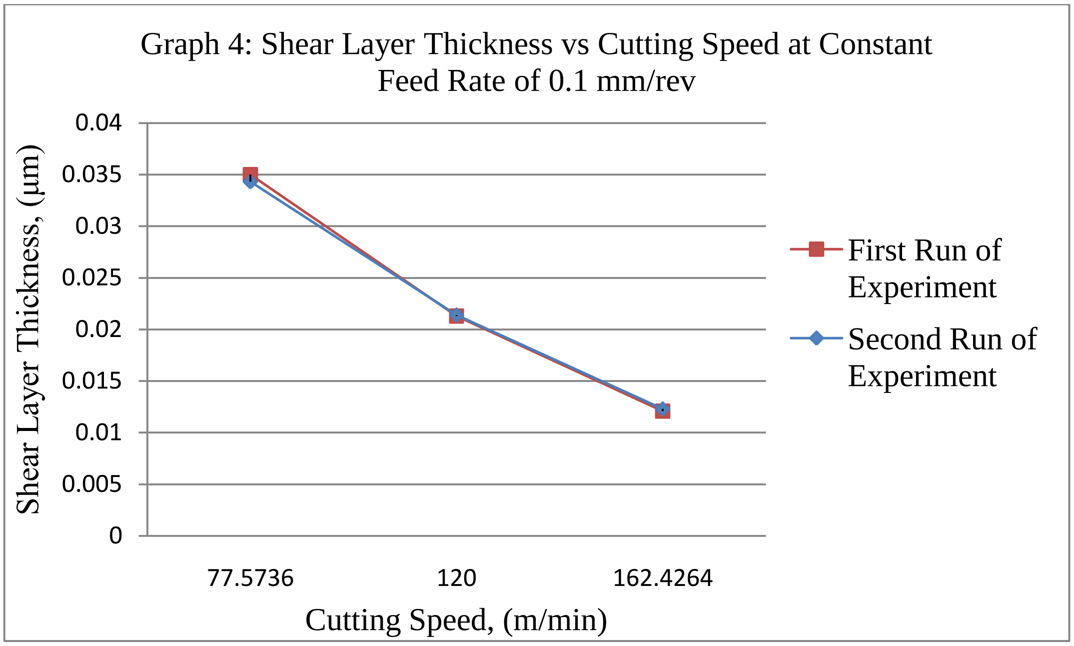


Figure 4.10: Graph of shear layer thickness versus cutting speed.

Referring to the graph 4, it shows that the shear layer thickness is inversely proportional to cutting speed, in which the shear layer thickness was reduced as the cutting speeds increase, and vice versa. Besides, the highest shear layer thickness was recorded as 0.035 µm at cutting speeds of 77.5736 m/min. whereas, the lowest shear deformation length was measured as 0.0121 µm at cutting speed of 162.4264 m/min.

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4.2.3 EFFECT OF CHIP THICKNESS VARIATION AND SHEAR LAYER THICKNESS ON TOOL WEAR

Crater wear and flank wear were two common tool wears found in the machining. Few analyses are conducted to investigate the effect on chip thickness and shear layer thickness on the tool wear. Figure 4.11 shows the lowest, middle and highest of crater wear and flank wear formed at the cutting tools respectively, which corresponds to the chips structure.

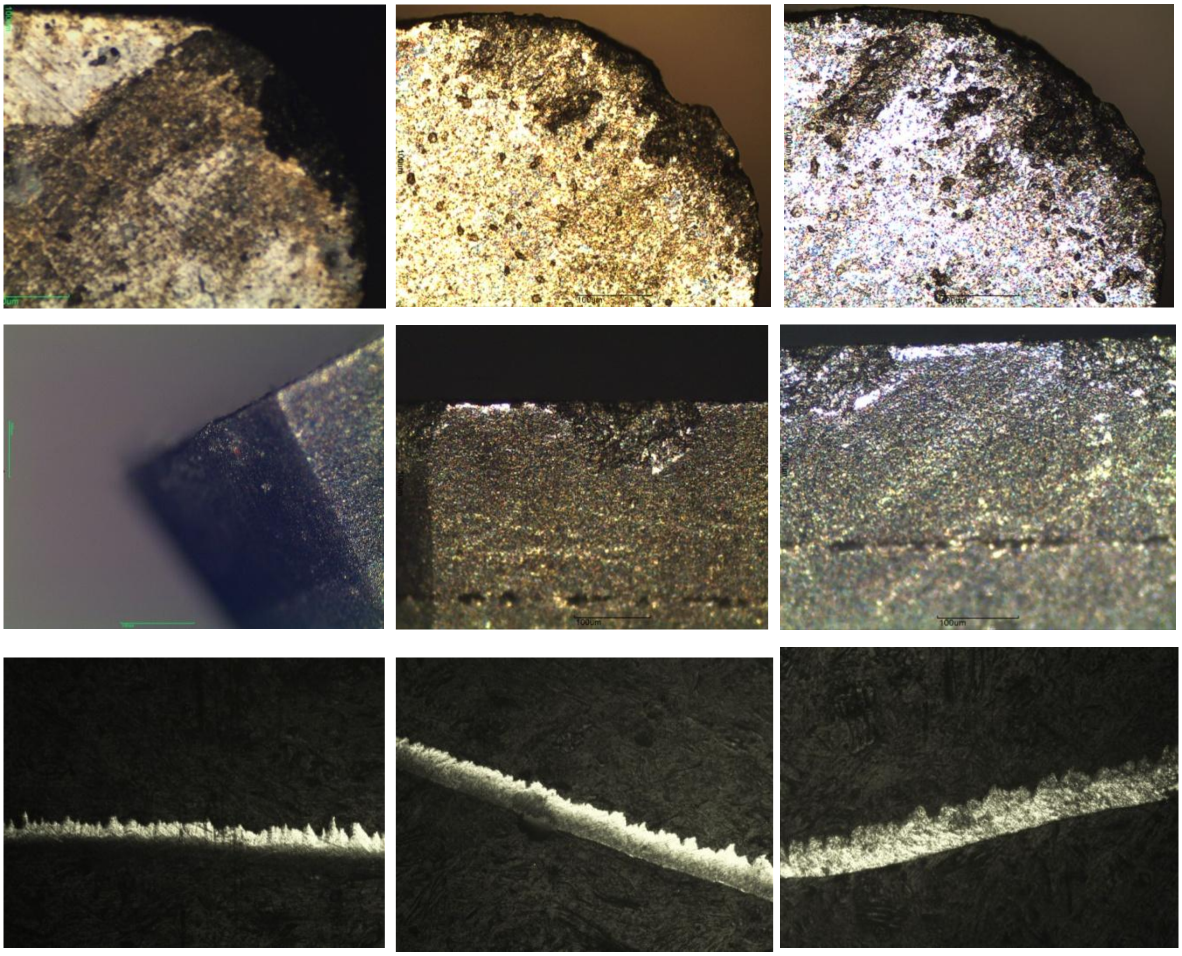


Figure 4.11: The rate of crater wear and flank wear formed corresponding to the chip structure.

According to the Figure 4.11, the first row of the pictures indicates the crater wear formed at the cutting tool. The lowest, middle and highest crater wear rate measured in the experiments are 7.8912 μm, 13.3684 μm and 18.7412 μm respectively. Whereas, the lowest, middle and highest flank wear measured are 1.2162 μm, 3.8623 μm amd 5.3098 μm, which is showed in second row of the pictures. Practically, the crater wear rates are found higher than flank wear in this study. This might be caused by the hardness of titanium, in which more friction forces were produced when the cutting tool was in contacted with workpiece. Thus, the machining rapid the crater wear rate instead of flank wear.

The third row of the pictures in Figure 4.11 shows the corresponding chip structure produced with the tool wear. The first picture shows the corresponding chip structure that produced the lowest wear rate, by the machining parameters such as 162.4264 m/min cutting speed and 0.10 mm/rev feed rate, with generated shear layer thickness of 0.0121 μm and chip thickness variation of 0.0187 mm. The second picture shows the chip structure corresponded to the middle rate of tool wear, which is produced by cutting speed of 90 m/min and feed rate of 0.05 mm /rev, along with shear layer thickness of 0.0296 μm and chip thickness variation of 0.0249 mm. The third picture shows the chip structure that corresponded to the highest tool wear. It was machined by 77.5736 m/min cutting speed and 0.10 mm/rev feed rate, with shear layer thickness of 0.0350 μm and 0.0195 μm chip thickness variation found.

Next, a graph of crater wear versus chip thickness variation, as well as crater well versus shear layer thickness were plotted in order to determine the kind relationship. The graphs were shown in Figure 4.12 and Figure 4.13 below.

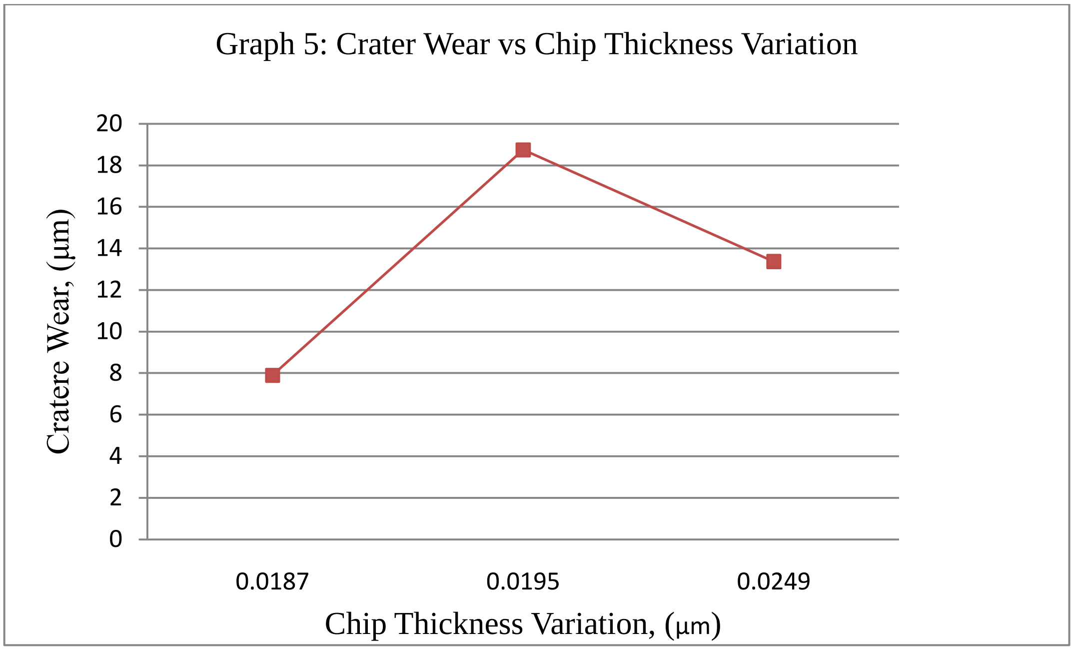


Figure 4.12: Graph of crater wear versus chip thickness variation.

Referring to the graph 5, it shows that the distribution of the graph is not consistent. However, the important information taken from the graph above was the lowest crater wear was formed at the lowest chip thickness variations, which were 7.8971 µm and 0.0187 mm respectively. Chip thickness variation was not a significant parameter that affects the crater wear.

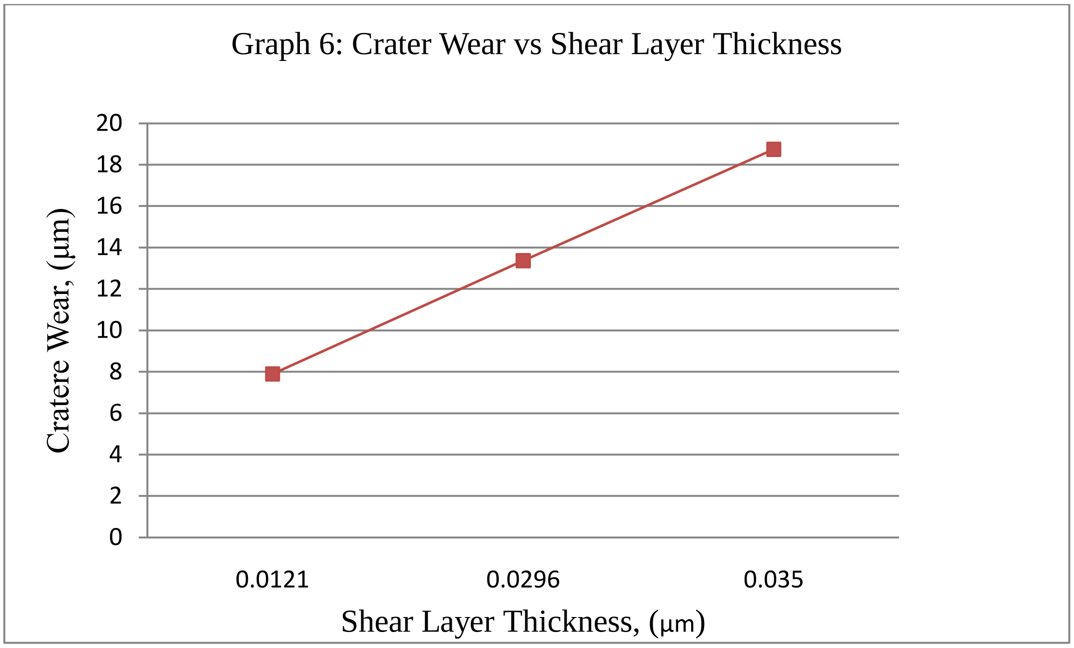


Figure 4.13: Graph of crater wear versus shear layer thickness.

According to the graph above, it shows that there is a linear relationship between craters wears and shears layer thickness, where the crater wear is directly proportional to shear layer thickness. The lowest crater wear was 7.8971 µm, which formed at the lowest shear layer thickness, 0.0121 µm. However, the highest shear layer thickness of 0.035 µm has produced the highest crater wear, which is 18.7412 µm. Thus, shear layer thickness was a significant parameter that affects the crater wear directly.

Next, the investigation was continued with the second tool wears, called flank wear. A graph of flank wear versus chip thickness variation, as well as flank wear versus shear layer thickness were plotted to find out the relationship. The results were shown in Figure 4.14 and Figure 4.15.

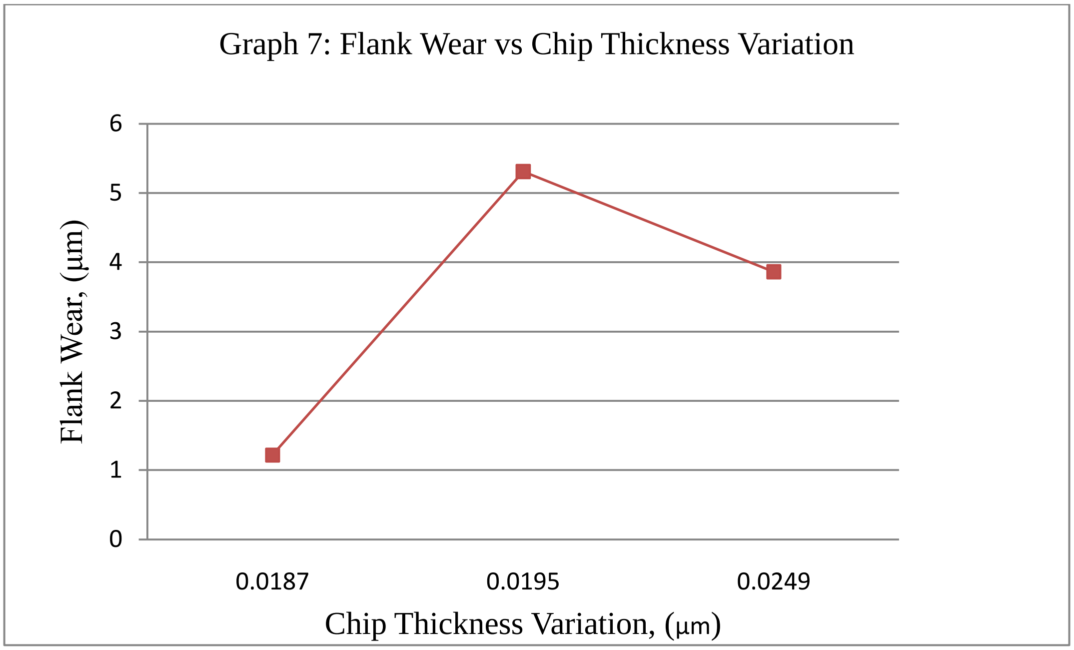


Figure 4.14: Graph of flank wear versus chip thickness variation.

According to the Figure 4.14, the graph 7 shows that the graph distribution is uneven. The lowest flank wear was measured as 1.2162 µm at chip thickness variation of 0.0187 µm. However, chip thickness variation was not a significant parameter that affects the flank wear.

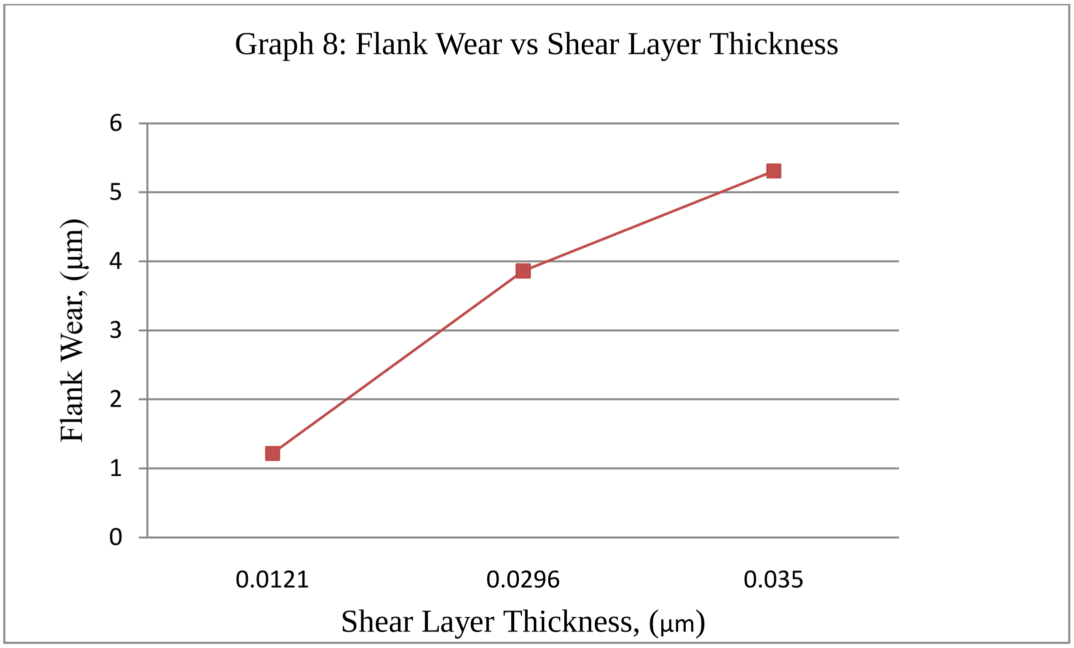


Figure 4.15: Graph of flank wear versus shear layer thickness.

Based on the graph 8, it shows that flank wear is directly proportional to shear layer thickness, in which the flank wear is increased, as the shear layer thickness increases, and vice versa. Therefore, shear layer thickness is a significant parameter that affects the flank wear in turning process. The lowest flank wear, 1.2162 µm, was generated by the shear layer thickness of 0.0121 µm. Whereas, the highest flank wear and the corresponding shear layer thickness are 5.3098 µm and 0.035 µm respectively.

4.3 DISCUSSION

There are few discussion can be made regarding to the results obtained from the experiments. The discussion is showed as following.

4.3.1 Inter-Relationship Between Tool Wear, Feed Rate and Cutting Speed

From the ANOVA analysis above, shear layer thickness was the variable that directly affects the tool wear (crater wear and flank wear) significantly. As the shear layer thickness in chip was increased, the tool wear was found to be increased as well, and vice versa. Therefore, a machining parameter that produces chip with low shear layer thickness was desired in order to minimize the tool wear. In this study, it was proved that there is a linear relationship between cutting speed and shear layer thickness, as well as feed rate and shear layer thickness. Thus, a relationship can be made between tool wear and cutting speed, as well as tool wear and feed rate.

From the experiment result, the lowest crater wear and flank were 7.8912 μm and 1.2162 μm respectively, which were produced along with lowest chip shear layer thickness, 0.0121 μm. The machining parameter that produced such lowest shear layer thickness was 162.4264 m/min cutting speeds and 0.10 mm/rev feed rate. Thus, these machining parameters were proved as the optimum values that produced minimum tool wear on the cutting tool. This data was desired as it could minimize the machining costs.

4.3.2 Difference Rate in Crater and Flank Wear

Practically, increasing cutting speed are increased the temperature at the shear zone and tool-chip interface which softens the workpiece being cut due to the material’s thermal softening behavior, thus reduced cutting forces are observed. Therefore, the shear layer thickness is decreased as well. In high speed metal machining process, there were two thin zones of intense plastic deformation can be analyzed. The first zone is the primary deformation/shear zone arising as the chip is initially sheared from workpiece being machined. The second zone is the secondary deformation/shear zone generally arising from frictional interaction between chip and tool.

Based on Shaw’s observation, secondary shear zone is a portion of the chip that has been rendered unusually plastic as a result of high temperature. Temperatures in secondary zone will be sufficiently high to enable the tool material diffused into the chip. If this zone is moving relative the tool face, wear is apt to be rapid due to diffusion. A crater will then rapidly form which may weaken the cutting edge as it grows and eventually cause tool point breakage. Therefore, this has rapid the crater wear rate in as compared to flank wear.

4.4 OTHER VARIABLE THAT AFFECT SHEAR LAYER THICKNESS

As discussed in this study, cutting speeds is one the variables that affect the shear layer thickness in chips. As the chip separated from the workpiece, it carried a great amount of heat resulting from primary shear. The chips then became hotter as a result of friction with the tool rake face. The bulk of the heat generated in metal cutting is dissipated into the chip. The structure of the chip was varied with cutting speeds. The secondary shear zone was thick at moderate speeds and thin at a higher speeds and which disappeared at very high speeds or under very low friction condition (V.C.Venkatesh, 1993). This statement was proved by the experiment result. However, there were some variables that affect the shear layer thickness besides cutting speeds and feed rate, and these variables were briefly discussed.

4.4.1 Depth of Cut

Depth of cut is proved as other parameters that influence the stress distribution at the secondary shear zone. When machining a workpiece at same machining parameters but different in depth of cut, there are more forces generated for the large depth of cut as compare d to small depth of cut. This is because the friction between the tool and workpiece is increased as the depth of cut increases. Thus, the high shear stress has made the shear layer thickness became bigger. In other words, the tool wears are increased.

4.5 ERRORS THAT AFFECT THE EXPERIMENTAL OUTCOME

Experimentally, there are some factors that might affect the results due to the presence of several phenomena such as workpiece deflection under strong rotating forces, vibration of the machine tool, the effect of chips that occur during machining process and zero error for vernier caliper.

i) Workpiece deflection under strong rotating forces caused the true depth of cut to be different from the nominal one. Non-infinite stiffness of the tool-machine-work piece system implies elastic deformation of the machine tool structure or of the clamping device. The unknown geometry of the raw part also made the true cutting depth different from the planned one. Therefore, workpiece deflection is recognized as one of the main sources of dimensional and geometric error in precision machining.

ii) Vibration of the workpiece due to rotating is a critical aspect of manufacturing error during turning machining. Workpiece deflection is recognized as one of the main sources of dimensional and geometric error in precision machining. Workpiece vibration is a very significant problem due to turning process due to high cutting forces generated.

iii) Heat generated by plastic deformation and friction involved in chip formation was transferred to the workpiece, tool and machine tool. Subsequently, the chips produced during machining also may be formed differently in microstructure and indirectly affecting the tool wear rate.

iv) In the present study, a vernier caliper was used to measure diameter of work piece for each experiment. Sometimes, the reading of vernier caliper was not zero reading at the start of the experiment. The constant depth of cut might effect by this error and not exactly remove 0.5mm material from work piece for every turning machining.

4.6 SUMMARY

From a practical point of view, the result obtained above can be interpreted as follows. There is a linear relationship between the chip thickness variation and feed rate, which means feed rate, is a significant parameter that affects the chip thickness variation directly. The higher the feed rate was, the bigger the chip thickness variation. However, cutting speed was proved as an insignificant parameter that influences the chip thickness.

In addition, there was a linear relationship between shear layer thickness and feed rate, as well as shear layer thickness and cutting speed. The shear layer thickness was found directly proportional to cutting speed. The results shown that feed rate of 0.1 mm/rev and cutting speed of 162.4264 m/min have produced the lowest shear layer thickness.

Moreover, it was proved that shear layer thickness is the significant parameter that affects the crater wears and flank wears, whereas chip thickness variation has only slight effects on tool wears, which is considered as insignificant. The lowest crater wear and flank wear were found at lowest shear layer thickness, which is 0.0121 μm.

4.7 CONCLUSION

In conclusion, a relationship between the independent variables (cutting speed and feed rate) and dependent variables (chip structure formation and tool wear) can be formed in machining of titanium. However, the inaccuracy of the results might also due to the presence of several phenomena which have been discussed in section 4.5.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

Chapter 5 summarizes the main research points of this dissertation. It concludes all the important information and observation gained from the project for the further research.

5.2 CONCLUSION

In conclusion, effects of the chip structure on tool wear of titanium in turning machining with diamond insert were performed successfully in the present study. In this study, cutting speed and feed rate were considered as important parameters in the machining process from the perspective of chip structure formation and tool wear, as approved by STATISTICA analysis.

According to the experiment result, a relationship between chip structure and tool wear are formed. As the cutting speed increases, the shear deformation lengths generated in chips are getting smaller, and vice versa. Same goes to the feed rate, it is proved that there is a linear relationship between shear layer thickness and feed rate. Thus, these two parameters are influencing the shear layer thickness.

From the graphical analysis between tool wear (known as crater wear and flank wear) and shear deformation zone, it is proved that the shear layer thickness is affected tool wear significantly, in which tool wear is directly proportional to shear layer thickness.

However, chip thickness variation has only slight effects on tool wear. Thus it is an insignificant parameter that influences the tool wear. The lowest recorded crater wear and flank wear in this study are 7.8912 µm and 1.2162 µm respectively, which corresponded to shear layer thickness of 0.0121 µm. This shear layer thickness was produced with cutting speeds of 162.4264 m/min and feed rate of 0.10 mm/rev. Thus, these machining parameters are best suggested to be used when machining titanium with lowest tool wears formed.

5.3 RECOMMENDATIONS

In this study, there are few recommendations suggested in term of machining condition, tools and method in order to improve the results. The recommendations are listed as below.

i. The range of the two investigated variables should be increased in order to clearly show their effects on chip structure, as well as tool wear.

ii. The use of Scanning Electron Microscopy (SEM) micrograph. The objective was to get clearly observed and measure the chip structure in term of shear deformation length and thickness.

REFERENCES

Donachie, M.J. 1988. Machining Titanium and Its Alloys.

Collings, E.W. 1984. The physical metallurgy of titanium alloys. OH, US: American Society for Metals.

Groover,M.P. 2006. Fundamental Of Modern Manufacturing: Materials, Processes and Systems. 3rd Edition. Hoboken, N.J: John Wiley & Sons, Inc.

Senussi, G.H. 2007. Interaction Effect of Feed Rate and Cutting Speed in CNC-Turning on Chip Micro-Hardness. *Journal of World Academy of Science, Engineering and Technology*.**28**:121-126

Poulachon.G. 2000. Hard Turning: Chip Formation Mechanisms and Metallurgical Aspects. *Journal of Manufacturing Science and Engineering.* **122**:406-412.

D.lee. 1985. The Effect of Cutting Speed on Chip Formation Under Orthogonal Machining. *Journal of Engineering for Industr*y. **107**:55-63

Hartung.P.D. 2008. *Tool Wear in Titanium Machining*.Thesis. Massachusetts Institute of Technoology,USA.

S. Sun. 2009. Characteristics of cutting forces and chip formation in machining of titanium alloys. *International Journal of Machine Tools and Manufacture.***49**:561-568

Suisman, M. 2005. Introduction to selection of titanium alloys. International Titanium Association:1-6.

Dnachie,M.J. 1988. Machining Titanium and its alloys. America Society for Metals.

Williams.J.C. 2003. Engineering Materials and Processes Titanium. 2nd edition. New York: Springer.

Emsley,J. 2001. “Titanium”. Nature’s Building Blocks: An A-Z Guide to the Elements. Oxford, England, UK: Oxford University Press: 457-456.

Collings,E.W. 1984. The physical metallurgy of titanium alloys. ASM International Metals Park, OH: 261.

Krar,S.F. 2004. Technology of machine tools. 5th edition. McGraw-Hill Science Engineering.

Tuholski,R.J. 1993. Don’t forget the cutting fluid. Journal of Industrial Technology **8**(3): 38-41

Kalpakjian, Schmid. 2003. Manufacturing Processes for Engineering Materials. 4th edition. Pretice Hall.

Montgomery, D.C. 2001. Design and Analysis of Experiments. 5th edtion. John Wiley & Sons Inc.

Daymi,A.,M.Boujelbene,S. Salem, Sassi,B.H. and S.Torbaty. 2009. Effect of the cutting speed on the chip morphology and the cutting force. *International Scientific Journal*.**1**(2):77-83.

Olayinka, O.A. and Sesan, P.A. 2008. Effect of type of workpiece material on chip formation process. *Au.J.T* .**11**(3):181-186.

Mchado,A.R.. and Wallbank,J. 1990. Maching of titanium and its alloys. *Journal of Engineering Manufacture*.**204**:53-59.

Gerard,P. and Alphonse.L.M. 2000. Hard turning: chip formation mechanisms and metallurgical aspects. *Journal of Manufacturing Science and Engineering*.**122**:406-412.

Komanduri, R. 1981. Some clarifications on the mechanics of chip formation when machining titanium alloys. *Wear.* **76**:25-34.

Shaw, M.C. 1984. Metal cutting principles. Oxford University Press, Toronto.

APPENDIX A

DEGREE FINAL YEAR PROJECT GANTT CHART

Gantt Chart for Session 09/10 SEM II (PSM 1): Part A (Thesis progress)
Name : Lee Ka Hung
Matric No. : ME07041
Project Title : Effect of Chip Formation on Tool Wear in Machining of Titanium
Supervisor : Mrs.Daw Thet Thet Mon

		Week														
Activities		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Meet with supervisor and fix weekly appointment	Planning	■	■													
	Actual	x	x													
Clarify the title, objective, problem statement and scope	Planning		■	■												
	Actual		x	x												
Find reliable journals and references	Planning			■	■	■	■									
	Actual			x	x	x	x									
Chapter 1: Introduction writing	Planning						■	■								
	Actual						x	x	x							
Chapter 2: Literature review writing	Planning							■	■	■	■					
	Actual								x	x	x					
Chapter 3: Methodology writing	Planning									■	■					
	Actual									x	x	x				
Chapter 4: Preliminary results writing	Planning										■	■	■	■		
	Actual											x	x	X		
Finalize the preliminary report	Planning												■	■		
	Actual												x	X		
Prepare presentation content and slides	Planning													■	■	
	Actual													x	x	
Presentation	Planning															■
	Actual															x

Gantt Chart for Session 09/10 SEM II (PSM 1): Part B (Machining progress)
Name : Lee Ka Hung
Matric No. : ME07041
Project Title : Effect of Chip Formation on Tool Wear in Machining of Titanium
Supervisor : Mrs.Daw Thet Thet Mon

		Week														
Activities		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Meet and set appointment with FKP lab instructor	Planning					█	█									
	Actual					x	x									
Identify the independent and dependent variables	Planning						█									
	Actual						x									
Build a design of experiment (DOE) using STATISTICA	Planning						█	█								
	Actual							x								
Start machining experiment according to the DOE	Planning								█	█	█					
	Actual								x	x	x	x				
Collect data for preliminary stage	Planning									█	█					
	Actual									x	x	x				
Analyze the data	Planning										█	█				
	Actual										x	x				
Interpret a preliminary result according to the data	Planning											█	█			
	Actual											x	x			

Gantt Chart for Session 10/11 SEM I (PSM 2): Part A (Thesis progress)
Name : Lee Ka Hung
Matric No. : ME07041
Project Title : Effect of Chip Formation on Tool Wear in Machining of Titanium
Supervisor : Mrs.Daw Thet Thet Mon

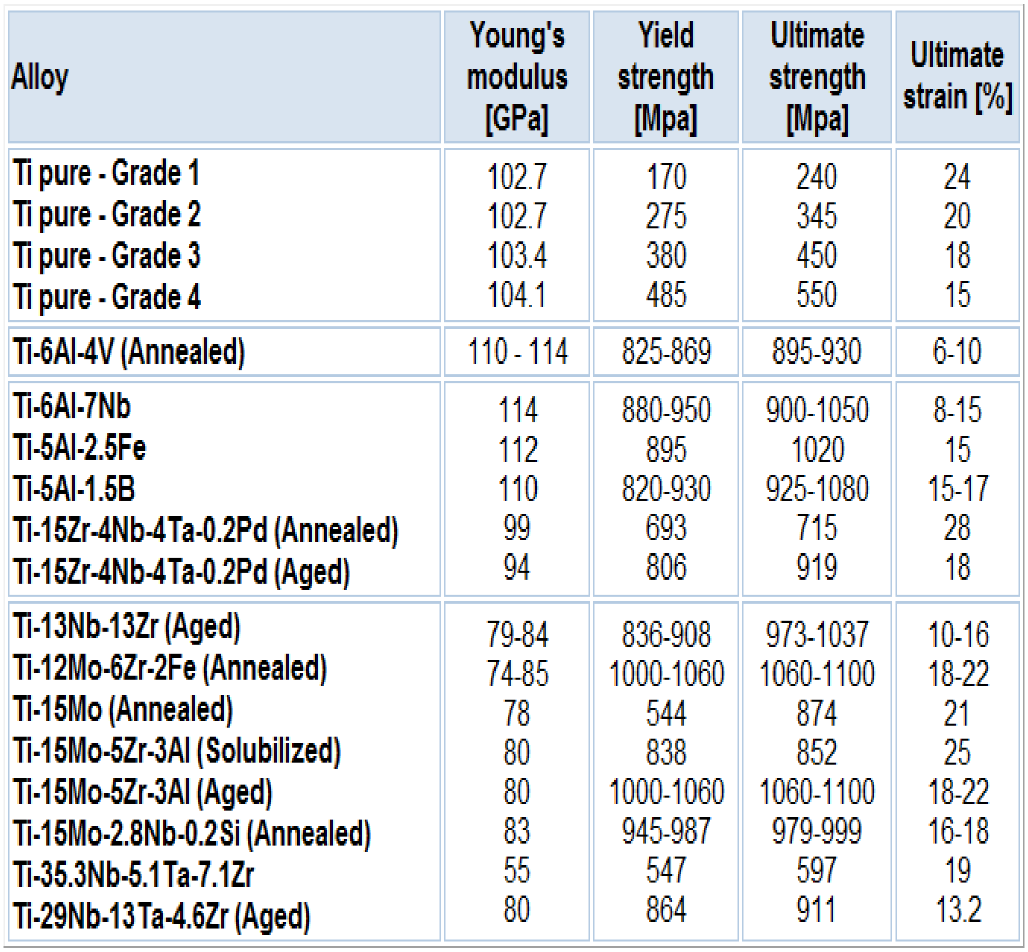
		Week														
Activities		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Edit project report PSM 1	Planning	■	■	■												
	Actual		x	x	x											
Refine the results obtained in Chapter 4	Planning				■	■	■	■	■							
	Actual								x	x	x	x				
Chapter 5: Conclusion and recommendation writing	Planning								■	■	■					
	Actual											x	x			
Editing thesis format and compilation	Planning										■	■	■			
	Actual												x	x		
Submit draft report	Planning													■		
	Actual													x		
Prepare presentation content and slides	Planning													■	■	
	Actual													x	x	
Presentation	Planning															■
	Actual															x

Gantt Chart for Session 10/11 SEM I (PSM 2): Part B (Machining progress)
Name : Lee Ka Hung
Matric No. : ME07041
Project Title : Effect of Chip Formation on Tool Wear in Machining of Titanium
Supervisor : Mrs.Daw Thet Thet Mon

		Week														
Activities		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Meet and set appointment with FKM lab instructor	Planning	■	■													
	Actual		x	x												
Start hot mounting process	Planning			■	■	■										
	Actual				x	x	x									
Proceed with grinding process	Planning					■	■									
	Actual						x	x								
Process with polishing process	Planning							■	■	■						
	Actual							x	x	x						
Process with etching process	Planning									■	■					
	Actual									x	x					
Observe and measure the chip structure	Planning										■	■				
	Actual										x	x				
Analyze and interpret the data	Planning											■	■			
	Actual											x	x			

Appendix B

The Mechanical Properties of Pure Titanium and Common Alloys.



Alloy	Young's modulus [GPa]	Yield strength [Mpa]	Ultimate strength [Mpa]	Ultimate strain [%]
Ti pure - Grade 1	102.7	170	240	24
Ti pure - Grade 2	102.7	275	345	20
Ti pure - Grade 3	103.4	380	450	18
Ti pure - Grade 4	104.1	485	550	15
Ti-6Al-4V (Annealed)	110 - 114	825-869	895-930	6-10
Ti-6Al-7Nb	114	880-950	900-1050	8-15
Ti-5Al-2.5Fe	112	895	1020	15
Ti-5Al-1.5B	110	820-930	925-1080	15-17
Ti-15Zr-4Nb-4Ta-0.2Pd (Annealed)	99	693	715	28
Ti-15Zr-4Nb-4Ta-0.2Pd (Aged)	94	806	919	18
Ti-13Nb-13Zr (Aged)	79-84	836-908	973-1037	10-16
Ti-12Mo-6Zr-2Fe (Annealed)	74-85	1000-1060	1060-1100	18-22
Ti-15Mo (Annealed)	78	544	874	21
Ti-15Mo-5Zr-3Al (Solubilized)	80	838	852	25
Ti-15Mo-5Zr-3Al (Aged)	80	1000-1060	1060-1100	18-22
Ti-15Mo-2.8Nb-0.2Si (Annealed)	83	945-987	979-999	16-18
Ti-35.3Nb-5.1Ta-7.1Zr	55	547	597	19
Ti-29Nb-13Ta-4.6Zr (Aged)	80	864	911	13.2

Source: E.W. Collings (1984)

APPENDIX C1

CHIP STRUCTURE FOR EXPERIMENT RUN OF 1-10

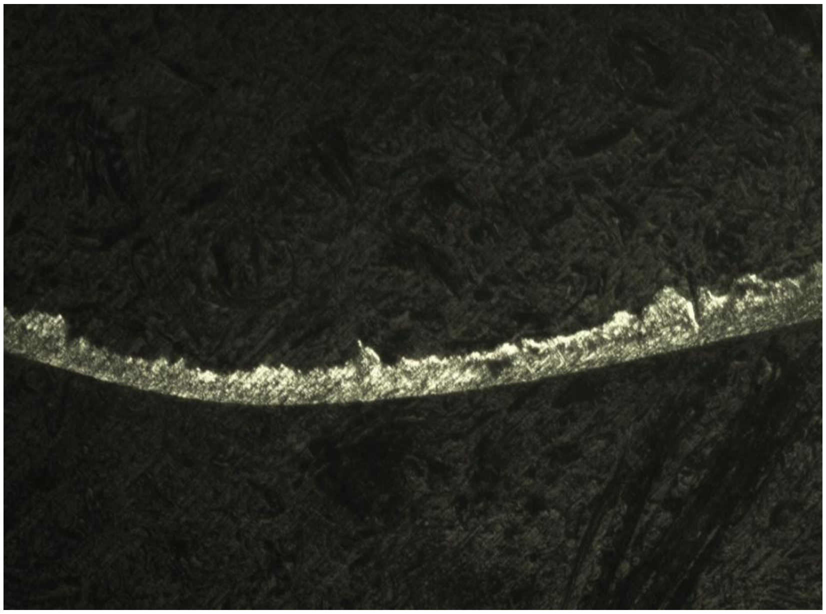


Figure C1.1: Chip structure produced with V= 90 m/min and *f*= 0.05 mm/rev

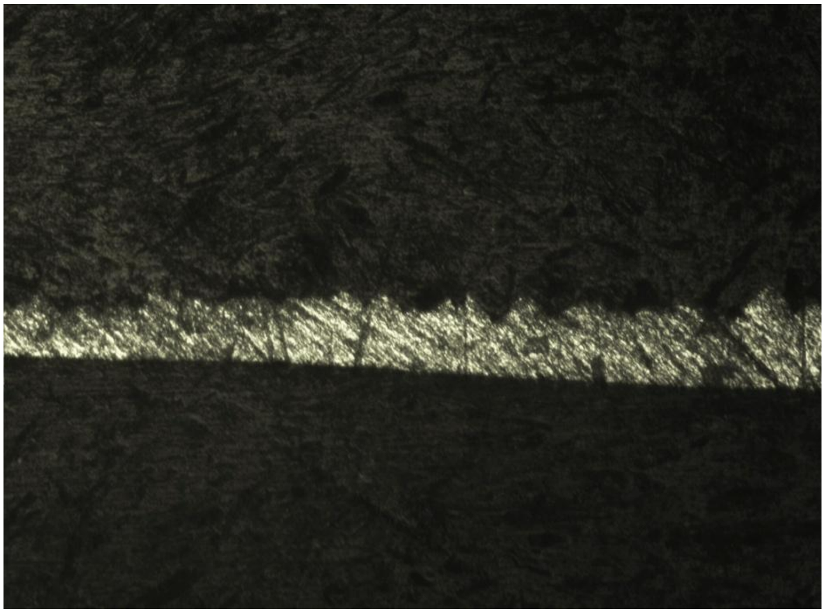


Figure C1.2: Chip structure produced with V= 90 m/min and *f*= 0.15 mm/rev

Figure C1.3: Chip structure produced with V= 150 m/min and *f*= 0.05 mm/rev

Figure C1.4: Chip structure produced with V= 150 m/min and *f*= 0.15 mm/rev

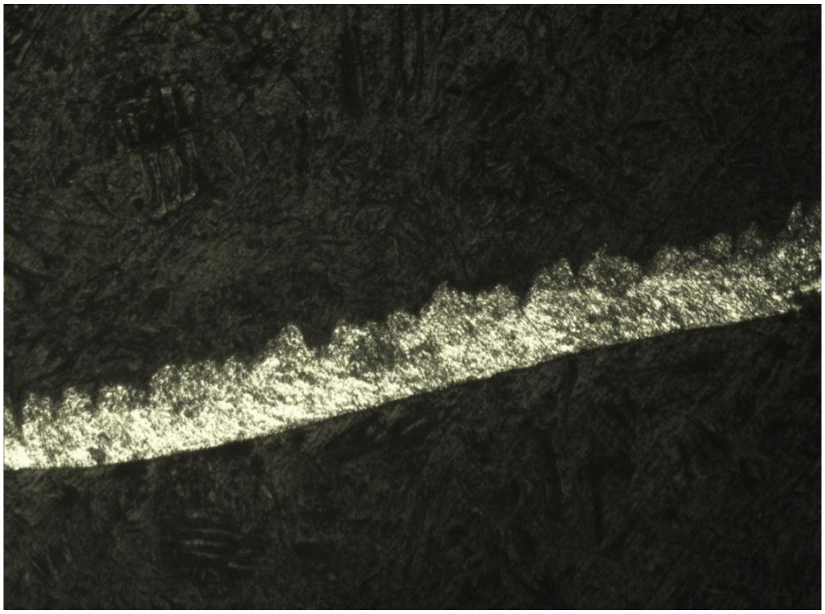


Figure C1.5: Chip structure produced with V= 77.5736 m/min and *f*= 0.1 mm/rev

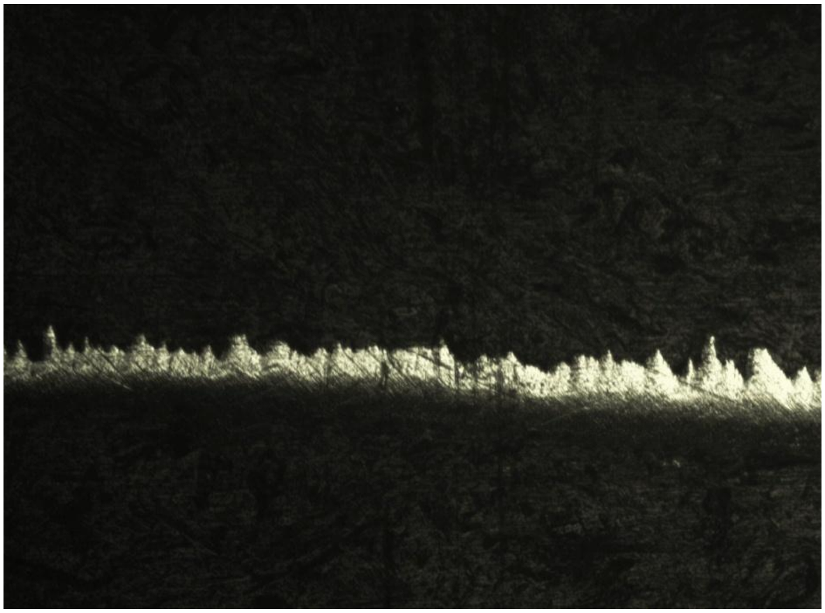


Figure C1.6: Chip structure produced with V= 162.4264 m/min and *f*= 0.1 mm/rev

Figure C1.7: Chip structure produced with V= 120 m/min and *f*= 0.0293 mm/rev

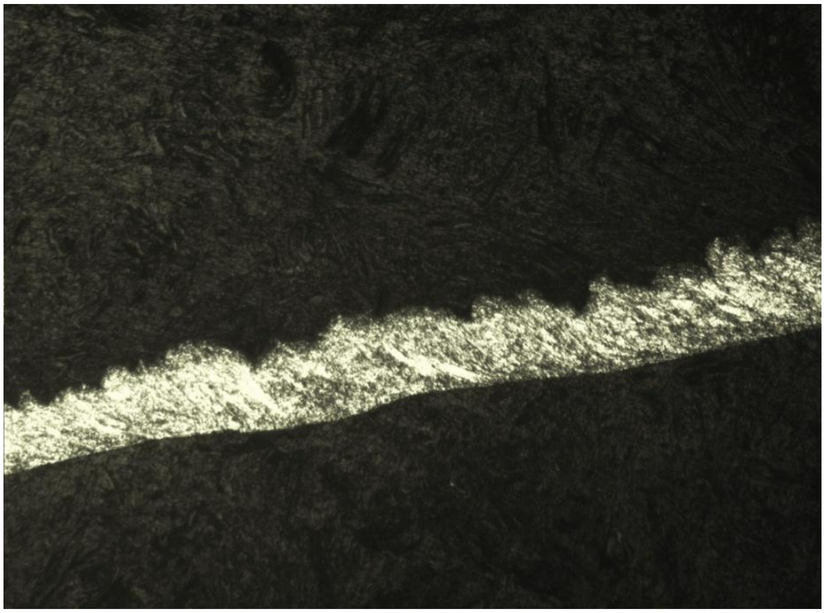


Figure C1.8: Chip structure produced with V= 120 m/min and *f*= 0.1707 mm/rev

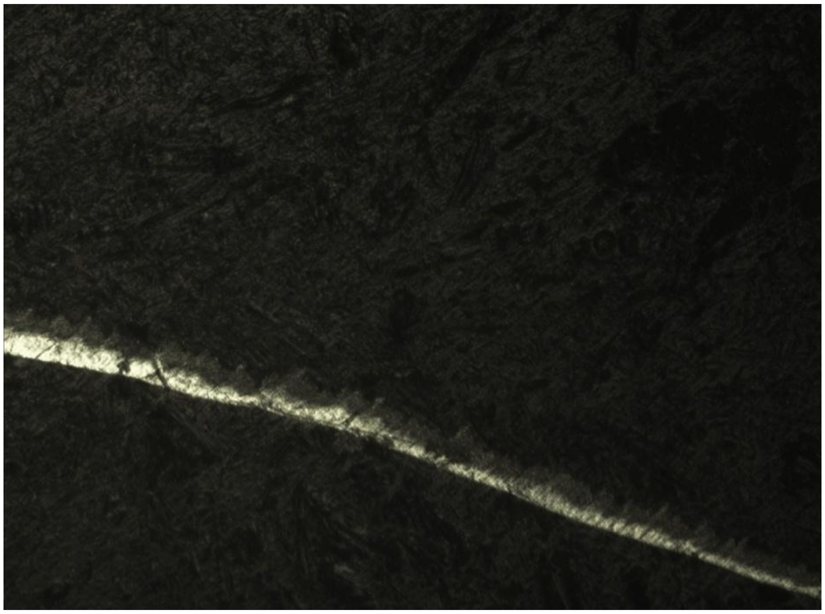


Figure C1.9: Chip structure produced with V= 120 m/min and *f*= 0.1 mm/rev

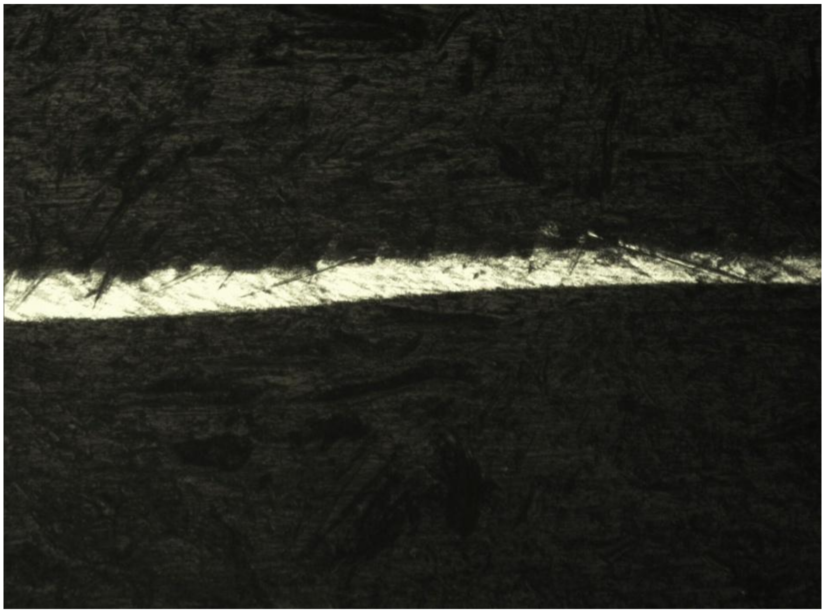


Figure C1.10: Chip structure produced with V= 120 m/min and *f*= 0.1 mm/rev

APPENDIX C2

CHIP STRUCTURE FOR EXPERIMENT RUN OF 11-20

Figure C2.1: Chip structure produced with V= 90 m/min and *f*= 0.05 mm/rev

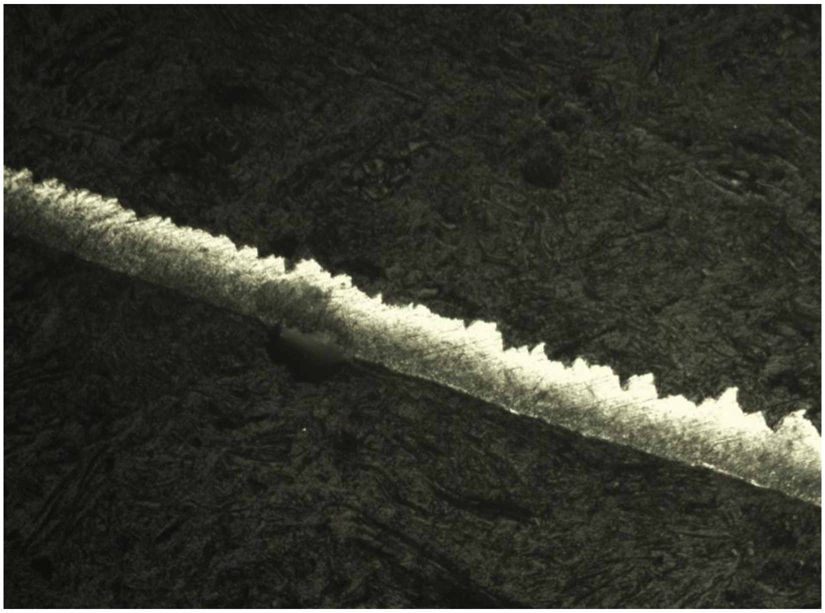


Figure C2.2: Chip structure produced with V= 90 m/min and *f*= 0.15 mm/rev

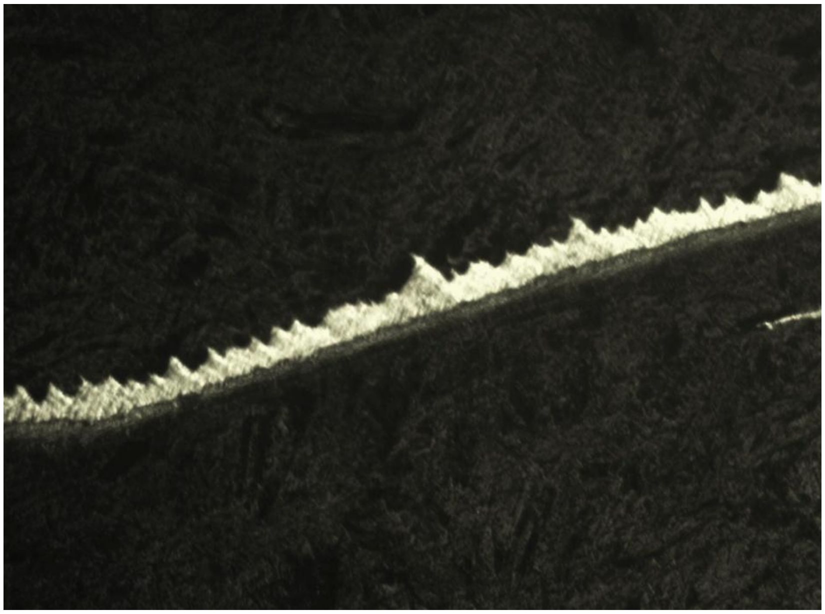


Figure C2.3: Chip structure produced with V= 150 m/min and *f*= 0.05 mm/rev

Figure C2.4: Chip structure produced with V= 150 m/min and *f*= 0.15 mm/rev

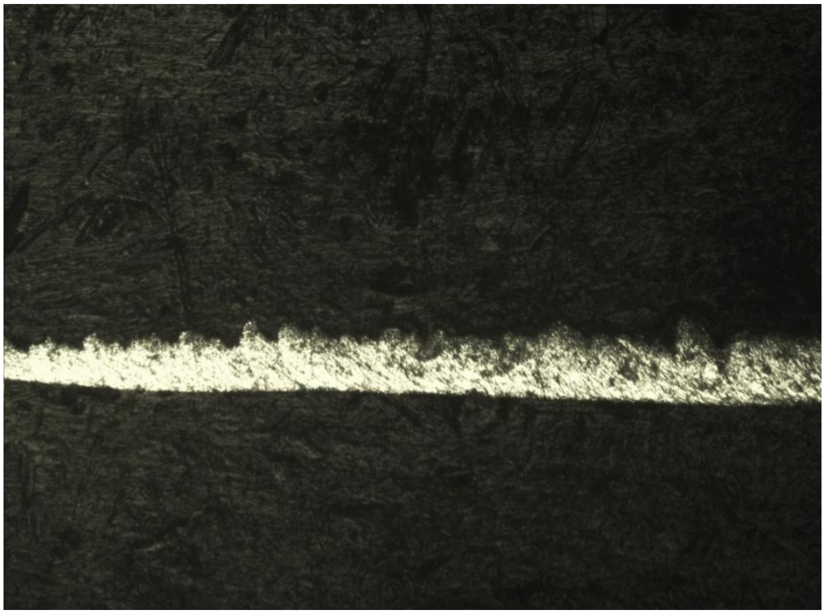


Figure C2.5: Chip structure produced with V= 77.5736 m/min and *f*= 0.1 mm/rev

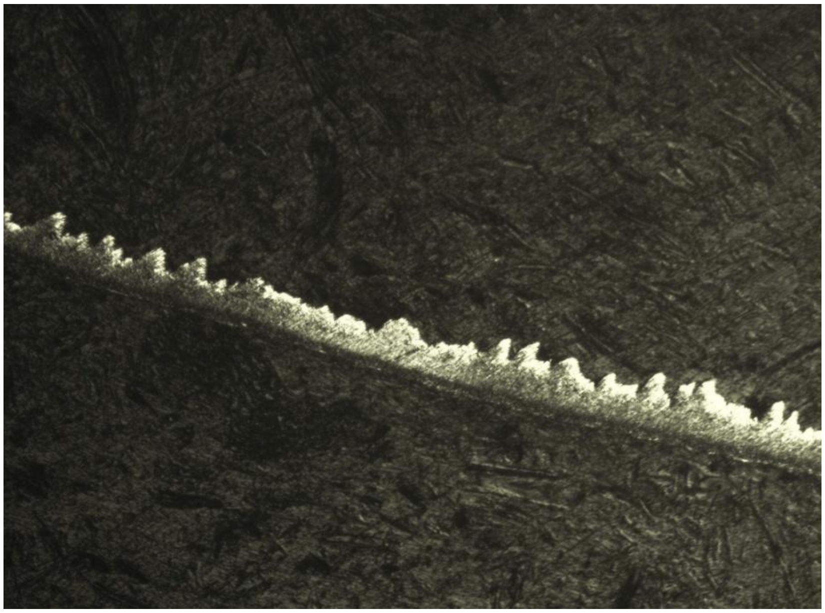


Figure C2.6: Chip structure produced with V= 162.4264 m/min and *f*= 0.1 mm/rev

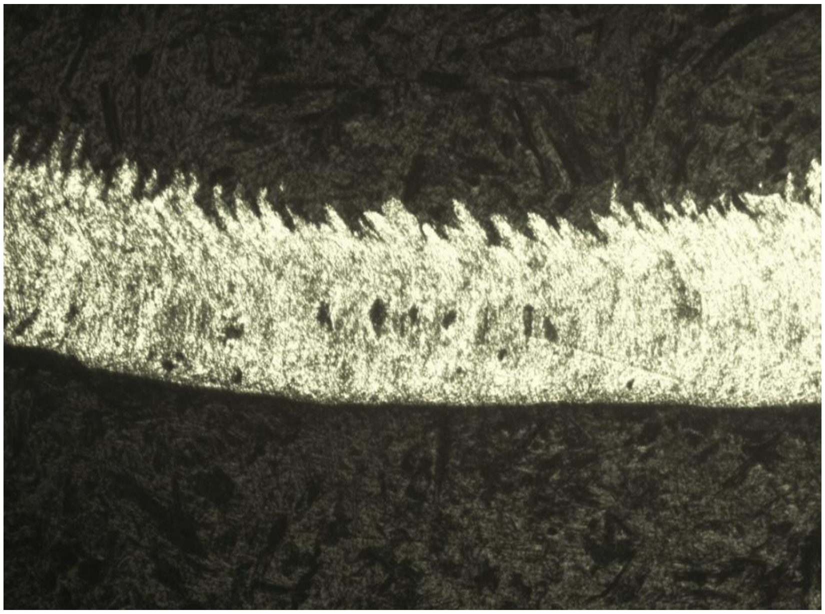


Figure C2.7: Chip structure produced with V= 120 m/min and *f*= 0.0293 mm/rev

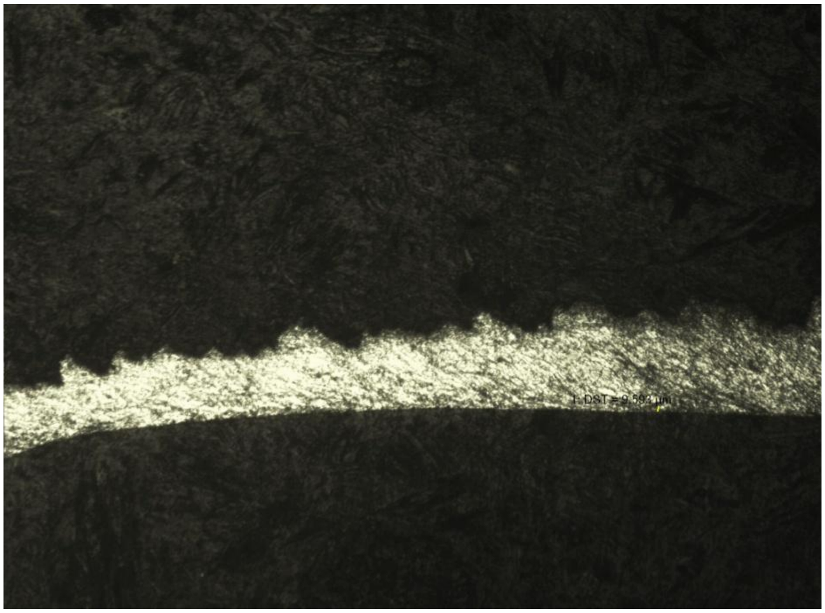


Figure C2.8: Chip structure produced with V= 120 m/min and *f*= 0.1707 mm/rev

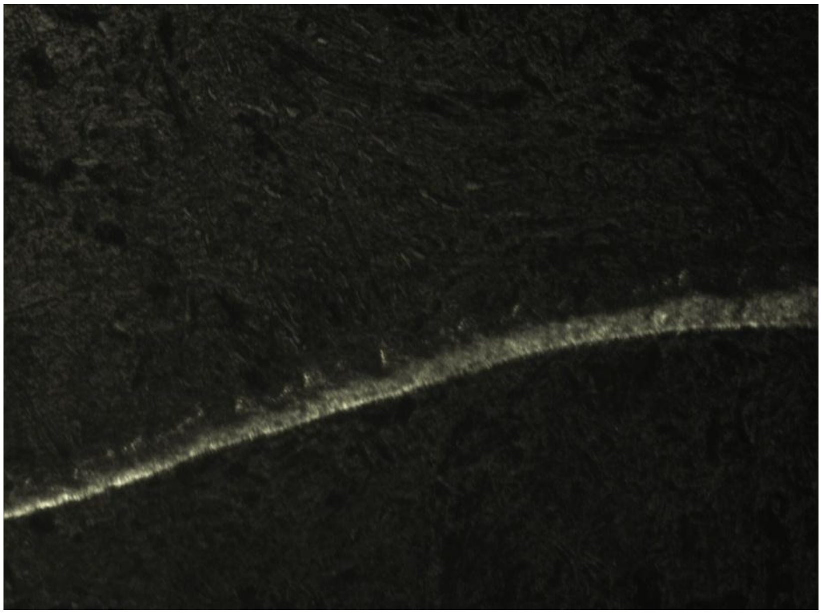


Figure C2.9: Chip structure produced with V= 120 m/min and *f*= 0.1 mm/rev

Figure C2.10: Chip structure produced with V= 120 m/min and *f*= 0.1 mm/rev