FE Simulation of turning/metal cutting with multi-coated tools

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ISLAMABAD

June 2021

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A thesis submitted in partial fulfilment of the requirements for the degree of

MS Design and Manufacturing Engineering

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June 2021

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Acknowledgement

I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

I am profusely thankful to my beloved parents who raised me when I was not capable of walking and continued to support me throughout in every department of my life.

I would also like to express special thanks to my supervisor Dr Hussain Imran for his help throughout my thesis. I can safely say that I haven't learned any other engineering subject in such depth than the ones which he has taught.

I would also like to pay special thanks to Dr Mushtaq Khan for his great cooperation. Each time I got stuck in something, he came up with the solution. Without his help I wouldn’t have been able to complete my thesis. I appreciate his patience and guidance throughout the whole thesis.

Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment.

Abstract

The metal cutting process is an integral part of today's industry. However, understanding the basic principles of the metal cutting processes through experiments has its limitations. On the other hand, FE modelling can provide researchers an unconventional way to better study the machining processes under different cutting conditions as it can calculate many complicated conditions at once such as metal temperature, chip tool interface, tool wear, etc. The aim of this research is to develop innovative methods to produce high grade products and decreasing the manufacturing time and cost at the same time.

Chip formation is still one of the more problematical parts in the field of machining that still requires numerous research. A number of different prediction models have been proposed over the years. The Johnson-Cook damage model was chosen to be the main focus for this research. The approach used in this research was to obtain the experimental data of the cutting process of Ti-6Al-4V alloy using the tungsten carbide (WC) tool. Then use FEM software to simulate the process with the exact conditions and then compare the results of both studies to propose a solution for any inaccuracy or inconsistency that may arise.

The FEM software used for this study is DEFORM-3D. It is a very unique simulation software that implements the Finite Elements Methods to model composite machining processes (cutting, turning, drilling etc.) in both 2D and 3D. The specific results were taken for the cutting forces and chip formation from the simulation and were compared with the experimental results for its accuracy.

Keywords: Ti-6Al-4V, FE Simulation, Metal cutting, DEFORM-3D, Oblique metal cutting, JC material model, Chip morphology

Table of Content

Chapter I: INTRODUCTION

Chapter II: LITERATURE REVIEW

Chapter III: FINITE ELEMENT MODELEING

Chapter IV: MODELING & SIMULATION

Chapter V: RESULTS

Chapter VI: CONCLUSION AD DISCUSSIONS

List of Figures

List of Tables

CHAPTER I

INTRODUCTION

1.0 Introduction

A machining process is defined as a combination of steps in which a piece of raw material is shaped into a desired final object. Among others cutting, turning, milling, boring and drilling are the most prominent machining processes in metal manufacturing. For over a century, these machining processes have been a hot topic of interest for several researchers to achieve better results and develop more efficient technologies.

Turning is the simplest form of machining process because it is a typical single-point machining process[1]. Hence studying turning can offer great insight to a skilled researcher. On the other hand, other machining procedures i.e. drilling is a multipoint machining process and can be broken down into a combination of single-point processes for easier solutions and understanding.

1.1 Turning process

Turning is the machining process in which a single point machining tool is used to remove the material from the workpiece in form of chips by giving the workpiece a rotational velocity. The cutting tool is held in a tool holder or clamps and is kept parallel to the workpiece surface. It is used to cut away unwanted material to transform it into the desired shape. It can be done manually (as in the case of a lathe operation), or by using a CNC (computer-controlled) machines. For this, a piece of metal (or any other material) is rotated along an axis of rotation while a cutting tool is moved linearly[2].

1.1.1 Types of Turning

There can be many different types of a typical turning process. Namely:

- ***Straight turning***
- ***Taper turning***
- ***Grooving***
- ***Profiling***

The bits of waste metal formed after a turning operations are known as ***chips***.

1.2 Finite Element Method (FEM) Simulation

The purpose of this research work is to establish a relation between the cutting data obtained from experimental results and the cutting data obtained from a detailed 3D FEM simulation of oblique cutting operation carried out on DEFORM-3D software. A detailed numerical model was constructed to simulate the problem.

The reason the finite element method (FEM) is becoming more and more common in industry and research is that it provides results and data as accurately as possible as mathematically can. In FEM, a problem is broken down into a set of a very small but finite number of elements and nodes. Then all these nodes and elements are studied under the given conditions separately. In the end, all the results are combined to obtain the results[3].

3D simulation allows the researcher to understand the machining methods exhaustively. That way, they can make more precise predictions.

1.3 Ti-6Al-4V

The material being used as the focus of investigation for this study is Ti-6Al-4V because, during the past years, it has gradually been increasing in popularity among many industrial uses as a focus of great interest due to an excellent combination of properties.

Among many others, some of the properties of Ti-6Al-4V are mentioned below[4]:

1.3.1 Chemical Properties

- Non-flammable
- Corrosion-resistant
- Resistant to oxidation below 500°C
- Low toxicity
- Is a low activation material.
- Is chemically stable

1.3.2 Physical Properties

Density	4.50 g/cm^3
Melting point	1650-1670 °C
Boiling point	3287 °C

Table 1.1: Physical properties of Ti-6Al-4V[5]

- Lightweight
- Ductile
- Low density
- Resistant to electricity

1.3.3 Mechanical Properties

Modulus of Elasticity	113,8 GPA
Hardness, Brinell	334
Poisson's Ratio	0.342
Fatigue Strength	510 MPa
Fracture Toughness	75 MPa-m1/2
Tensile Strength (*Ultimate*)	1170 MPa
Tensile Strength (*Yield*)	1100 MPa

Table 1.2: Mechanical properties of Ti-6Al-4V[6]

1.3.4 Uses of Ti-6Al-4V

- In the Automobile industry as automotive core structures (lightweight and corrosion resistance)
- In making advanced armor and weapons (due to strength)
- In biomedical procedures such as to make a Sternal wire, used in a heart bypass, as an alternative to Nickel, which many are allergic to.
- In the aerospace industry for its high-temperature resistance.

1.4 Problem Statement

With the increase in competition and the demand for high efficiency and performance, machining processes are required to be more efficient. Recently, the field of FE methods has presented a lot of solutions to understand and solve these problems. The use of the FE methods in machining operations is arguably the most efficient way to explain the cutting and chip formation processes. In general, the simulation studies using FE methods are a great guiding tool in order to design and/or to optimize the current machining processes rapidly.

It is very difficult to determine the most efficient conditions for any machining process because a large number of dependent and independent variables are always being involved in the process simultaneously. In old times, to achieve a high level of process optimization, a large number of experiments had to be run while changing all the variables ever so slightly to determine the effects of each variable. The ultimate result was a better understanding of the process but the cost was high enough that the justification of such a tedious procedure was very difficult. It involved a lot of wasted materials, labour hours, energy utilized, and many other factors which made this task very expensive and time-consuming.

In FEM, a problem is broken down into a set of a very small but finite number of elements and nodes. Then all these nodes and elements are studied under the given conditions separately. In the end, all the results are combined to obtain the results.

1.5 Objectives

The general aim of this study is to develop a 3D model of oblique metal turning/cutting using DEFORM-3D software. Common room parameters are determined beforehand to reduce the chances of errors. Once the model is ready and the parameters have been entered into the software, the simulation is submitted for processing. After obtaining the results from DEFORM-3D, they are compared to the experimental results obtained already in the lab. The data that has been taken into consideration is:

- Cutting speed
- Tool velocity
- Shear angle
- Feed rate
- Temperature
- Depth of cut
- Cutting force
- Thrust force
- Cutting angle
- Material properties (density, UTS, yield strength, etc.)
- Material interaction
- Coolant temperature

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

For a long time, scientists have been attempting to develop a vivid theoretical and mathematical model that can describe the complicated mechanics involved in a machining process. They have also been trying to develop methods that can predict the behaviour of different variables involved in the machining process without the need to conduct any cutting test beforehand.

In this chapter, many publications focusing on the process of metal cutting are reviewed. These publications are briefly discussed in the following pages.

2.2 Fundamental of Metal Cutting

Metal cutting is a process in which the metal specimen is processed to convert it into the desired shape for various uses. In all the metal cutting procedures, a workpiece is held in place with the help of fixtures (in case of milling) or a rotating chuck (in case of the lathe). A single-point tool (in the case of the lathe) and a multi-point tool (in the case of milling) are used to remove the unwanted material. The tool is usually made out of reinforced material for better performance and long life. The contact is made between the surface of the workpiece and the tip of the tool[7].

Rotatory motion is given to either the tool or the workpiece to remove the excess material. Feed is given to moves the tip of the tool around the surface of the workpiece to move the removing process around the entire workpiece. As a result, a refined product is obtained with all the unnecessary martial removed. The most common metal cutting operations are:

- *Turning*
- *Milling*
- *Drilling*

A brief description of all these processes is discussed below.

2.2.1 Turning

Turning is a cutting process that is usually carried out on a lathe machine. A tool is secured in its place using clamps or a tool holder. Contact with the workpiece is made at the desired point on the surface of the workpiece and the tip of the tool. A controlled amount of rotation is given to the workpiece and feed is given to the tool. The tool removes all the unwanted material and produces a product with the desired geometries. Figure 2.1 shows a typical graphics of a turning operation[8].

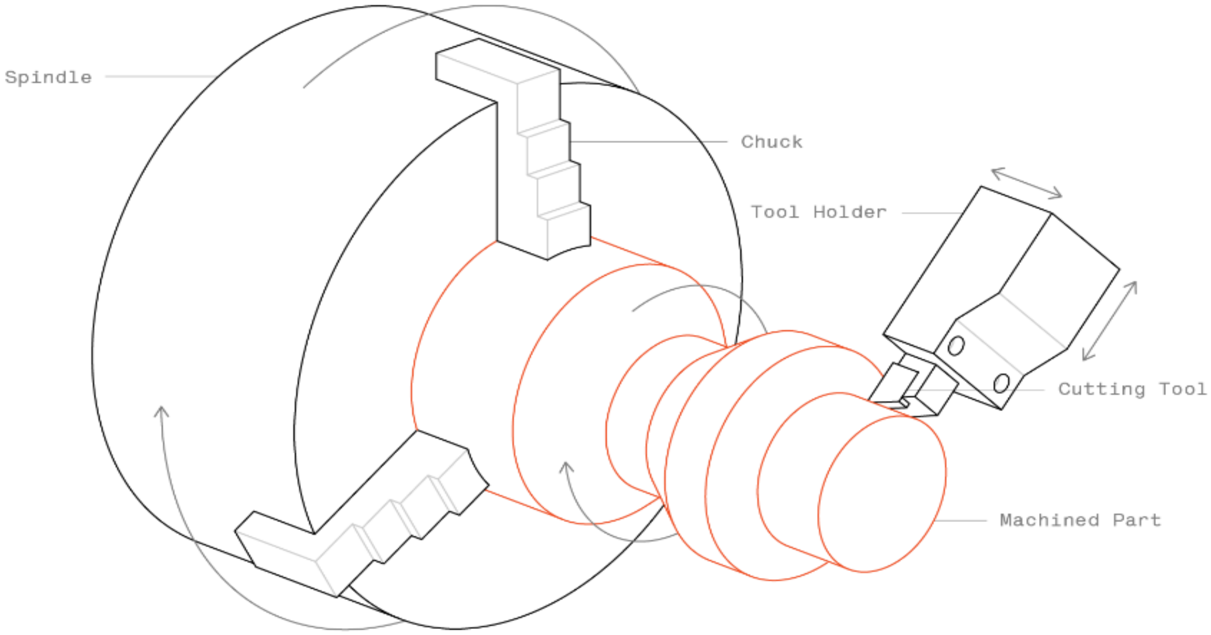


Figure **2.1**: Three-dimensional view of turning operation

2.2.2 Milling

Milling is a process that is usually carried out on specialized milling machines. In the case of milling operations, the workpiece is kept fixed on the milling table with the help of fixtures. The tool is fixed in the spindle which is given a controlled rotation by the operator or computer if the machine is CNC. Unlike lathe turning, the feed can be given to either the workpiece or the tool. Milling is a complicated and often preferred operation because, in the case of milling, the tool can be rotated in many different angles along all the 3-axis. As a result, more complex and detailed shapes can be obtained from milling. Figure 2.2 shows a typical graphics of a milling operation[8].

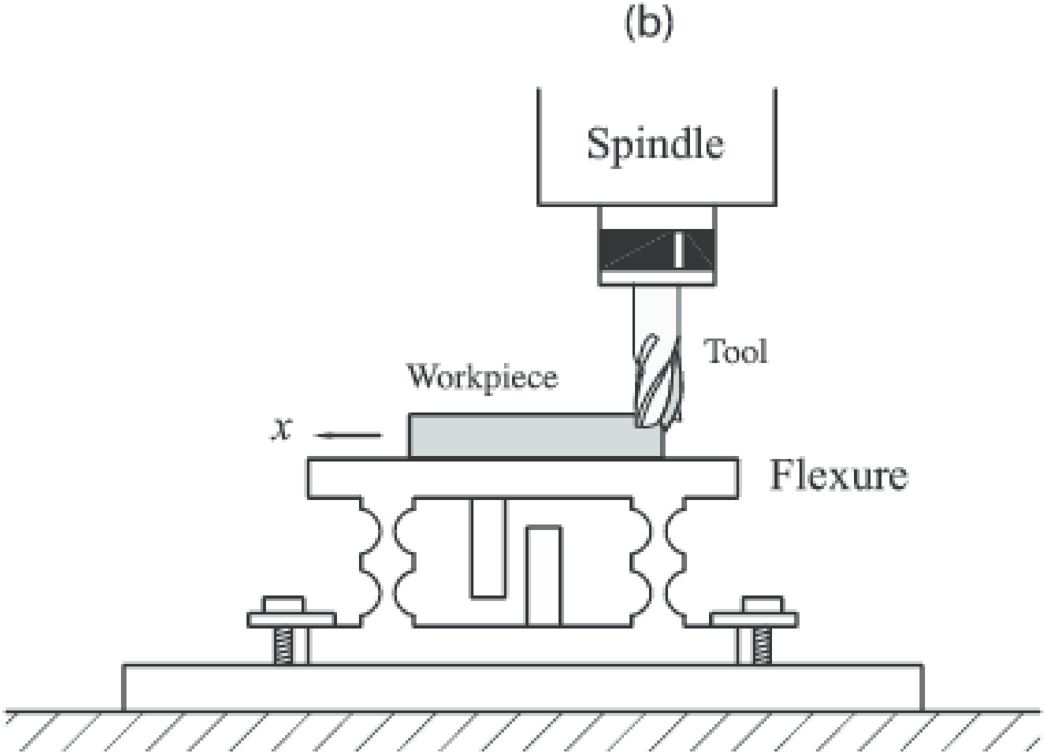


Figure **2.2**: Three-dimensional view of milling operation

2.2.3 Drilling

Drilling is a process that can be carried out on both lathe and milling machines. In addition to both, most of the labs and machine shops have specialized drilling machines which are designed just for drilling. It is a multi-point machining operation. In a typical drilling operation, the material is removed from the workpiece with the help of a rotating drilling bit.

At first, the drill bit is secured in a vice or fixtures on a working table. A drilling bit of determined diameter is fixed in a spindle which is attached to the machine motor with gears. A controlled amount of rotation is given to the drill bit. Contact is made on the surface of the workpiece. Feed is given to the drill bit as well. The whole operation is overseen by a trained operator or is controlled by computers in the case of CNC machines. Figure 2.3 shows a typical graphics of a drilling operation[8].

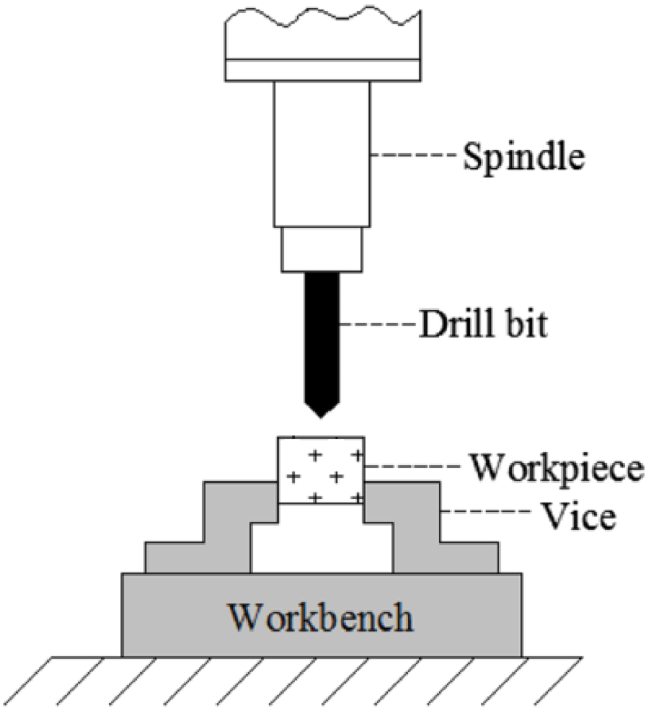


Figure **2.3**: Three-dimensional view of the drilling operation

2.3 History of Cutting Process Modelling

In today's world of technological advancement, a basic process such as metal cutting holds a role of vital importance because it is being used in almost every sector in the world. From manufacturing a needle to an airplane, from a tennis ball to spaceships, and so on. Today, efficiency, accuracy, and cost reduction are the main focuses of research in the field of metal cutting. In addition to that, a machining process should be feasible enough that the product it is producing should justify the expenses of the operation.

The significance of machining methods has been completely standardized in today’s industrial world. Both basic and applied researches have been promised to provide any dependable predictions to the performances of the cutting procedures. They are also aimed to impact the process of producing quality and process productivity[9].

For over 50 years, researchers have been working tirelessly to better understand the process and to introduce new methods and techniques to improve the basic principles and mechanisms of the process.

Decade	**Researchers**
1940-1950	Martellotti *(1941)* Merchant *(1944)*
1950-1960	Lee et.al. *(1951)* Dio, Salje *(1956)* Tobias *(1958)*
1960-1970	Gurney, Albrecht *(1961)* Zorev, Oxley *(1963)* Cumming, Wallace (*1965)*
1970-1980	Okushima *(1971)* Hannas, Oto *(1974)* Baily, Pandit *(1975)*
1980-1990	Komanduri *(1981)* Johnson and Cook *(1983)* Rubenstein *(1985)* Carrol, Strenkowski *(1986)* Yang *(1989)*
1990-Present	Minis, Parthimos *(1990)* Arsecularatne *(1996)* Ng et. Al *(1999)* Becze, Elbestawi *(2002)*

Table **2.1**: History of Cutting Processes Modelling

2.4 Types of Cutting Operations

In any conventional cutting operation, cutting tool is kept in place using clamps or tool holders, rotational velocity is given to the workpiece along a prescribed axis and a liner velocity is given to the tool in a specified direction only. The type of the cutting operation entirely depends on the inclination angle between both workpiece and the tool. If the angle is exactly equal to 90^o then the process is called an Orthogonal cutting operation. And if the angle between the workpiece and tool is anything other than a 90^o, then the process is called an Oblique cutting operation[10].

2.4.1 Orthogonal Cutting

It is the simplest form of the metal cutting which is hardly used in any practical applications. The main purpose of orthogonal cutting is to understand and explain the basic principles of a simple cutting model in any theoretical and/or experimental task as it is the easiest process that can be modeled in a 2-dimensional model.

In an orthogonal cutting, independent variables, i.e. rake angle and surface smoothness, are reduced so that the effects of the basic parameters can be calculated more precisely.

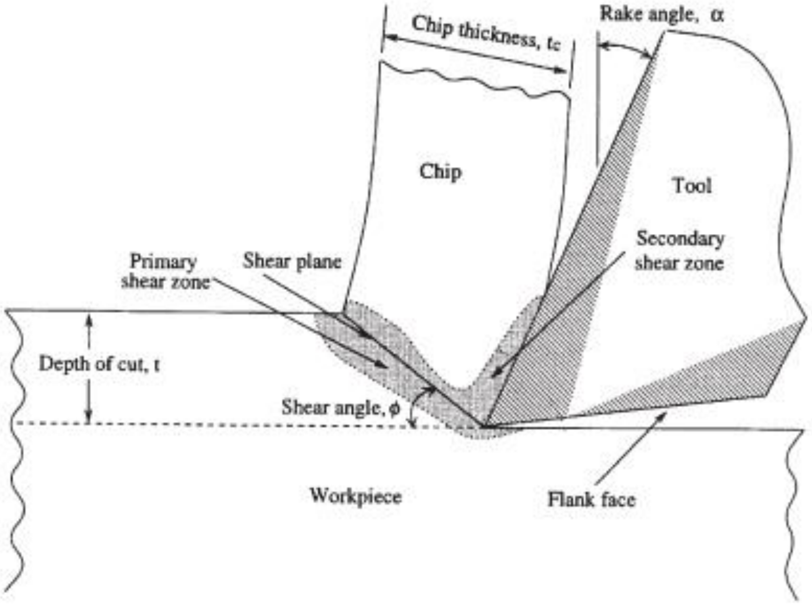


Figure **2.4 (a)**: 2-D Orthogonal cutting

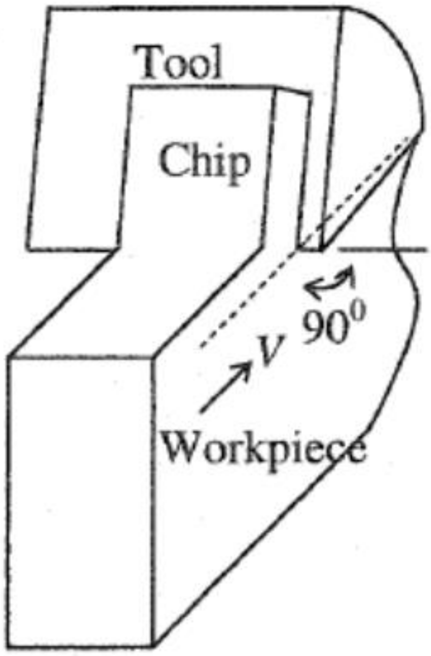


Figure **2.4 (b)**: 3-D orthogonal cutting

2.4.2 Oblique Cutting

Almost all of the cutting operations are carried out in the principles of the oblique cutting. In this process, there is a clear angle of inclination between the tool and the workpiece. Usually this angle is kept from 5º-15º to minimize the tool damage. Here the angle is represented by *i*, that makes the oblique cutting process more difficult to simulate.

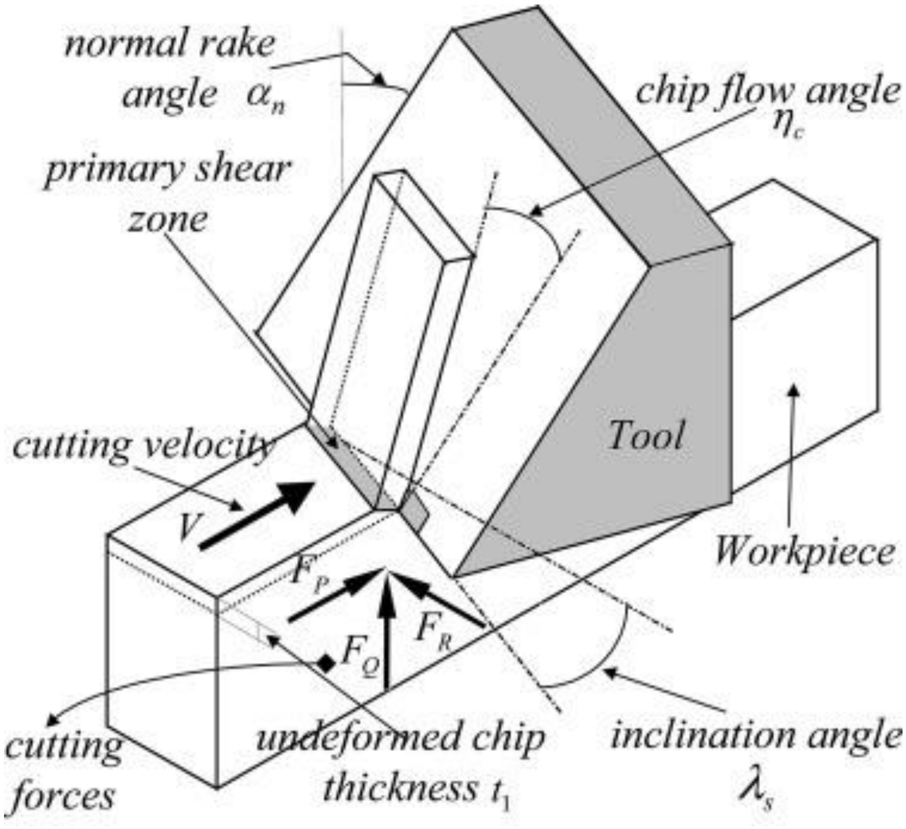


Figure **2.5**: 3-D Oblique cutting

2.4.3 Schematic comparison of the oblique and orthogonal cutting process

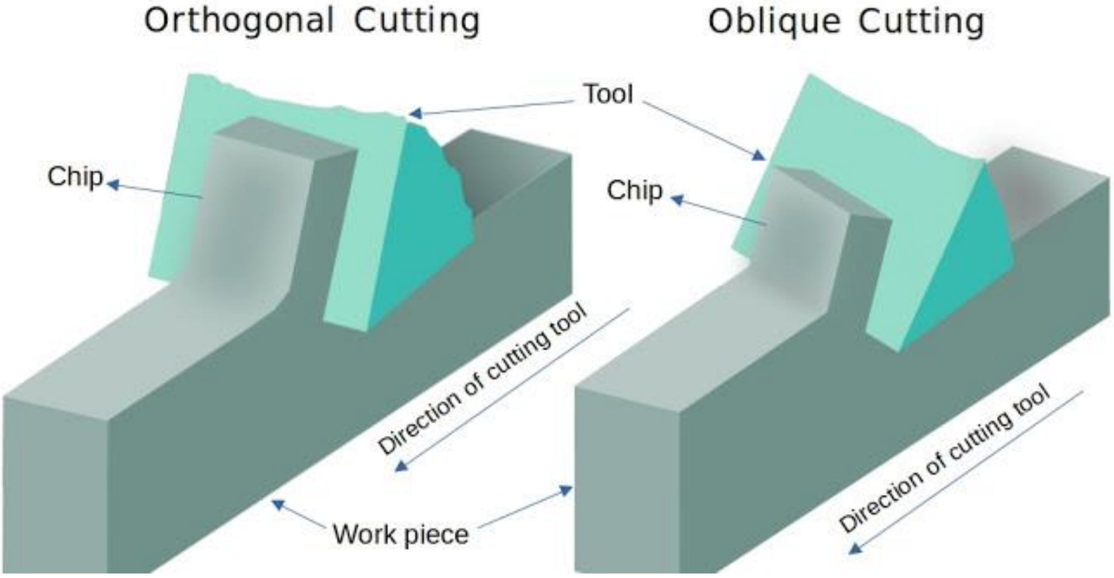


Figure **2.6**: Schematic comparison of the oblique and orthogonal cutting process

2.5 Friction model

The phenomenon known as ‘Friction’ can be defined as an opposing force generated between two surfaces while in contact as a result of sliding. It is caused due to irregularities present on both surfaces. Friction can also be characterised as a force to resist motion/sliding[11].

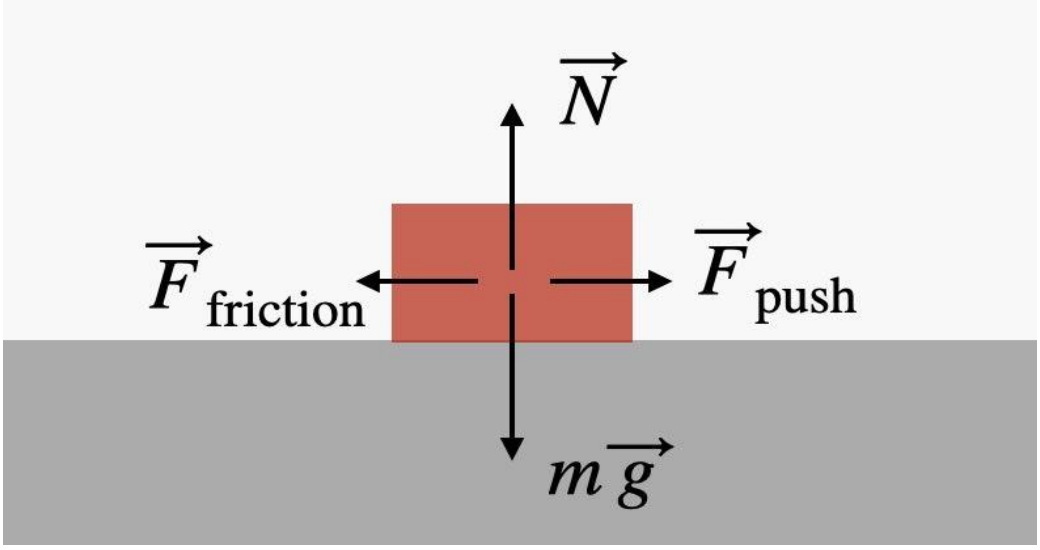


Figure **2.7**: Friction model

As shown in Figure 2.7, both normal force N and horizontal force F_{lush}, are acting simultaneously on both bodies. According to the second law of motion, the force N is the normal force that acts in reaction to the weight force mg of the body. While the friction force F_{friction} acts to counter balance the force F_{push}.

In general, *static friction* and *kinetic friction* are the two distinct types of frictions (Figure 2.8). With the increase the push force F_p, friction force F_f also increases as well as a reaction. The blocks are unable to move until the push force F_p exceeds the maximum value of F_f. The static friction force can be expressed as:

$$F_{static} = \mu_S N \qquad \text{………..} \ (2.1)$$

Where,

μ_s = coefficient of static friction.

When F_p becomes greater than F_{static}, the body starts moving. While in motion, the rough irregularities present on both surfaces don't have enough time to interlock and hence the value of the frictional force is decreased. This new value of friction is called the kinetic frictional force. Since in maching processes, both tool and workpiece are constantly in motion, we only consider the kinetic friction coefficient which can be calculated by:

$$F_{kinetic} = \mu_k N \qquad \text{……….. (2.2)}$$

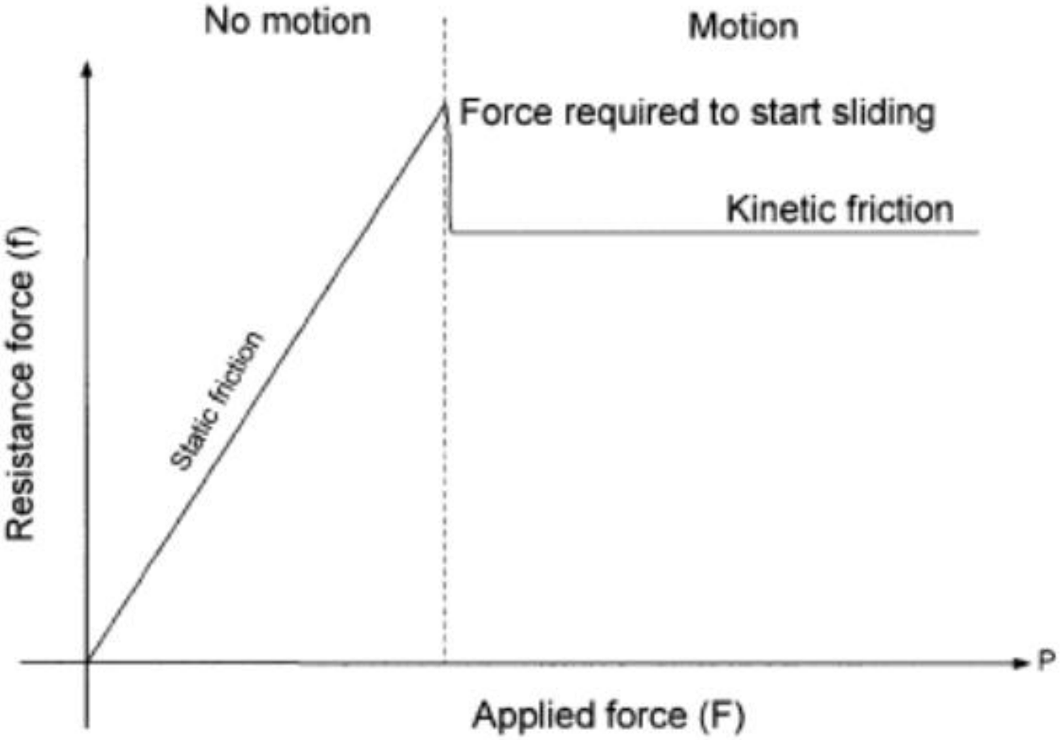


Figure 2.8: Static and kinetic friction

2.7 Johnson and Cook damage model

The JC damage model was first introduced during the 1980s to study the large explosive problems. Ever since then, the model has been recognised to be the most accurate among all other models and has been commonly used by a large number of researchers to study the cutting processes[12].

According to the JC model, a fracture on the workpiece occurs when the damage value exceeds the maximum allowable strain of the material. In that case, the integrity of the workpiece material is compromised. This approach is often referred to as the cumulative strain method (CSM). After the introduction of the JC model in the 1980s, many researchers focused on it and have developed some different variations of the same model, such as the Simplified Johnson-Cook model[13], modified Johnson-Cook model[14] etc. These models have been widely used in machining process analysis.

The JC model assumes that material failure is due to the plastic deformation. The damage variable D is defined as:

$$D = \int_0^{\varepsilon_p} f(field\ \mathrm{var}iables)\, d\varepsilon_p \qquad \text{………. (2.3)}$$

For any material, when $\mathbf{D} > \mathbf{D}_c$ where D is the overall damage, and D_c is the critical value, the material will always fail.

The JC model is the most commonly used model which describes both strength function and failure function. Its strength function deals with hardening, strain rate, and temperature. The equivalent stress σ_{eq} is defined as:

$$\sigma_{eq} = [A + B\varepsilon_p^n]\left[1 + C\ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_{melt} - T_0}\right)^q\right]$$

……….. (2.4)

Where,

$\boldsymbol{\varepsilon}_p$ = the equivalent plastic strain rate

$\boldsymbol{\varepsilon}_0$ = the reference plastic strain rate

$\boldsymbol{T_0}$ = room temperature

$\boldsymbol{T_{melt}}$ = melting temperature

$\boldsymbol{A}$ = material constant

$\boldsymbol{B}$ = material constant

$\boldsymbol{C}$ = material constant

$\boldsymbol{n}$ = material constant

$\boldsymbol{q}$ = material constant

The first term in the equation (2.4) explains the relationship between stress and strain. The second term explains the strain hardening. And the third term deals with the temperature.

The damage criterion, ***D***, is a weighted integral with respect to the effective strain (Johnson-Cook, 1985). Mathematically it can be defined as below:

$$D = \int_0^{\varepsilon_c} \frac{d\varepsilon_p}{\varepsilon_f\left(\frac{\sigma_m}{\sigma_{eq}}, \dot{\varepsilon}_p, T\right)} \quad \text{……….. (2.5)}$$

Where σ_m is the normal stress:

$$\sigma_m = \frac{(\sigma_{11} + \sigma_{22} + \sigma_{33})}{3} \quad \text{……….. (2.6)}$$

And $\boldsymbol{\varepsilon}_f$ is the effective strain:

$$\varepsilon_f = \left[D_1 + D_2 \exp\left(D_3 \frac{\sigma_m}{\sigma_{eq}}\right)\right]\left[1 + D_4 \log \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right]\left[1 + D_5 \frac{T - T_0}{T_{melt} - T_0}\right],$$

……….. (2.7)

Where

D_1 = material constant

D_2 = material constant

D_3 = material constant

D_4 = material constant

D_5 = material constant

Note: All the material constants values have to be determined by different material specimen tests.

CHAPTER III

FINITE ELEMENT MODELLING (FEM)

3.1 Basics

With the progress in the fields of numerical analysis and computer simulations, difficulties regarding the calculations and the modelling of the machining processes have become a lot less troublesome.

The reason the finite element method (FEM) is becoming more and more common in industry and research is that it provides results and data as accurately as possible as mathematically can. In FEM, a problem is broken down into a set of a very small but finite number of elements and nodes. Then all these nodes and elements are studied under the given conditions separately. In the end, all the results are combined to obtain the results.

In FEM, the material properties i.e. density, temperature, failure value, crack initiation/propagation are all considered as functions of strain and temperature. Relationship between the tool and the chip can be represented as a function of simple sliding. However, in rare cased, a large amount of deformation can occur at any element during the simulation process which can greatly influence the simulation results. That is why for each simulation case, great thought is always given while choosing the formulation type of the FEM process[15].

3.2 Types of formulations in FEM

The main kinds of FEM formulations which are most widely implemented in any FE simulation are:

- Lagrangian Formulations
- Eulerian Formulations
- Arbitrary Lagrangian-Eulerian (ALE) Formulations

3.2.1 Lagrangian Formulations

3.2.1.1 Advantages

- It is the most commonly applied formulation machining simulations.
- It is highly desirable when an unrestricted material is involved.
- In this formulation, the mesh is always attached to the workpiece only.
- It is also very appropriate for metal cutting simulation because to has a unique ability which enables it to accurately govern the chip geometry.

3.2.1.2 Limitations

- The elements in this formulation are often highly distorted.
- Implementing mesh regeneration is highly advisable.
- Lagrangian formulation demands that the material removal criteria must be calculated beforehand.
- This shortcoming of the Lagrangian formulation can be removed by using automatic re-meshing techniques.

3.2.2. Eulerian Formulations

3.2.2.1 Advantages

- In this approach, the mesh is attached to the entire volume of the system.
- All the system elements are attached to the mesh separately.
- All of the material properties are re-calculated at fixed intervals
- It requires a lower amount of total elements which in return decreases the computational time.

3.2.2.2 Limitations

- It requires that the chip boundaries and shape are determined beforehand.
- Additionally, some specific variables such as contact conditions and chip thickness must be kept constant.
- Hence, Eulerian formulation is not a realistic approach to the metal cutting simulations.

3.2.3. Arbitrary Lagrangian-Eulerian (ALE) Formulations

In this technique, a unique blend of of both Lagrangian and Eulerian formulations are combined. In ALE formulation, the FE mesh is neither fixed to the system volume nor is it attached to the workpiece material only. Instead, it follows the material flow.

The central idea of the ALE f is to apply the Eulerian formulation for modeling the tooltip where the cutting process occurs and the Lagrangian formulation is applied for the entire system including the boundaries boundaries. ALE has following distinct advantages:

- ALE can avoid severe element distortion.
- There is no need for the remeshing techniques.
- The chip formation can be calculated as a function of the plastic deformation of the material.

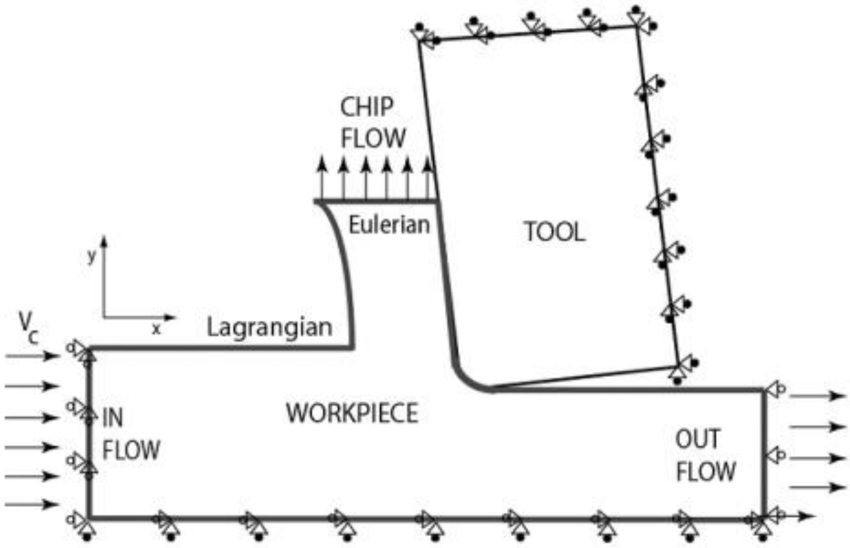


Figure **3.1**: Eulerian and Lagrangian boundary conditions in ALE simulation

3.3 Meshing

In FEM, a problem is broken down into a set of a very small but finite number of elements and nodes. This is called ***discretization*** or ***meshing***. A simple designed FEM mesh is highly susceptible to material deformation under high force changes. This deformation can cause many problems with the simulation procedures and the results obtained from a regular mesh can range from 5% to 500% skewed from the intended results. Therefore, using a regular mesh for any simulation is always a recipe for disaster. This can be resolved by introducing a new meshing technique called adaptive mesh procedure (AMP). In AMP, whenever the material starts deteriorating rapidly, the system slows down the cutting process and calculates the new mesh. Once the new mesh is finalised, it is implemented onto the material and the cutting process is carried out as normal. AMP is shown in Figure 3.2 and 3.3.

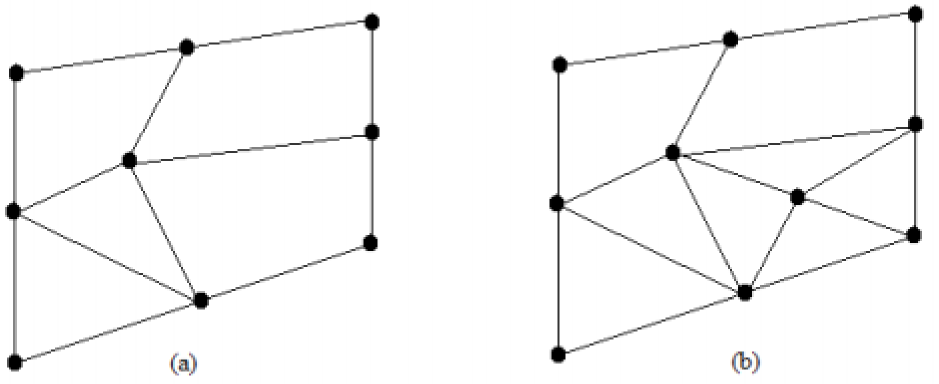


Figure **3.2:** (a) Initial local mesh (b) Reducing element size

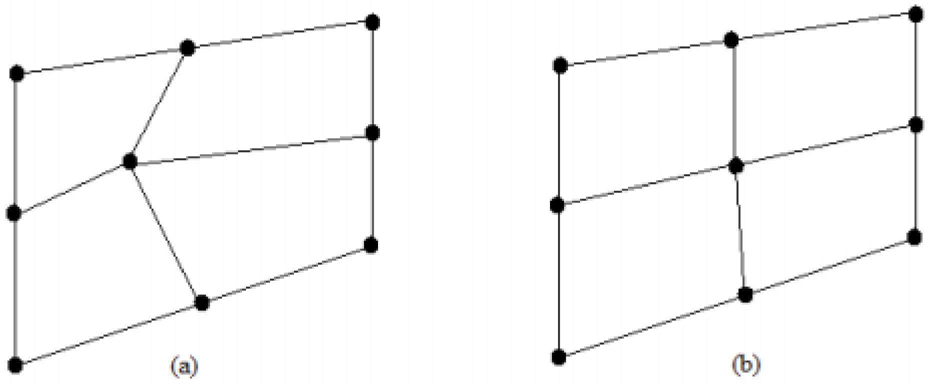


Figure **3.3**: (a) Initial local mesh, (b) Reallocating of the nodes

The AMP increases the accuracy of the simulation by reducing the number of errors during the calculation phase. As a result, AMP is always used in FE simulations where a large amount of plastic deformation has higher chance of occurring. These simulations can be of a simple process such as metal cutting or a complex process such as metal forming.

CHAPTER IV

MODELLING AND SIMULATION

4.1 Introduction

The modeling phase of a metal cutting simulation is the most integral step to achieving accurate results. A small error in design input can greatly alter the results. In this chapter, we will discuss the details of the modelling process and parameters for both tool and workpiece.

4.2 Tool Modelling

In this study, the cutting tool is assumed to be a rigid body. The geometric constants of the tool are given in Table 4.1.

Table 4.1: Geometric constants of the tool (WC)

Clearance Angle, $\boldsymbol{c}$ (°)	Rake Angle, $\boldsymbol{\alpha}$ (°)	Tip Radius, $\boldsymbol{r}_T$ (mm)
4°	0°	0.05

Tool used for this research was uncoated tungsten carbide (WC) the physical properties of which are given in Table 4.2.

Table 4.2: Physical properties of tungsten carbide (WC)[16]

Elastic Modulus, *E* (MPA)	65 x 10^4
Poisson's Ratio, *v*	0.25
Thermal Expansion (1/ºC)	5.10
Thermal Conductivity (N/sec/ºC)	50
Heat Capacity (N/mm2 ºC)	4

FE mesh of the tool is modelled while using a total number of 2085 nodes and 1852 elements. The distribution of mesh on the tool is modelled high on the tooltip and a part of the rake face to reduce the computational time.

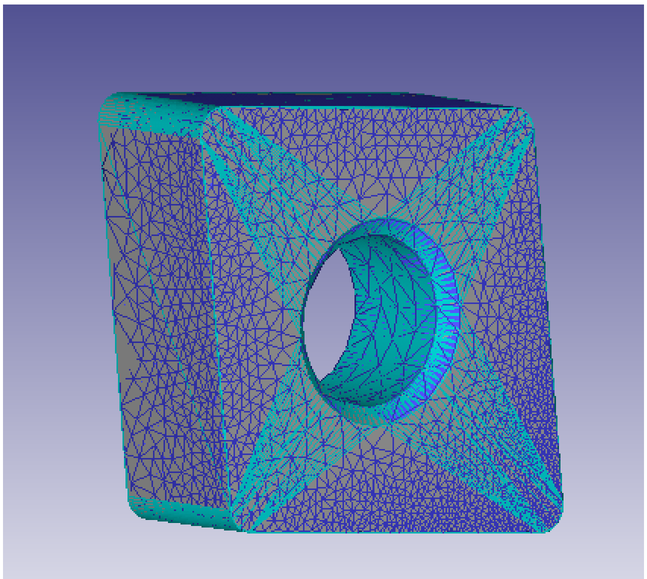


Figure 4.1: Mesh design of the tool

4.3 Workpiece Modelling

Modeling of the workpiece geometry is also of equal importance in order to achieve acceptable results. In the analysis, Ti-6Al-4V is used as the workpiece material. The JCk material damage model is used to predict the plastic behaviour of Ti-6Al-4V.

$$\sigma_{eq} = [A + B\varepsilon_p^n]\left[1 + C\ln\left(\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_0}{T_{melt} - T_0}\right)^q\right]$$

The JC material constants used in this research are listed in table 4.3.

Table 4.3: J–C material constants for Ti-6Al-4V[5, 17]

A (MPa)	B (MPa)	C	n	m
862	331	0.012	0.34	0.8

Table 4.4: J–C failure parameters for Ti-6Al-4V[5, 17]

D_1	D_2	D_3	D_4	D_5
-0.09	0.25	-0.5	0.014	3.87

During this analysis, it is assumed that the workpiece does not undergo any elastic deformation but rather it shows only plastic behaviour. The FE mesh of the workpiece is modeled using 5630 nodes and 4985. As in the case of tool mesh, mesh density in the workpiece is kept high near the contact region of the deformation zone to reduce the calculation time and to find more precise results (Figure 4.2).

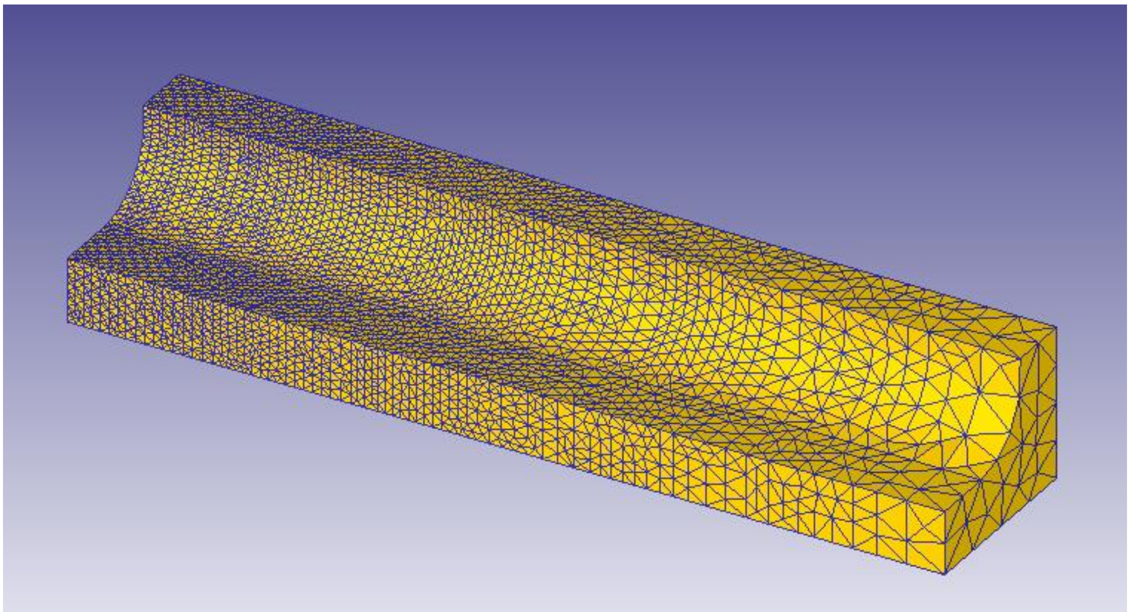


Figure 4.2: Mesh design of the workpiece

4.4 System Modelling

After modeling the tool and the workpiece individually, the next step is to assemble them and apply the boundary conditions and the cutting conditions. Figure 4.3 shows the 3d schematics of the tool-WP interaction.

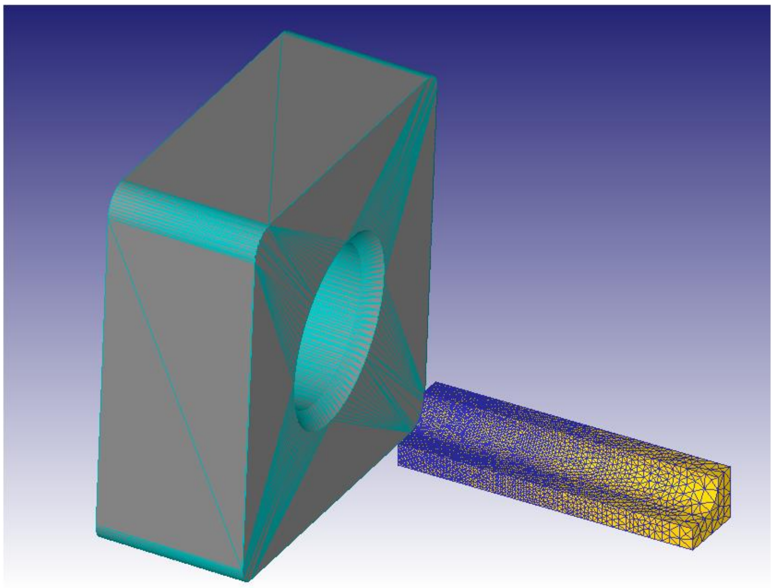


Figure 4.3: Mesh design of tool and workpiece assembly

The main focus of this research was to compare the effects of changes in cutting velocity, feed rate, and depth of cut. A total of nine combinations are used in this research this (Table 4.4).

Table 4.5: Cutting conditions[18]

Sr. no.	Feed rate (*mm/rev*)	Cutting velocity (*m/min*)	Depth of cut (*mm*)
1.	0.12	50	1
2.	0.12	100	1.5
3.	0.12	150	2
4.	0.16	50	1.5
5.	0.16	100	2
6.	0.16	150	1
7.	0.2	50	2
8.	0.2	100	1
9.	0.2	150	1.5

CHAPTER V

RESULTS

In this study, a mechanical 3D model of oblique metal cutting process is presented. In results we can observe the chip to be of serrated nature. The developed model can predict the cutting forces, chip shape and thicknesses, shear angles as well as temperature, strain, strain rate, and stress distributions.

In this study, all the variables were kept constant except for three namely cutting velocity, feed rate, and depth of cut. A total of nine combinations of these variables were used in the study. The details of these combinations are given in the previous chapter. Here we will briefly discuss the simulation results with the help of graphs.

In addition to the cutting forces, chip morphology and chip formation are also studied in this thesis. A graphical representation of the chip formation process is also discussed in this chapter.

5.1 Cutting Force Distributions

The results obtained from simulation results are compiled into a graph form and are shown here for discussion.

Experiment no. 1:

Feed Rate = *0.12 mm/rev*

Cutting Velocity = *50 m/min*

Depth of Cut = *1.0 mm*

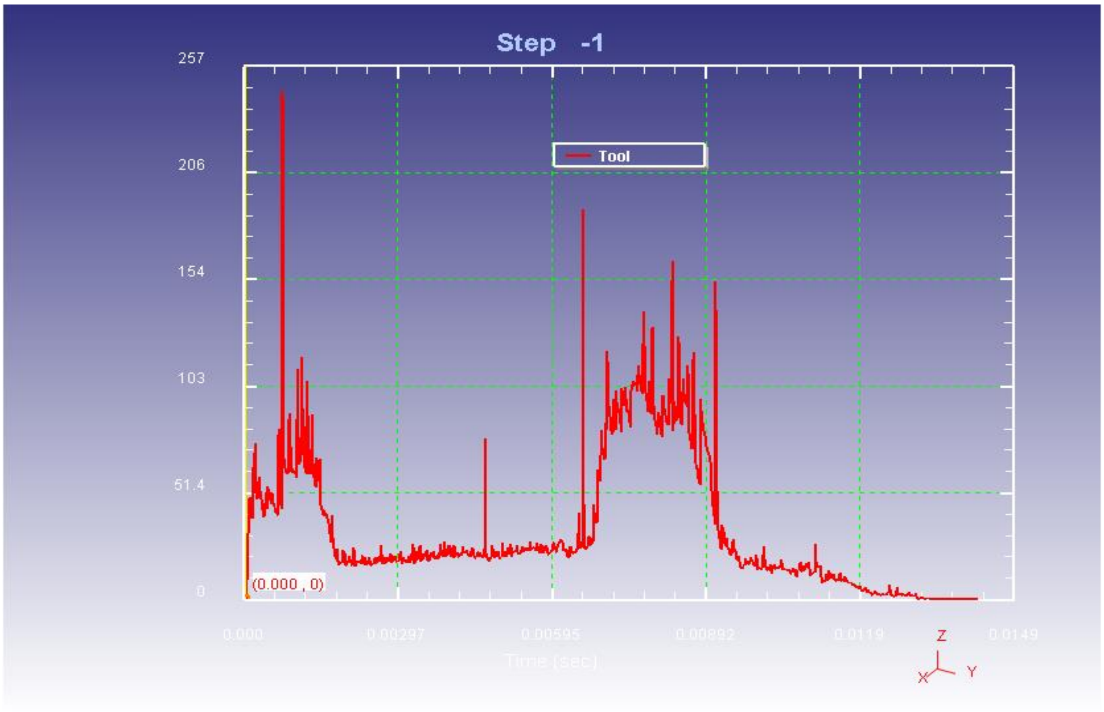


Figure 5.1: Results of cutting forces from exp. no. 1

Experiment no. 2

Feed Rate = *0.12 mm/rev*

Cutting Velocity = *100 m/min*

Depth of Cut = *1.5 mm*

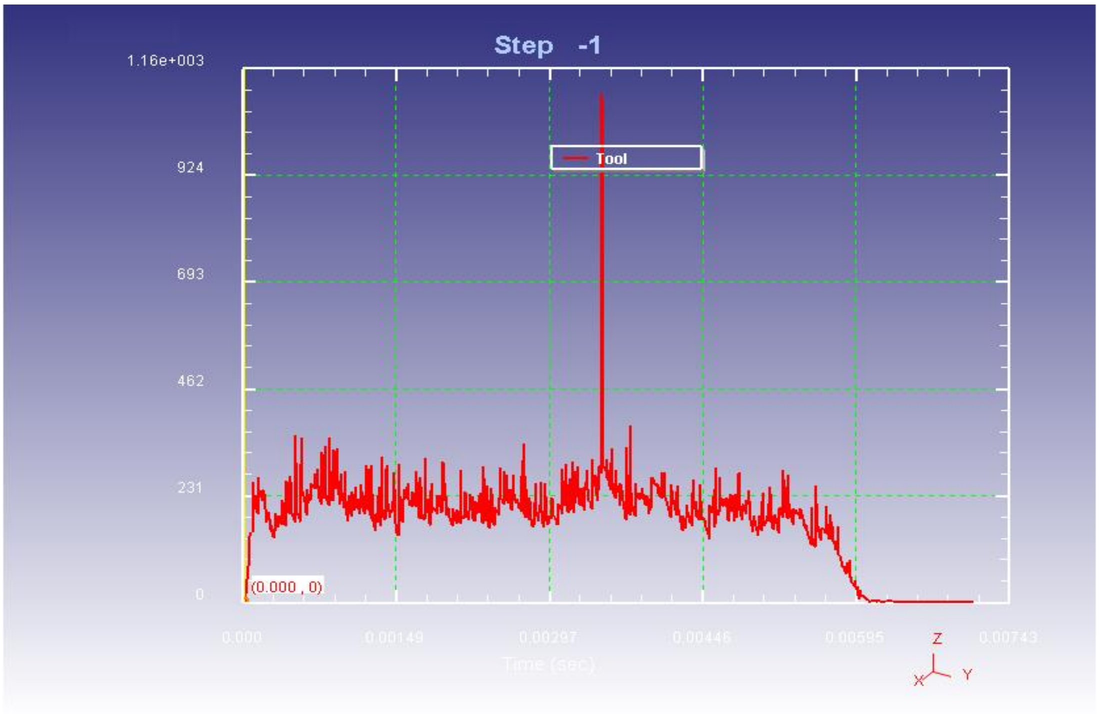


Figure 5.2: Results of cutting forces from exp. no. 2

Experiment no. 3

Feed Rate = *0.12 mm/rev*

Cutting Velocity = 1*50 m/min*

Depth of Cut = *2.0 mm*

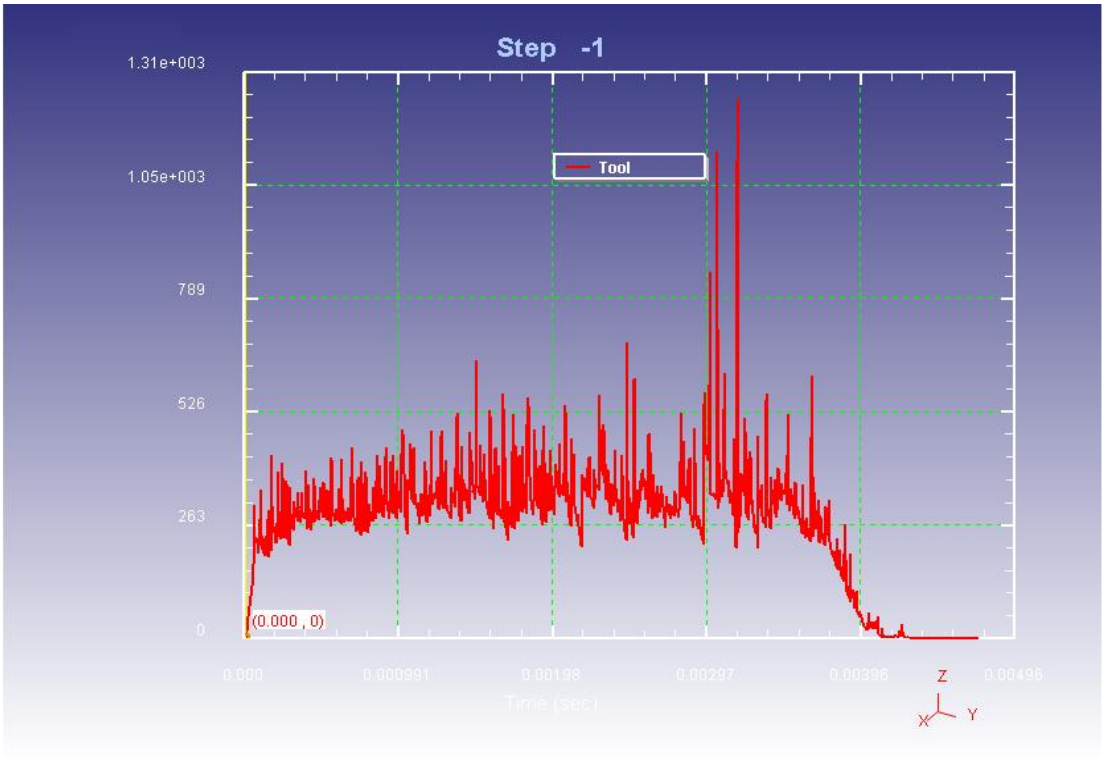


Figure 5.3: Results of cutting forces from exp. no. 3

Experiment no. 4

Feed Rate = *0.16 mm/rev*

Cutting Velocity = *50 m/min*

Depth of Cut = *1.5 mm*

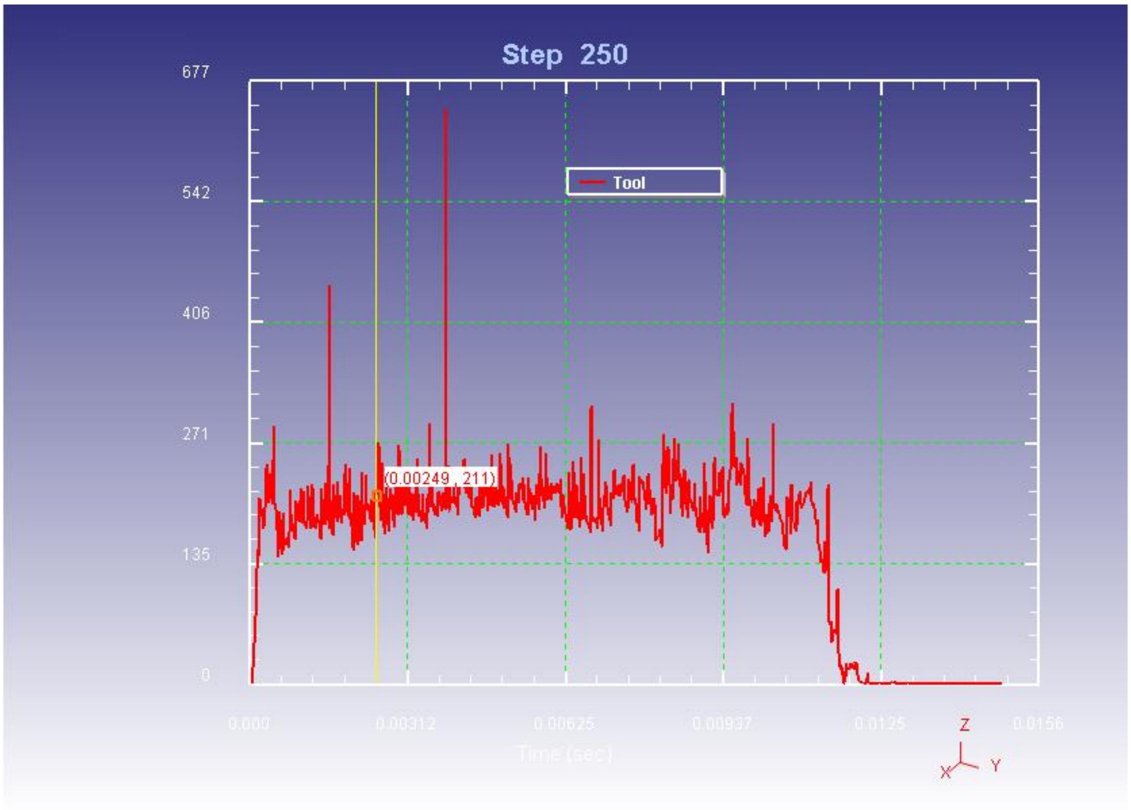


Figure 5.4: Results of cutting forces from exp. no. 4

Experiment no. 5

Feed Rate = *0.16 mm/rev*

Cutting Velocity = *100 m/min*

Depth of Cut = *2.0 mm*

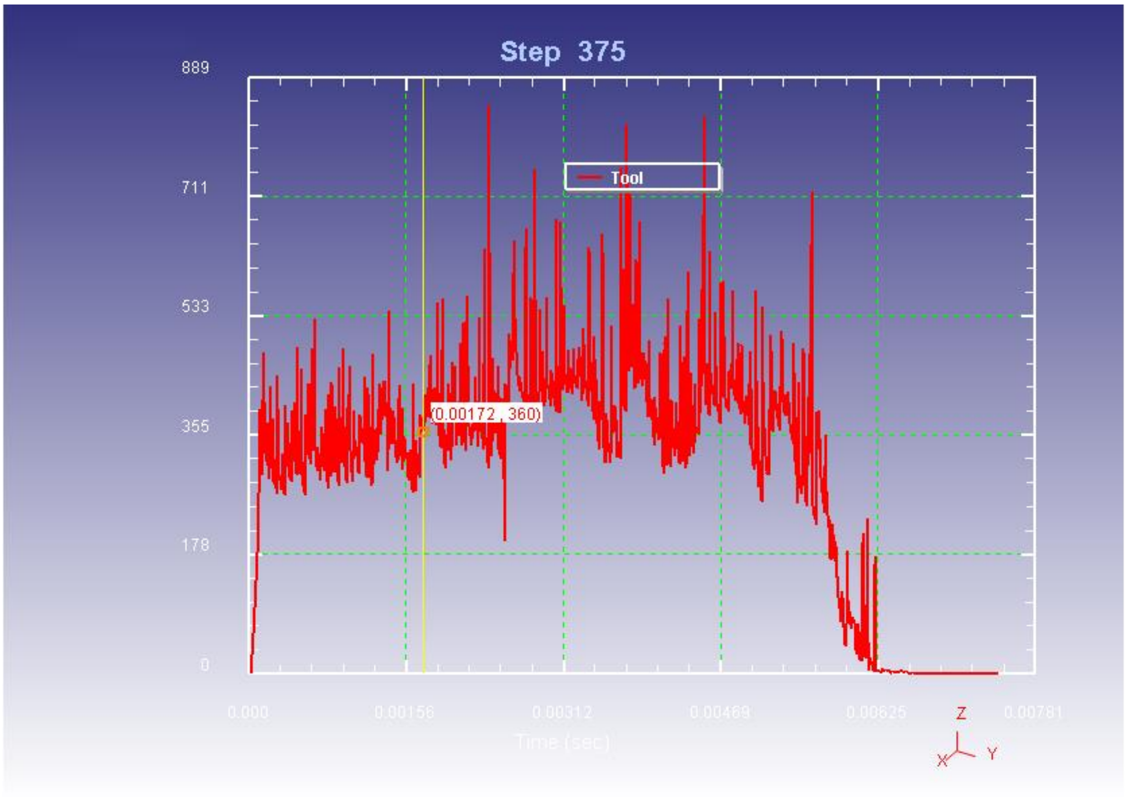


Figure 5.5: Results of cutting forces from exp. no. 5

Experiment no. 6

Feed Rate = *0.16 mm/rev*

Cutting Velocity = 1*50 m/min*

Depth of Cut = *1.0 mm*

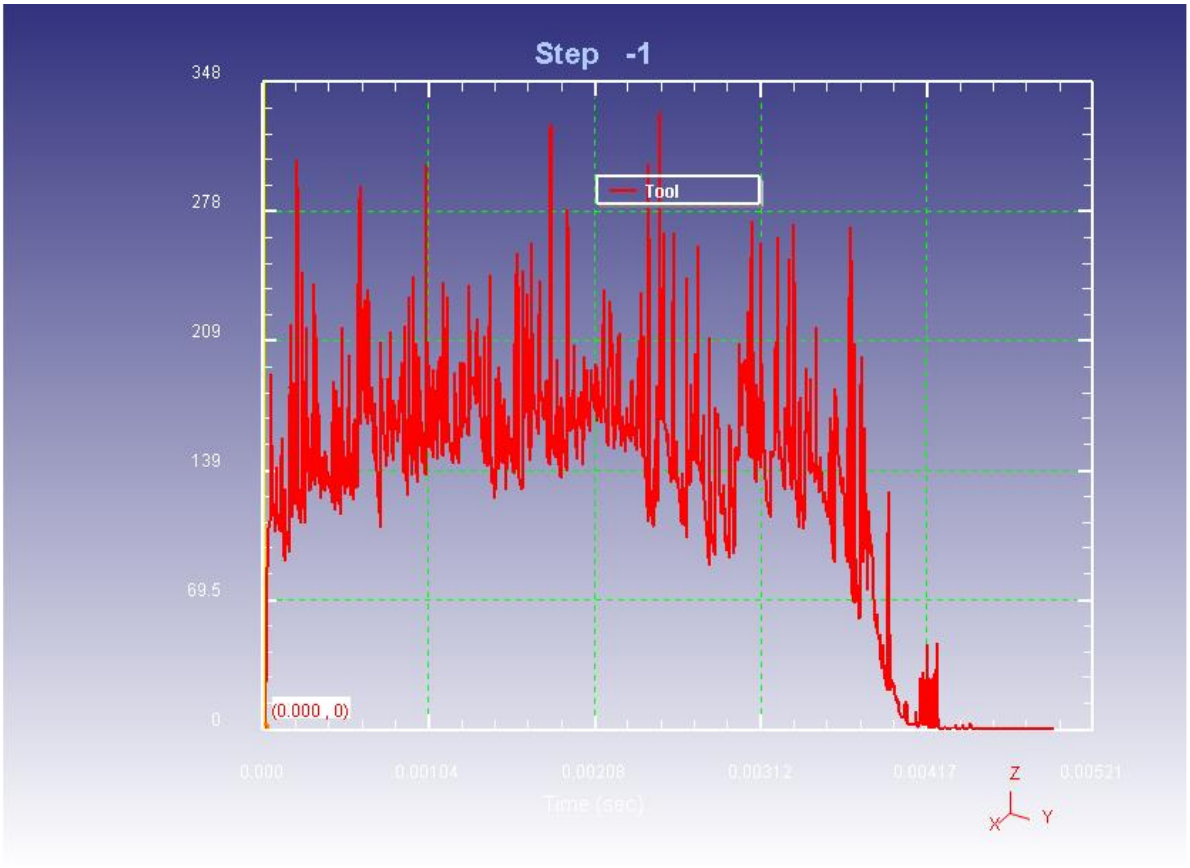


Figure 5.6: Results of cutting forces from exp. no. 6

Experiment no. 7

Feed Rate = *0.20 mm/rev*

Cutting Velocity = *50 m/min*

Depth of Cut = 2.*0 mm*

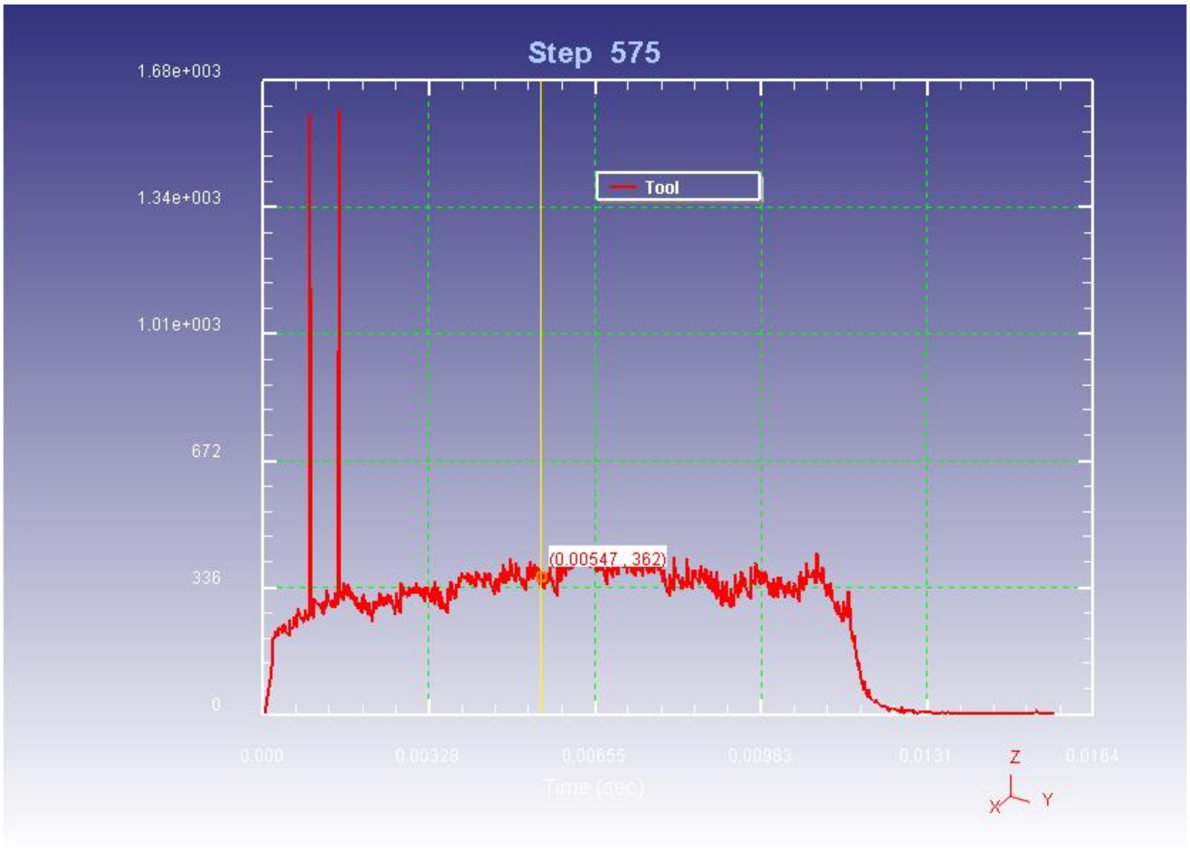


Figure 5.7: Results of cutting forces from exp. no. 7

Experiment no. 8

Feed Rate = *0.20 mm/rev*

Cutting Velocity = *100 m/min*

Depth of Cut = *1.0 mm*

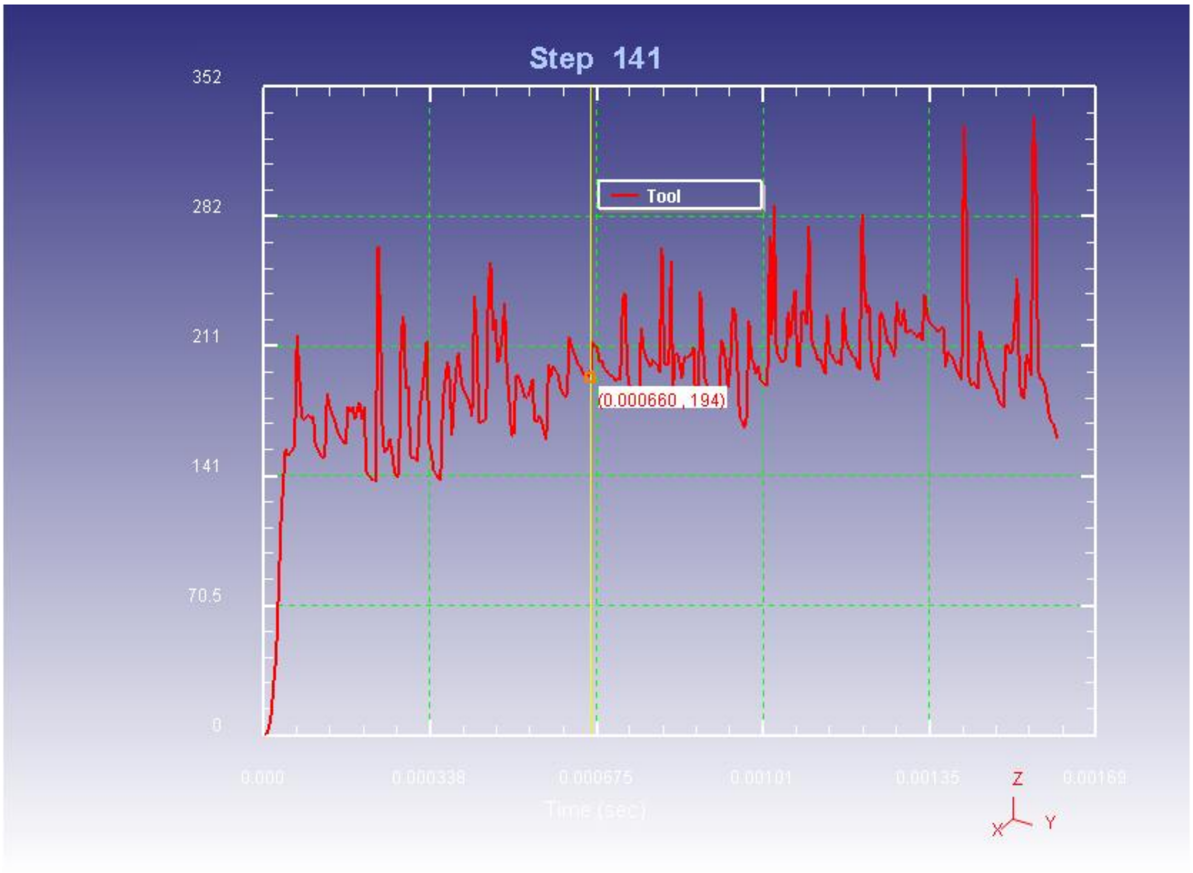


Figure 5.8: Results of cutting forces from exp. no. 8

Experiment no. 9

Feed Rate = *0.20 mm/rev*

Cutting Velocity = 1*50 m/min*

Depth of Cut = *1.5 mm*

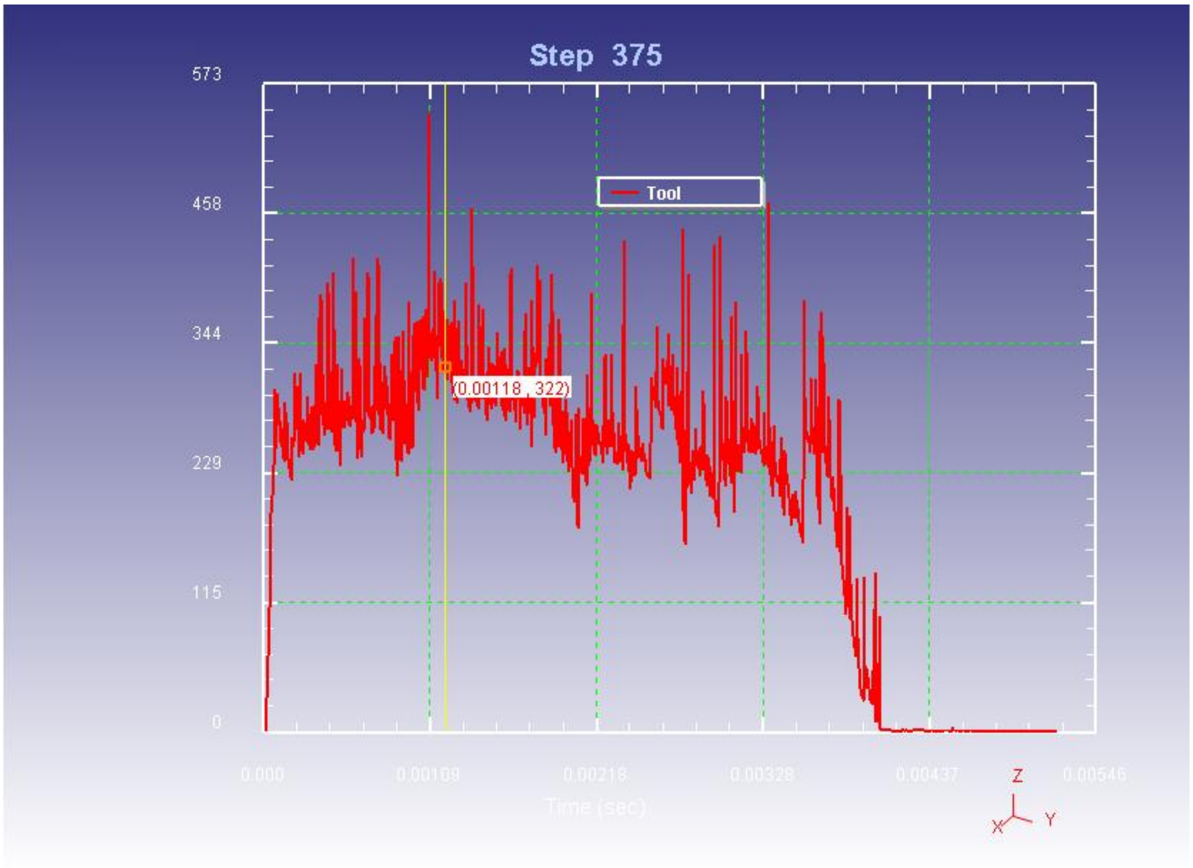
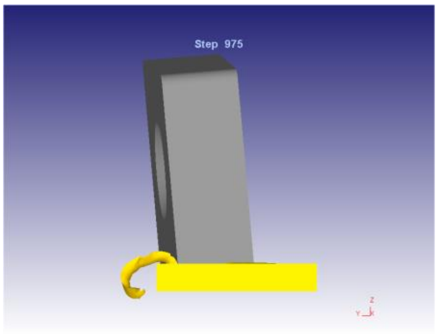


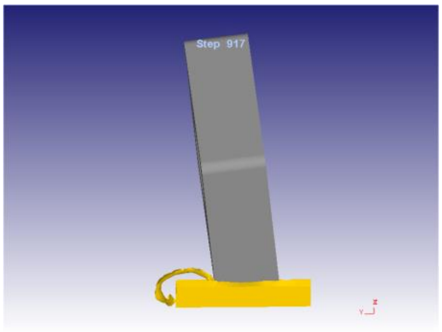
Figure 5.9: Results of cutting forces from exp. no. 9

5.2 Chip Morphology

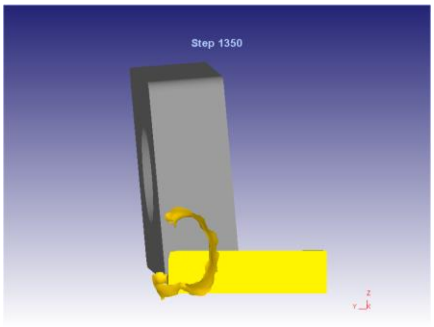
Chips are a bi-product result of a machining process such as material cutting, turning, drilling, or boring through a mechanical operation. In this study, specific attention was given to the chips that were formed as a result of each experiment. Graphical representation of these chips are given below:



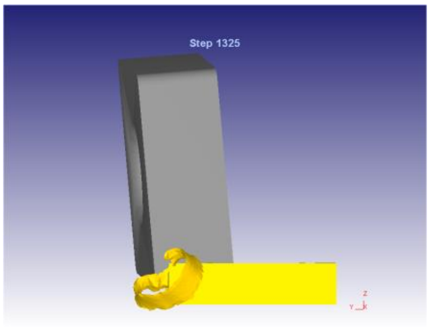
Experiment no. 1



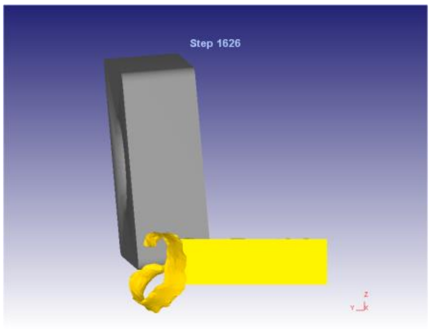
Experiment no. 2



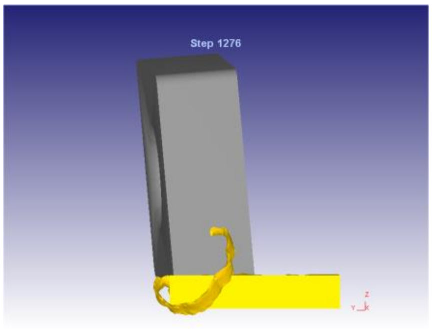
Experiment no. 3



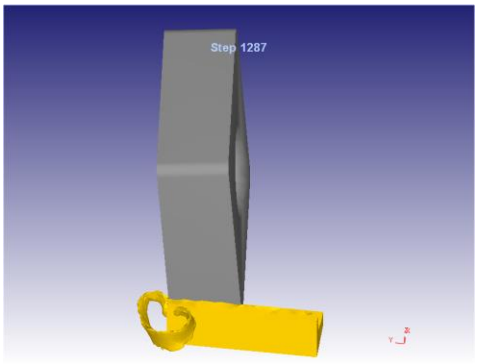
Experiment no. 4



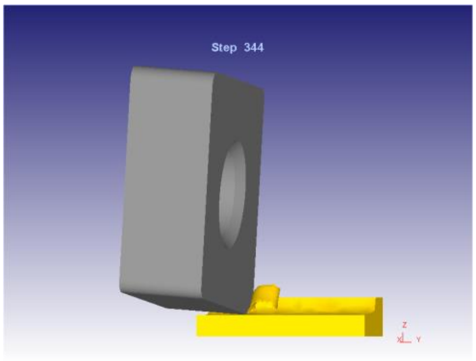
Experiment no. 5



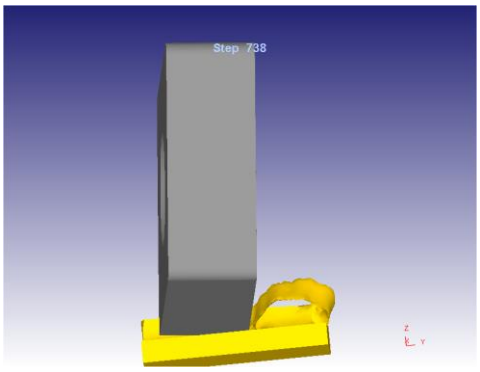
Experiment no. 6



Experiment no. 7



Experiment no. 8



Experiment no. 9

Figure 5.10: Results of chip formation of the simulation

CHAPTER VI

CONCLUSION AND DISCUSSION

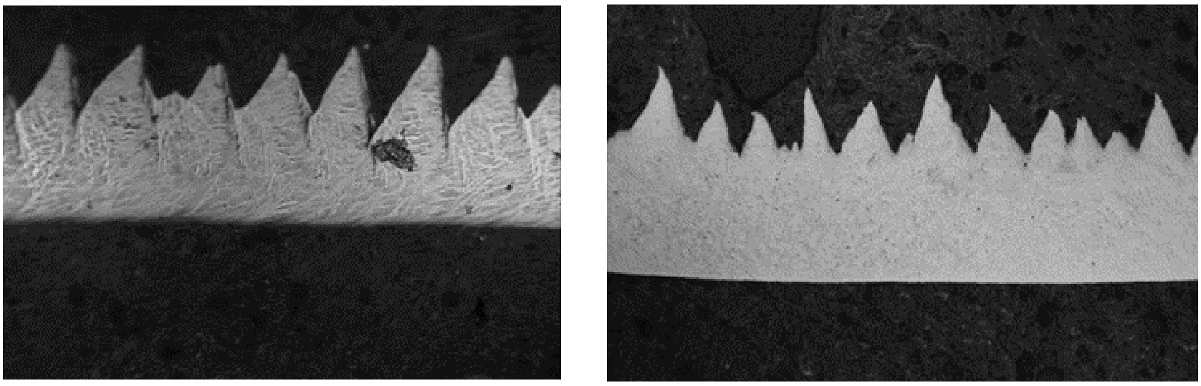
6.1 Conclusion

In common practice, it is not possible to accurately calculate the parameters for a JC Model for materials of interest in the same temper, grain size, etc., as used in cutting experiments. Finding the values of JC model parameters was exceptionally hard since only a limited amount of experimental research data is available for the machining of Ti_6Al_4V.

Before this simulation project, a predecessor of mine named Dr. Muhammad Yunous conducted a lab experiment for finding the actual values of the titanium alloys machining process. In this project, a lot of their data has been used and compared for reference as well. In this section, the findings from both of our research will be compared briefly and discussed. Also, future recommendations will be presented for future researchers to continue the work.

6.1 Chip Morphology

A key aspect of metal cutting is the chip formation process that can reveal information about the cutting process. In this research, a pattern has been noticed that machining of titanium alloys generally produces segmented chips as shown in figure 6.1.



(a) (b)

Figure 6.1: Chip morphology of titanium alloys

(Source: Muhammad Yonuas et. all 2021)

6.2 Discussion

The results show that with the increase in cutting velocity and/or feed rate, the wear rate R also increases as shown in figures 5.1-5.9. This increase can be a result of the longer tool-workpiece contact duration at the interface that increases the period for which the tool is in contact with the workpiece and as a result, it experiences higher forces and deteriorates more.

Furthermore, higher tool velocity (*v*) and tool feed rate (*f*) are also the cause of higher localized temperature at the contact point. It is because of higher cutting velocity, the material removal rate is also higher which means the energy is being dissipated in form of temperature at the point of contact.

In addition, the analysis of the chips formed, showed that at the higher cutting speed it is also higher and as a result, the shear plane angle is lowered and the SCE is increased.

The results also proposed that the cutting conditions i.e.

- $V = 100$ m/min
- $f = 0.16$ mm/rev

are best suited for the dry turning of Ti-6Al-4V alloy while using the uncoated tools. This can improve the material removal rate (MRR) can be improved up to 127% as long as the appropriate cutting parameters are used.

6.3 Recommendations

The results show that the cutting condition ranges (V = 55–70 m/min and f = 0.16−0.2mm/rev) gives different results for every run. The tool wear and cutting forces are observed to range from very high to very low. More investigation is recommended in this area.

The optimal cutting conditions are recognized in the previous topic. These conditions can be used and observed very closely for further improvements. In addition, if the reason(s) for the wide variations in results for the ranges (V = 55–

70 m/min and *f = 0.16−0.2mm/rev*) is understood then both these findings can be used at the same time for increasing the tool life and in return increasing the process efficiency and thus decreasing the manufacturing cost parts/products made from Ti-6Al-4V.

Alternate material failure models can also be implemented in place of the Johnson-Cook damage model in the Simulation, to check their suitability against the experimental results. And other specialized machining simulation software (ABAQUS, Advant-Edge, etc.) may be checked for more robust and quick solutions.

References

1. Takeyama, H. and R. Murata, *Basic investigation of tool wear*. 1963.
2. Milton, C.S. and M. Shaw, *Metal cutting principles.* ed: Clarendon Press, Oxford Science Publication, UK, 1984.
3. Mamalis, A., et al., *Finite element simulation of chip formation in orthogonal metal cutting.* Journal of Materials Processing Technology, 2001. **110**(1): p. 19-27.
4. Özel, T., et al., *Investigations on the effects of multi-layered coated inserts in machining Ti–6Al–4V alloy with experiments and finite element simulations.* CIRP annals, 2010. **59**(1): p. 77-82.
5. Chen, G., et al., *Finite element simulation of high-speed machining of titanium alloy (Ti–6Al–4V) based on ductile failure model.* The International Journal of Advanced Manufacturing Technology, 2011. **56**(9): p. 1027-1038.
6. Vijay Sekar, K. and M. Pradeep Kumar, *Finite element simulations of Ti6Al4V titanium alloy machining to assess material model parameters of the Johnson-Cook constitutive equation.* Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2011. **33**(2): p. 203-211.
7. Komvopoulos, K. and S. Erpenbeck, *Finite element modeling of orthogonal metal cutting.* 1991.
8. Kalpakjian, S., *Manufacturing engineering and technology*. 2001: Pearson Education India.
9. Ehmann, K., et al., *Machining process modeling: a review.* Journal of Manufacturing Science and Engineering, Transactions of the ASME, 1997. **119**(4B): p. 655-663.
10. Guo, Y. and C. Liu, *3D FEA modeling of hard turning.* J. Manuf. Sci. Eng., 2002. **124**(2): p. 189-199.
11. Arrazola, P.J., *Investigations on the effects of friction modeling in finite element simulation of machining.* International journal of mechanical sciences, 2010. **52**(1): p. 31-42.
12. Johnson, G.R., *A constitutive model and data for materials subjected to large strains, high strain rates, and high temperatures.* Proc. 7th Inf. Sympo. Ballistics, 1983: p. 541-547.
13. DiLellio, J.A. *Signal-In-Space User Range Error Assessment via Combined Space and Ground-based Measurement Data*. in *Proceedings of the 15th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2002)*. 2002.
14. Teng, X., T. Wierzbicki, and H. Couque, *On the transition from adiabatic shear banding to fracture.* Mechanics of Materials, 2007. **39**(2): p. 107-125.
15. Thepsonthi, T. and T. Özel, *Experimental and finite element simulation based investigations on micro-milling Ti-6Al-4V titanium alloy: Effects of*

cBN coating on tool wear. Journal of Materials Processing Technology, 2013. **213**(4): p. 532-542.

16. Zhang, Y., J. Outeiro, and T. Mabrouki, *On the selection of Johnson-Cook constitutive model parameters for Ti-6Al-4 V using three types of numerical models of orthogonal cutting.* Procedia Cirp, 2015. **31**: p. 112-117.
17. Akram, S., et al., *Numerical and experimental investigation of Johnson–Cook material models for aluminum (Al 6061-T6) alloy using orthogonal machining approach.* Advances in Mechanical Engineering, 2018. **10**(9): p. 1687814018797794.
18. Younas, M., et al., *Development and analysis of tool wear and energy consumption maps for turning of titanium alloy (Ti6Al4V).* Journal of Manufacturing Processes, 2021. **62**: p. 613-622.