FINITE ELEMENT SIMULATION OF MACHINING AISI 1045 STEEL USING UNCOATED CARBIDE TOOL

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ABSTRACT

In recent years, finite element methods (FEM) have become widely used in research and industrial applications because of the advancements in computational efficiency and speed. FEM is a useful tool for the analysis of metal cutting process where this method provide better prediction of process variables whereas interaction of the tool and the chip can also be examined. Much cutting force models have been developed to predict the machining parameter. Most focus mainly on dry conditions even though coolants are widely used in practical machining. Research for modeling of minimal quantity lubricant (MQL) conditions is scarce and not really established. The use of coolants in machining makes it very difficult to determine the friction coefficient at the tool-chip interface. Hence, a better understanding of friction modeling is required in order to produce more realistic finite element models of machining process. In this study, a rigorous investigation on the role played by the implemented friction model within a 2D simulation was carried out. The simulation tool used for the purpose of this study is DEFORM2D. DEFORM 2D can simulate large deformation accompanied by elastic, plastic, thermal and friction effects. The simulation results on cutting forces and temperature were compared with experimental measurement in order to verify wether it is possible to identify the best friction model and indicate the consistency and accuracy of the results when conducting the comparison. From the result, it shows that friction models affect predicted result for both cutting force and temperature in dry and MQL conditions.

ABSTRAK

Beberapa tahun kebelakangan ini, kaedah unsur terhingga (FEM) telah digunakan secara meluas dalam bidang penyelidikan dan perindustrian disebabkan oleh kemajuan dan kecekapan dalam pengiraan. FEM adalah kaedah yang berguna untuk analisis proses pemotongan logam di mana kaedah ini menyediakan ramalan yang lebih baik bagi pembolehubah proses manakala interaksi antara mata alat dan tatal juga boleh diperiksa. Banyak model daya pemotongan telah dibangunkan untuk meramal parameter pemesinan. Tumpuan paling utama adalah pada keadaan kering walaupun bahan penyejuk digunakan secara meluas dalam proses pemesinan yang praktikal. Penyelidikan untuk pemodelan bagi keadaan kuantiti minima pelincir (MQL) adalah terhad dan tidak benar-benar dibuktikan. Penggunaan bahan penyejuk dalam proses pemesinan menyukarkan pekali geseran untuk ditentukan. Oleh itu, pemahaman yang baik bagi model geseran diperlukan untuk menghasilkan model unsur terhingga yang lebih realistik dalam proses pemesinan. Dalam kajian ini, penyiasatan yang rapi mengenai peranan yang dimainkan oleh model geseran telah dijalankan menggunakan simulasi 2D. Perisian FEM yang digunakan untuk tujuan kajian ini adalah DEFORM 2D. DEFORM 2D mampu menjalankan simulasi bagi ubah bentuk yang besar yang disertai oleh elastik, plastik, kesan haba dan geseran. Keputusan simulasi daya pemotongan dan suhu dibandingkan dengan pengukuran eksperimen untuk mengesahkan jika ia adalah mungkin untuk mengenalpasti model geseran terbaik dan menunjukkan ketepatan keputusan semasa perbandingan dilakukan. Keputusan menunjukkan bahawa model geseran mempengaruhi hasil yang diramal untuk daya pemotongan dan suhu dalam keadaan MQL dan kering.

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LIST OF SYMBOLS

V_c - Cutting speed (m/min)
f_r - Feed (mm/rev)
d - Depth of cut (mm)
F_r - Resultant force (N)
F_t - Thrust force (N)
F_c - Cutting force (N)
F_f - Frictional force (N)
N - Normal force (N)
m - Mass(kg)
g - Gravity(m/s2)
μ - Coefficient of friction
α - Rake angle (°)
β - Clearance angle (°)
t_o - Uncut chip thickness (mm)
t_c - Chip thickness (mm)
l_c - Contact length (mm)
ALE - Arbitrary Lagrangian Eularian
BUE - Built up edge
FEM - Finite element method
MQL - Minimal Quantity Lubricant
NDM - Near dry machining

CHAPTER 1

INTRODUCTION

1.1 Introduction

Metal cutting is a process in which, by action of a cutting edge (or edges) of a tool, unnecessary material is removed. It is one of the most common manufacturing processes for producing parts and obtaining specified geometrical dimensions and surface finish. Many studies and experiments were performed since beginning of the 20th century. One of the widely used machining processes is turning process. Turning is a process of removing excess material from the work piece to produce an asymmetric surface, in which the work piece rotates in a spindle and the tool moves in a plane perpendicular to the surface velocity of the job at the tool-job operation. Turning operations are performed on a machined tool called lathe and the process is shown in Figure 1.1.

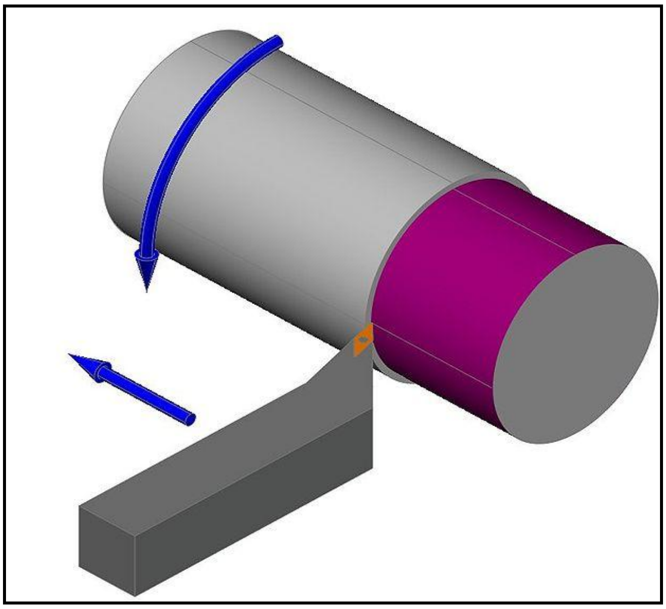


Figure 1.1: Turning Process

The performance of a turning operation is greatly influenced by the application of cutting fluid, and, in this regard, turning operations can be classified into dry turning, turning with minimum quantity lubrication (MQL), flood turning, and cryogenic turning. Of these, flood turning is the most traditional technique and by far the most widely used in industry. The two major functions of cutting fluids are (i) to increase tool life and (ii) to improve the surface finish of manufactured parts. However, with the advent of various new tool materials and their deposition techniques, the tool lives of modern tools have increased significantly. Dry turning is characterised by the absence of any cutting fluid, and unlike MQL and cryogenic turning does not require any additional delivery system [1] .Consequently, dry turning has gained renewed interest for its potential environmental and economic benefits. Nevertheless, in spite of all its economic and environmental benefits, the dimensional accuracy and surface finish of component parts produced by dry turning should not be sacrificed [2]. In minimal quantity lubrication (MQL), a very small lubricant flow (ml/h instead of l/min) is used. In this case, the lubricant is directly sprayed on the cutting area. It guarantees a good level of lubrication, but the cooling action is very small and the chip removal mechanism is obtained by the air flow used to spread the lubricant [3].

1.2 Problem Statement

In recent years, finite element methods (FEM) have become widely used in research and industrial applications because of the advancements in computational efficiency and speed. FEM is a useful tool for the analysis of metal cutting process where this method provide better prediction of process variables whereas interaction of the tool and the chip can also be examined.

The understanding of interactions during the cutting process is a fundamental task where this knowledge enables tool makers to evaluate the performance of the cutting tool design. Besides, it also enables the users of cutting tools to evaluate the effects of the working conditions on tool life and on the quality of the final part. Many experimental observations with trial and error are needed for the optimization of cutting conditions. Furthermore, repeating the experiment to achieved desired optimized cutting condition will be expensive and time consuming. Hence, FEM is an effective method as it would decrease experimentation and reduce cost.

In addition, much cutting force models have been developed to predict the machining parameter. Most focus mainly on dry conditions even though coolants are widely used in practical machining. Beside, research for modeling of MQL conditions is scarce and not really established. As for FEM simulation of machining, the main problem is to determine the boundary conditions at the tool-chip interface. The use of coolants in machining makes it very difficult to determine the friction coefficient at the tool-chip interface. Hence, a better understanding of friction modeling is required in order to produce more realistic finite element models of machining process. The contact behavior between the chip and the tool is critical due to its effect on the tool performance. Furthermore, the coolant method will not only affect the friction coefficient but also the heat transfer coefficient between the tool and workpiece combination.

This study includes the effect of dry and MQL conditions on cutting force and temperature. It is expected that at the end of this project, a good agreement is obtained between simulation and experiment data to indicate that the simulation is capable of predicting cutting force and temperature.

1.3 Objective of study

The objectives of the proposed project are;

i. To study effect of various friction models, in order to predict the tool temperature and cutting force using FEM in two different conditions; dry and MQL.
ii. To investigate the effect of various heat transfer coefficient for MQL conditions.
iii. To validate the simulations results by comparing with experimental result for dry and MQL conditions.
iv. To propose the best possible friction model involved in dry and MQL turning process.

1.4 Scope of Study

The scopes of this study are:

i. Deform 2D version 9.0 software
ii. Simulation is performed in two conditions; dry and MQL
iii. Cemented carbide is used as cutting tool.
iv. Workpiece material is AISI 1045
v. Experiment are running in fixed condition; Cutting speed, V_c= 160 m/min, feed, f_r =0.15 mm/rev, depth of cut, d= 0.30 mm
vi. Friction model used are Coulomb, Shear, and Coulomb-Shear.

1.5 Rationale

The rationales of the present research are:

i. Finite element analysis give better prediction of turning variables such as cutting forces, workpiece and tool temperature which is essential to the optimization of cutting tool design and cutting conditions such that product quality, productivity, and tool life are maximized.

ii. FEM proved to be an efficient tool to optimize several industrial metal machining processes. The use of FEM in modeling of machining allows for considering process details that analytical models cannot handle and for predicting variables.

1.6 Overview

This study concentrates on finite element method used to simulate machining process. Simulations are running using the commercial software DEFORM 2D developed by Scientific Forming Technologies Corporation (STFC). Effects of machining parameters on cutting forces and temperature distribution are studied.

In Chapter 2, earlier experimental studies, results, and analyses reported in the literature on the topic are presented. General well known theories in metal cutting being discussed to well understand the mechanics of metal cutting. Literature on finite element analysis of machining also reviewed and discussed. Constitutive material model, material properties for these models, friction model are some of the important issues in the FEM simulation of metal cutting. Work reported in the literature addressing these issues is presented.

The experimental test procedure and the modelling of metal cutting are mentioned in Chapter 3. All results, both from experiments and simulations are given in Chapter 4. Simulations results are compared with the experimental results of this work. This work is discussed and concluded in Chapter 5. Some recommendations for future work are given in that chapter as well.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of literature related to experimental and numerical procedures, finite element method (FEM) in turning operation. Since finite element simulation is nowadays assuming a large relevance, many studies on this topic have been published. The present chapter starts with mechanics of metal cutting. Early attempts from the previous researchers considering development of FEM method are also being discussed.

2.2 Mechanics of Metal Cutting

Metal cutting is the process of removing unwanted material from the workpiece to obtain a part with high quality surfaces and accurate dimensions with acceptable tolerances. This process has represented a very large segment in industry since last century. It is estimated that 15 percent of the value of all mechanical components manufactured worldwide is derived from machining operations [4]. The metal cutting process includes different forms of machining process such as grinding, turning, milling, sawing, etc. For all these types of machining, the productions of chips have different forms and each process has unique chip morphology. Therefore, it is important to understand the mechanism of chip formation in order to understand the machining process.

In the middle of the 19th century, the old (trial and error) experimental method was the earliest way to develop models of the metal cutting process. The simplified models were also presented and used based on the shear zone theory [5]. The chip formation was assumed to take place as the result of shear actions in the shear zone. Later, finite element analysis was utilized, trying to optimize metal cutting processes. This opened a new way to investigate the state of stresses, strains, temperatures, and feed and cutting forces in the deformation zones. These models provide a better understanding of metal cutting and provided ways to do detailed studies of the effect of different parameters where the magnitude of some parameters such as the temperature cannot be easily measured experimentally.

2.2.1 Orthogonal Cutting

Metal cutting process can be divided into two basic categories; orthogonal and oblique metal cutting. In orthogonal metal cutting, the cutting edge is perpendicular to the relative cutting velocity and also normal to the feed direction, as shown in Figure 2.1. However in oblique cutting, the cutting edge is inclined at an acute angle to the direction of the cutting velocity as shown in Figure 2.2. During the machining, the tool will be given a certain position to obtain the amount of feed that will be removed from the workpiece. In general, the cutting edge of the tool will engage into the workpiece; therefore, high pressure and high temperature will occur at the front of the tool.

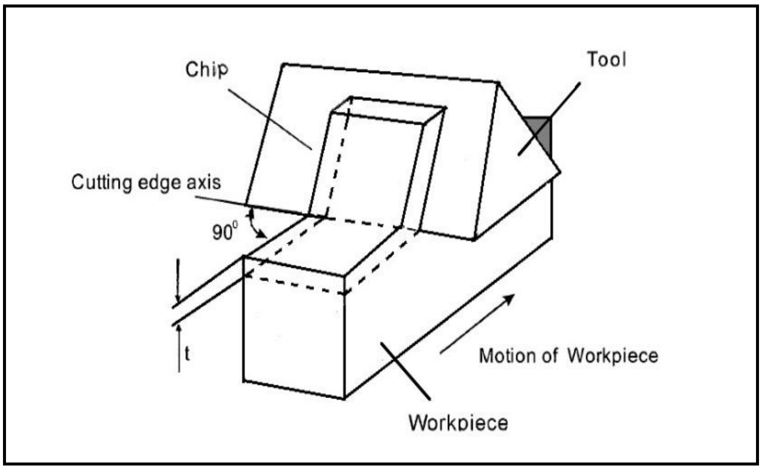


Figure 2.1: Orthogonal cutting geometry [6]

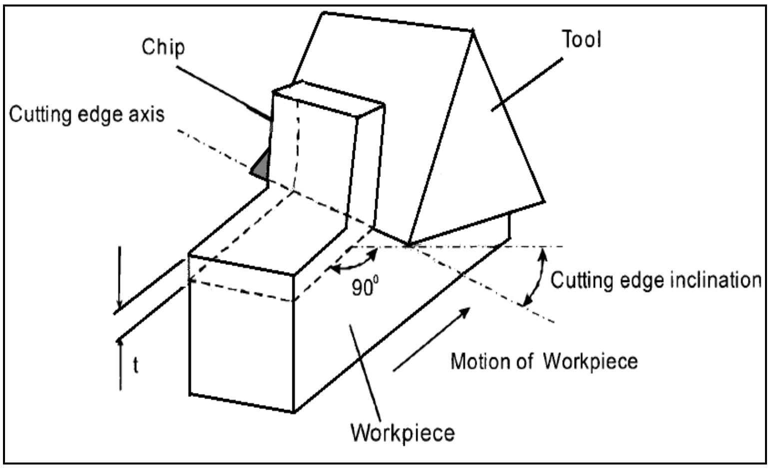


Figure 2.2: Oblique cutting geometry [6]

The easiest way to present the fundamentals of the orthogonal metal cutting process is by the two dimensional metal cutting geometry a shown in Figure 2.3. As the workpiece start moving, the cutting edge penetrates into the workpiece and forces the chip to grow up so that the chip will be formed and moved along the rake face of the tool. This process causes high pressure and plastic deformation is expected to take place in the front of the cutting edge. The shape of the formed chip will be affected by the cutting conditions (cutting speed, feed and depth of cut), tool geometry and material properties.

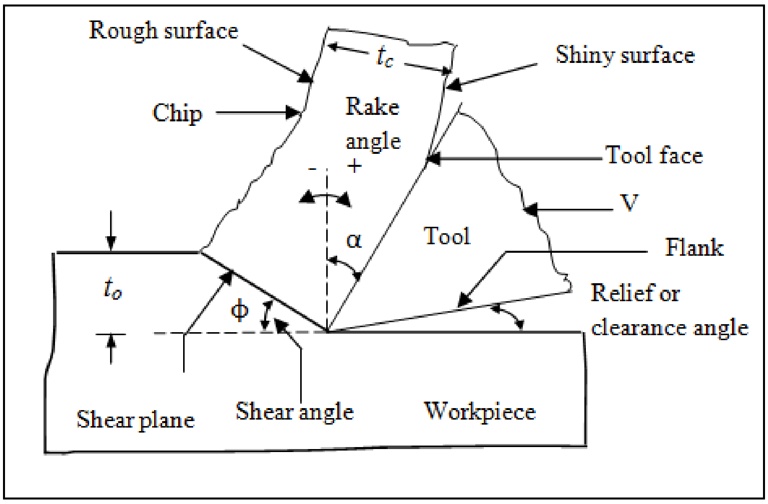


Figure 2.3: Schematic illustration of two-dimensional orthogonal cutting [7]

The uncut chip thickness (t_0) is known as the feed while the deformed chip has a different chip thickness (t_c). The tool will be defined by rake angle (α) and relief or clearance angle (β). The rake angle is defined to be positive on the right side (clockwise from vertical) and negative on the left side (counter clockwise). The contact length (l_c) is defined as the distance from the tip of the tool to the point where the chip loses contact with the tool on the rake face. The friction between the chip and the tool plays a significant role in the cutting process because of the heat energy that is transferred into the workpiece. It may be reduced by optimized tool geometry, tool material, cutting speed, rake angle, and cutting fluid. Because of the high pressure and temperature, a built up edge (BUE) may exist near the tool tip.

In orthogonal machining the shearing action takes place along the shear plane so the chip will start to flow over the rake face. The shearing zone has been modelled using either one of two assumptions. Merchant developed an orthogonal cutting model by assuming the shear zone to be thin as shown in Figure 2.4.

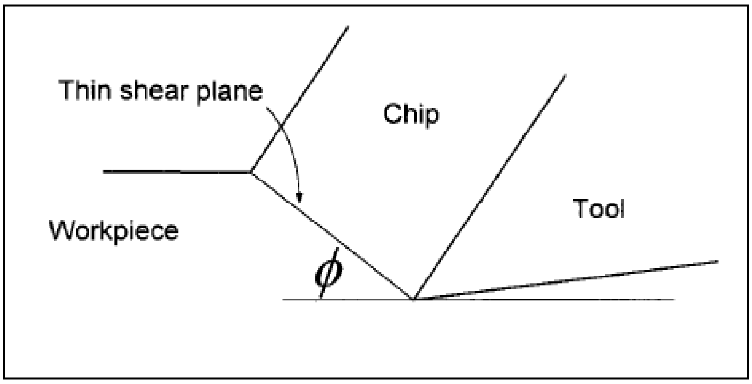


Figure 2.4: Thin shear plane model [6]

Once the material approaches the shear plane, the plastic deformations begins. A thin shear zone is usually created at high cutting speeds. Some researchers had different assumptions where the shear zone would be thick as shown in Figure 2.5. This kind of shear zone is more complicated and normally seen when using low cutting speeds.

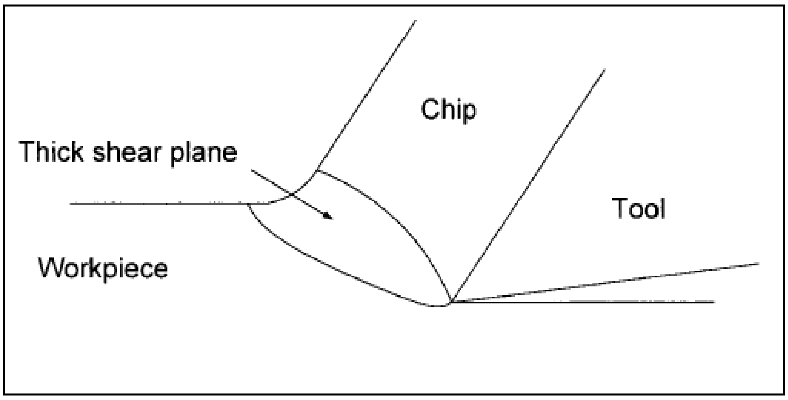


Figure 2.5: Thick shear plane model [6]

Both models have been used to analyze metal cutting processes where the thin shear zone relates to the shear plane angle, cutting condition, material properties, and friction behaviour, while the thick shear zone model is based on the slip-line theory [5].

2.2.2 Cutting Force in Turning

Knowing the forces that are acting in metal cutting is important for many reasons such as for the power requirement. Some parameters including the cutting speed, feed, and depth of cut influence the forces. Most likely, the forces can be reduced to two main forces in 2-D instead of three forces in 3-D.

In orthogonal cutting the resultant force (F_r) applied to the chip by the tool lies in a plane normal to the tool cutting edge (Figure 2.6). This force is usually determined, in experimental work, from the measurement of two orthogonal components: one in the direction of cutting (known as cutting force F_c), the other normal to the direction of cutting (known as thrust force F_t). The cutting or tangential force (F_c), acts downward on the tool tip allowing deflection of the workpiece upward. It supplies energy required for the cutting operation. The thrust force (F_t) acts in the longitudinal direction. It is also called the feed force because it is in the feed direction of the tool. This force tends to push the tool away from the chuck.

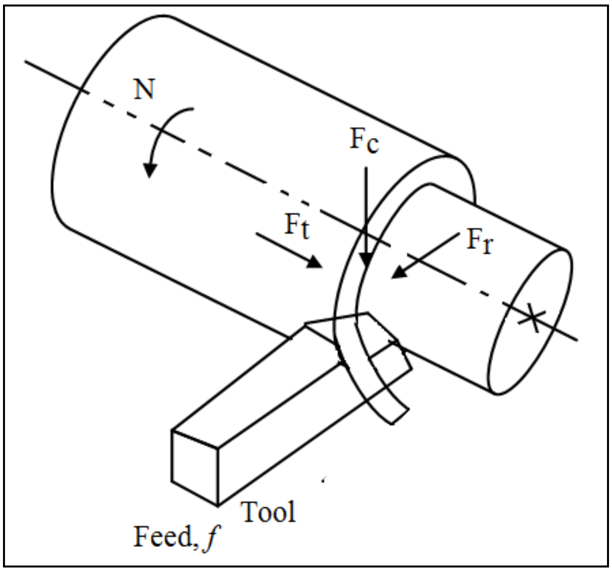


Figure 2.6: Cutting (F_c) and thrust (F_t) force components of resultant tool force (F_r)[6]

Many researchers have correlated the measured cutting force components acting on a tool with tool wear [8] relates the wear of the cutting tool to the temperatures and measured forces acting on the tool. Force is also considered by [9] in the determination of the temperature of a machine surface. He successfully shows that the forces acting on the flank face, even with sharp tool, have been shown to be the most significant contributor to the temperatures in the workpiece.

Force modeling in metal cutting is important for thermal analysis, tool life estimation, chatter prediction, and tool condition monitoring purposes. Significant efforts have been devoted to understanding the force profiles in metal cutting. Along with a laborious experimental approach, several numerical and analytical approaches have been proposed to model the chip formation process and the associated cutting forces. Finite element method (FEM) has been applied to simulate the machining process since the early 1970s. Since then, FEM with different derivatives has received widespread attention in numerical modelling of machining processes [10].

Although some successes have been gained in modelling the chip formation forces in metal cutting by FEM, it is not yet ready to be applied due to the fact that it is laborious and not very easily extended to practical 3-D turning cases.

2.2.3 Cutting Temperature in Turning

The total work done by the cutting tool in removing metal can be determined from the values of the forces components on the cutting tool. Approximately all of this work or energy is converted into heat, which is dissipated into the tool and workpiece material; the higher the forces on the tool, the more work is needed in material removal, which in turn affects temperature. At high temperature, the cutting tool if not enough hot hard may lose their stability quickly or wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life.

The magnitude of this cutting temperature increases, though in different degree, with the increase in cutting velocity, feed and depth of cut, as a result, high production machining is constrained by rise in temperature. This problem increases further with the increase in strength and hardness of the work material. Knowledge of the cutting temperature rise in cutting is important because increases in temperature will adversely affect the strength, hardness and wear resistance of the cutting tool, cause dimensional changes in the part being machined, making control of dimensional accuracy difficult and can induce thermal damage to the machined surface, adversely affecting its properties and service life.

Three regions of heat generation can be distinguished in turning; the shear zone, the chip-tool interface and the tool-workpiece interface (Figure 2.7). The primary shear zones temperatures affect the mechanical properties of the workpiece-chip material and temperatures at the tool-chip interfaces influence tool wear.

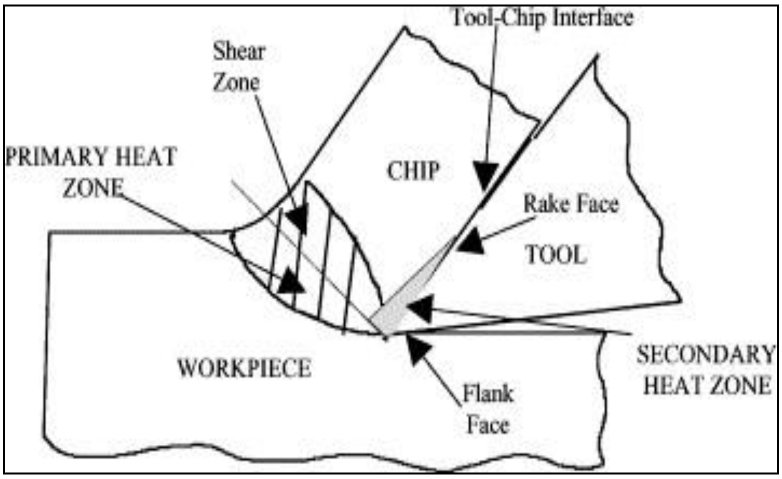


Figure 2.7: Region of heat generation in turning [11]

Much research has been undertaken into measuring the temperatures generated during cutting operations. The main techniques used to evaluate the temperature during machining (tool-chip thermocouple, embedded thermocouple, and thermal radiation method) have been reviewed by [12] and are discussed below. Thermocouples have always been a popular transducer used in temperature measurement. Thermocouples are very rugged and inexpensive can operate over a wide temperature range. A thermocouple is created whenever two dissimilar metals touch and the contact produces a small open-circuit voltage as a function of temperature. If these two dissimilar materials are the cutting tool and the workpiece material, then this thermocouple is called a tool-chip or tool-work thermocouple.

The tool-work thermocouple technique is used to measure the cutting temperatures at the interface between the tool and the chip. This technique is easy to apply but only measures the mean temperature over the entire contact area [13].High local of flash temperatures which may occur for a short period of time cannot be observed. Standard thermocouples embedded in the cutting tool or workpiece material can be used to measure the temperature at a single point or at different locations to establish the temperature distribution in the tool. They can also be positioned at the interface between an indexible insert and the tool holder. Standard thermocouples are readily available at low cost and can be supplied with different types of insulation depending on the application.

Embedded thermocouples have been found to provide a good indication of the transient changes in transient changes in frictional heat generation that accompany contact area changes. Cozzens et al. [14] use many thermocouples embedded in an aluminium tube. Temperature measurements were taken at various radial and longitudinal positions in the workpiece as the tool moved down the tube. From these results, the author develops a temperature distribution model. This model then accurately predicted the peak temperatures after a coolant was used for the same cutting tests.

2.3 Minimum Quantity Lubrication (MQL)

Minimum Quantity Lubricant (MQL), also known as Near Dry Machining (NDM) or semi-dry machining, is alternative to traditional use of cutting fluids. There are many similarities between dry machining and MQL, in fact, many research papers treat that true dry machining and MQL as the same technology. As the name implies, MQL uses a very small quantity of lubricant delivered precisely to the cutting surface. Often the quantity used is so small that no lubricant is recovered from the piece. Any remaining lubricant may form a film that protects the piece from oxidation or the lubricant may vaporize completely due to the heat of the machining process. With the large volumes of cutting fluid used in traditional machining, misting, skin exposure, and fluid contamination are problems that must be addressed to assure minimal impact on worker health. With MQL, the problem of misting and skin exposure is greatly reduced, and fluid does not become contaminated because it is not re-used [15].

In near-dry machining operations with MQL supply, however, secondary characteristics as biodegradability, oxidation stability and storage stability, are even more important because the lubricants must be compatible with the environment and chemically stable under long-term usage when there is a very low consumption rate

[16]. With this in mind, some description of lubricant performance regarding secondary characteristics is important. Because of biodegradability characteristics of synthetic ester and fatty alcohol as shown in Table 2.1:

Table 2.1: Characteristics of synthetic esters and fatty alcohol [17]

<table>
<tr><td>Synthetic Esters</td><td>Fatty alcohols</td></tr>
<tr><td>Chemically modified vegetables oils</td><td>Long-Chain alcohols made from natural raw materials or from mineral oils</td></tr>
<tr><td colspan="2">• Good biodegradability
• Low level of hazard to water
• Toxicologically harmless</td></tr>
<tr><td>• High flash and boiling point with low viscosity
• Very good lubrication properties
• Good corrosion resistance
• Inferior cooling properties
• Vaporizes with residuals</td><td>• Low flash and boiling point, comparatively high viscosity
• Poor lubrication properties
• Better heat removal due to evaporation heat
• Little residuals</td></tr>
</table>

There is report, which indicates that MQL in end-milling process is very much effective [18]. This is considered to be because lubricant can reach the tool face more easily in milling operations compared to other cutting operations. MQL with rapeseed oil has only a small lubricating effect in light loaded machining conditions [19]. This was because the boundary film formed on the tool surface is not strong enough to sustain low friction and to avoid adhesion of work material; but MQL with water droplets showed good lubrication performance during the same cutting conditions. MQL means only tiny quantities of a coolant are fed to the cutting process. With the use of very small amount of water and soluble oil, MQL uitilizes a compressed air stream to form an oil mist that is directed at the cutting edge. The fine oil mist is able to get close to the tool-chip and tool-workpiece interface, thereby reducing friction and cutting forces generated during machining. Temperature reduction at the cutting zone is achieved by its evaporation and vaporization, which differ from flood coolant application. Rahman et al. [20,21] used MQL in end milling of ASSAB 718HH steel and concluded that the MQL technique can be adopted as a replacement of dry cutting, and it may also be an alternative economic approach for flood coolant.

Wakabayashi et al. [22] also used the MQL technique in the turning process. They found that MQL provided satisfactory cutting performance compared with conventional flood coolant. Dhar et al. [23] employed MQL machining technique in turning AISI 4340 steel with uncoated carbide tool (SNMM 120408). During experimentation, process parameters such as cutting velocity, feed rate and depth of cut were kept constant at 110m/min, 0.16 mm/rev and 1.5mm respectively. Water-soluble cutting fluid was supplied at flow rate of 60 ml/h and mixed with compressed air prior to being impinged on the cutting zone at a high speed. Under same cutting conditions, MQL caused a significant reduction in tool wear and surface roughness as compared to dry and wet turning. Machado and Wallbank [24] conducted experiments on turning medium carbon steel AISI 1040 using a venture to mix compressed air (the air pressure was of 2.3 bar) with small quantities of a liquid lubricant, water soluble oil (the mean flow rate was in between 3 and 5 ml/min). The mixture was directed onto the rake face of carbide tool against the chip flow direction.

The application of mixture of air and soluble oil was able to reduce the consumption of cutting fluid, but it promoted a mist in the environment with problems of odours, bacteria and fungi growth of the overhead flooding system. For this reason, the mixture of air and water was preferred. However, even if the obtained results were encouraging, the system needed yet some development to achieve the required effects in terms of cutting forces, temperature, tool life and surface finish.

2.4 Finite Element Analysis

In recent years, finite element analysis has become the main tool for simulating metal cutting processes. Early analyses were made by [25] and [26] who analyzed the steady state orthogonal cutting. The goal of finite element analysis is to derived reliable computational models predicting the deformations, stresses and strains in the workpiece, as well as the loads on the tool working under specific parameters. Until the mid-1990s, most of the researchers used in-house finite element code; however, the use of commercial packages has increased recently. General-purpose FEM codes capable of modelling the machining process include NIKE2D, ABAQUS/Standard, ABAQUS/Explicit, MARC, ALGOR, FLUENT, LS DYNA etc. Unfortunately the majority of general –purpose FEM codes are only applicable for continuous chip formation. There are specially developed FEM codes, such as DEFORM 2D, FORGE2D, AdvantEdge, which are capable of simulating segmented and discontinuous chip formation.

Ceretti [27] conducted simulation of orthogonal plane strain cutting process using FE software Deform2D. To perform this simulation with relevant accuracy, damage criteria have been used for predicting when the material starts to separate at the initiation of cutting for simulating segmented chip formation. Beside, influences of cutting parameters such as cutting speed, rake angle, and depth of cut also studied. Later, the computed cutting force, temperature, deformations and chip geometry have been compared with cutting experiments.

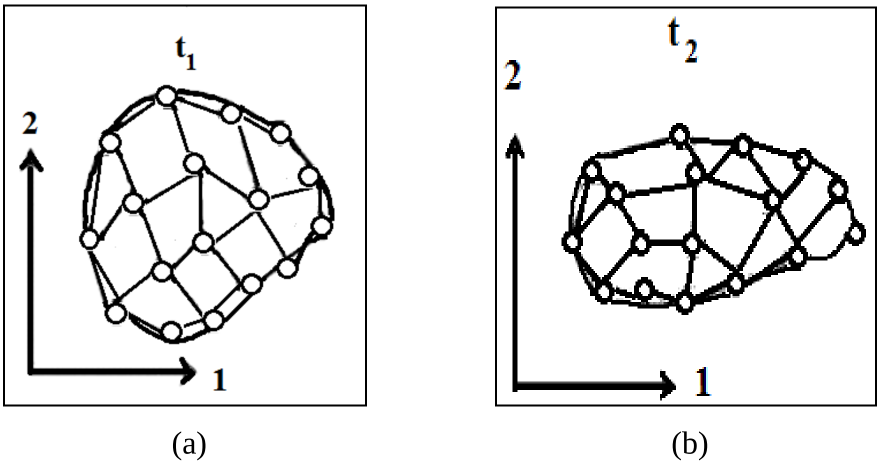
Halil et al. [28] compared various simulation models of orthogonal cutting process with each other as well as with the results of various experiments. Commercial implicit finite element codes MSC. Marc, Deform2D and the explicit code Thirdwave AdvantEdge have been used. In simulation with MSC. Marc and Thirdwave AdvantEdge, there is no separation criterion defined since chip formation is assumed to be due to plastic flow, therefore, the chip is formed by continuously remeshing the workpiece. However, in simulations with Deform 2D, the Cockroft-Latham damage criterion is used an elements, which exceed the predefined damage value, are erased via remeshing. Besides this different modelling of separation, the three codes also apply different friction models and material data extrapolation schemes. Estimated cutting and thrust forces, shear angles, chip thicknesses and contact lengths on the rake face by three codes are compared with experiments performed and with experimental results supplied in literature.

A new approach to carry out a coupled thermo-mechanical analysis of orthogonal cutting was proposed by [29] based on the Arbitrary Lagrangian-Eulerian formulation. Deform 2D numerical code was utilised for the plane strain simulation. The value of heat transfer coefficient is calculated through an inverse procedure, taking into account a set of experimental data and the output of the simulations.

Finally, the dependence of the above coefficient on both the average temperature and the pressure at the tool-workpiece interface was analysed and an effective model was defined through a statistical data regression.

2.4.1 Finite Element Formulation

The specific mesh formulations used for models of orthogonal machining are Lagrangian, Eulerian, and Arbitrary Lagrangian Eulerian. The Lagrangian or updated-Lagrangian method is often used in FEM. These formulations are similar. The only difference is that updated-Lagrangian uses an adaptive mesh technique to reduce mesh distortion. The updated Lagrangian formulation was first used for machining model by Klamecki [30]. The basic concept of the Lagrangian definition is that the mesh will follow the material. The deformation can happen by increments in time. After each increment the reference domain is updated based on material coordinates. In this way, the history of the material is easily taken into account. This updated position situation is used as an initial condition for the next increment, so the FE mesh is connected with its material. However, the updated-Lagrangian method can be costly because of the mesh distortion during the large deformation in these calculations (Figure 2.8).

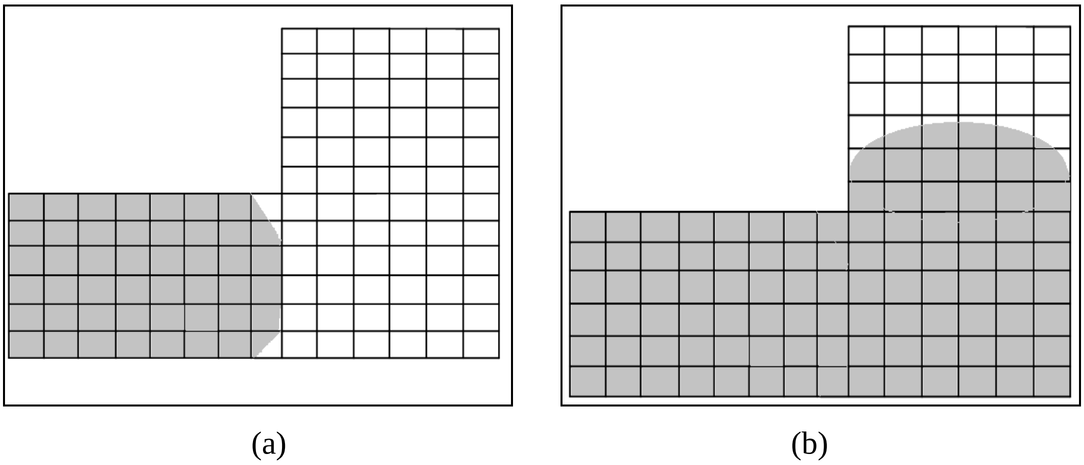


(a) (b)

Figure 2.8: Lagrangian definition (a) Initial Mesh (b) Deformed mesh [30]

Carroll formulated two models. The first one was Updated-Lagrangian and the second was Eulerian. The updated-Lagrangian model successfully determined the deformed chip, stress, and the temperature under the failure criteria to control the chip formation process [31]. Shih and Yang [32] have developed an FEM for metal cutting based on Updated-Lagrangian which includes the effect of elasticity, viscoplasticity, temperature, strain rate and the effect of frictional force. Marusich and Ortiz [33] presented an interesting FEM analysis of machining, based on a Lagrangian formulation with adaptive mesh processing for modelling high speed machining work. Recent work with the Updated-Lagrangian formulation was done by Ozel [34].

Another FEM option is to use the Eulerian formulation. The simple definition of the Eulerian formulation is that the mesh will be fixed in space and the material will flow through the mesh. The advantage of the Eulerian formulation is that this formulation does not have any mesh distortion because the mesh is spatially fixed during the simulation (Figure 2.9). However, the mesh does not connect to the material. It is difficult to obtain accurate data from free surfaces, which is an important result of the simulation of the forming process. Strenkowski and Moon [35] built an FEM of orthogonal metal cutting with an Eulerian formulation. The model predicted temperature distribution. He found that the shear stress occurred over a finite region in front of the tool. In the same year, Childs and Maekawa [36] used the Eulerian formulation to create an FEM to study the tool wear of cemented carbide tools in high speed machining. The results of the model were very good except there is small percentage of errors in the cutting forces.


(a)

(b)

Figure 2.9: Eulerian definition (a) Initial Mesh (b) Deformed mesh [6]

Recently, researchers have been focusing on the Arbitrary Lagrangian Eulerian (ALE) formulation to combine the best features of both the Lagrangian and Eulerian formulations. The concept of ALE was first proposed lately. This formulation was called "the coupled Eulerian-Lagrangian method" and later on was changed to "the Arbitrary Lagrangian Eulerian Model." The ALE method was introduced into the finite element method by Belytschko and Kennedy [37] .It was applied to finite strain deformation problems in solid mechanics. The ALE formulation helps to solve problems with large deformation in solid mechanics. Olovsson et al. [38] developed FEM by using the ALE formulation so that the large strain that is caused from the high deformation in metal cutting does not affect the element distortion at the tool tip. Movahhedy et al. [39] presented that the arbitrary Lagrangian- Eulerian (ALE) formulation offers the most efficient modelling approach. He included the features of an ALE analysis of the cutting process in his conclusion.

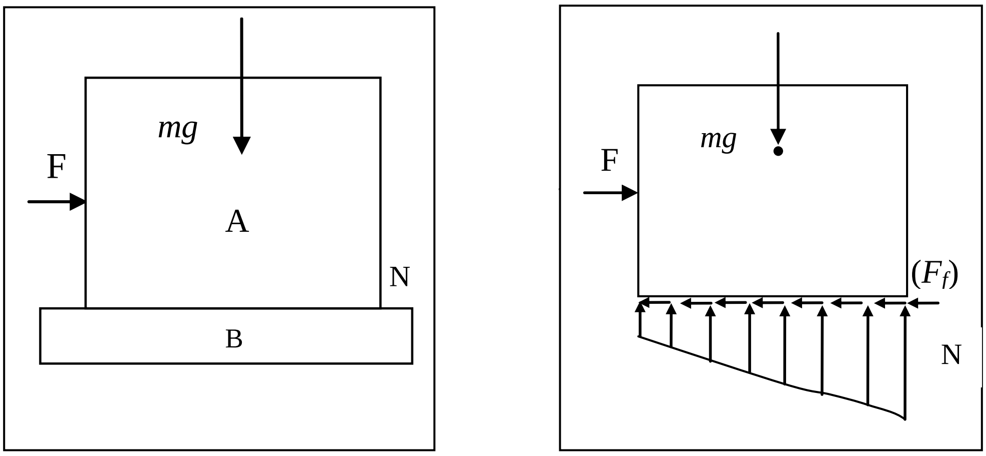
2.4.2 Modelling of Material Properties

Childs [40] stated that the success and reliability of FE based models are heavily dependent upon work material constitutive flow stress models in function of strain, strain rate and temperatures, as well as friction parameters between tool and work material interfaces. Methods to determine the flow stress data through orthogonal turning experiments were proposed by different researchers [41]. Shatla et al. [42, 43] introduced the inverse mapping of Oxley’s machining theory to determine the flow stress parameters of a modified Johnson & Cook’s equation in conjunction with orthogonal slot milling tests.

In general, the strains, strain rates, and temperatures in practical machining operations are much higher than for other deformation processes. These parameters are typically several orders of magnitude higher than can be handled by normally available materials testing equipment. Thus derivation of the appropriate material properties experimentally is difficult as the conditions existing during cutting are generally outside the range of available material testing equipment.

2.5 Friction Model

A general concept of friction can be considered as the tangential force generated between two surfaces. Friction can be represented as the resistance force acting on the surface to oppose slipping. Figure 2.10 (a) shows a simple example of friction where a block is pushed horizontally with mass m over rough horizontal surface. As showing in the free body diagram, Figure 2.10 (b), the body has distributions of both normal force (N) and friction force (F_f) along the contact surface. From the equilibrium, the normal force (N) acts to resist the weight force of the mass mg and the friction force (F_f) acts to resist the force F.



(a) (b)

Figure 2.10: Explanation of contact between two surfaces (a) Two bodies with friction after applying load (b) Free body diagram for the block on rough surface [6]

Basically, there are two types of friction, which are static and kinetic as shown in Figure 2.11. By increasing the force, F, friction force (F_f) increases. The blocks cannot move until the force F reaches the maximum value. This is called the limiting static fractional force. Increasing of the force F further will cause the block to begin to move. In the static portion, the limiting friction force can be expressed as:

$$F_{static} = \mu_s N \tag{2.1}$$

Where μ_s is called the coefficient of static friction.

When the force F becomes greater than F_{static}, the frictional force in the contact area drops slightly to a smaller value, which is called kinetic frictional force. Machining models generally just consider the kinetic friction coefficient which can be calculated by the following equation;

$$F_{kinetic} = \mu k\, N \tag{2.2}$$

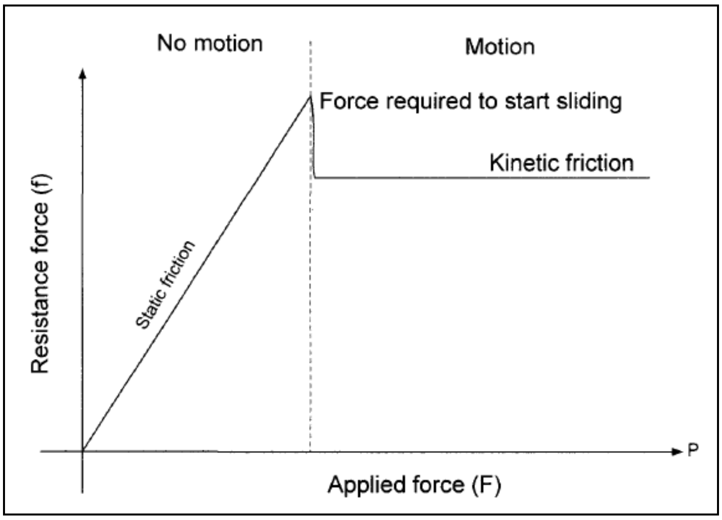


Figure 2.11: Static and kinetic friction [6]

2.5.1 Friction models for machining

The attention of the researches involved in machining field was focused on friction modelling since the beginning of the studies on this process. During the time several models were proposed all over the world as summarized in the following. In the early metal cutting analysis, friction conditions at the tool-chip interface were neglected or the simple Coulomb's law was considered on the whole contact zone, using a constant coefficient of friction μ

$$\tau = \mu \cdot \sigma_n \tag{2.3}$$

being τ the frictional stress and σ_n the normal one.

Another well known friction model is the constant shear model, which neglects altogether the low stress variation of τ with σ_n. In this case, a constant frictional stress on the rake face is assumed, equal to fixed percentage of the shear flow stress of the working material *k*

$$\tau = m \cdot k \tag{2.4}$$

A more realistic model is related to the actual distribution of stresses on the rake face. The latter is rather complicated and it is typically non-linear. The normal stress decreases from the tool edge to the point where the chip separates from the tool [44]. On the contrary, the frictional stress is equal to the shear flow stress near the tool edge and then decreases. According to this distribution the existence of two distinct regions on the rake face was proposed, as shown in Figure 2.12.

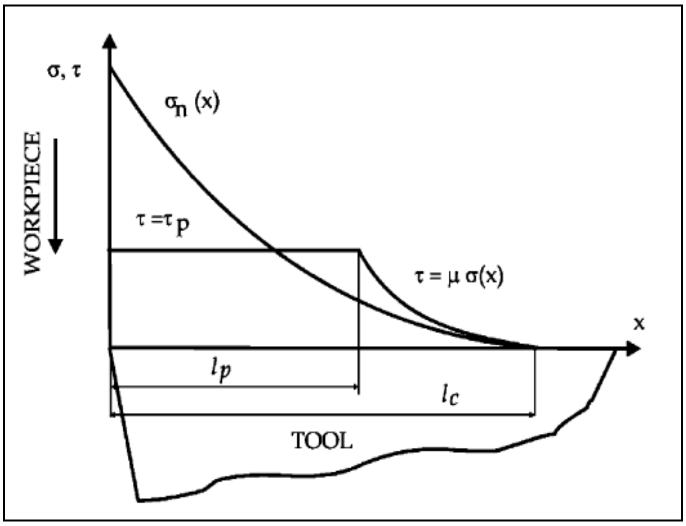


Figure 2.12: Stresses distribution on rake face [44]

In the first region, named sticking zone, the normal stress is very large and the frictional stress is assumed to be equal to the shear flow stress of the material being machined. In the latter, on the contrary, the normal stress is small and Coulomb's theory is able to provide a suitable model of the phenomenon. This can be expressed by means of the following formulation:

$$\tau(x) = \mu\sigma_n(x) \quad \text{when } \tau < k$$
$$\tau(x) = k \quad \text{when } \tau \geq k \tag{2.5}$$

2.6 Conclusion

Finite element simulation of orthogonal metal cutting is become very popular nowadays and there are many research were conducted on this subject. A lot of work has been carried out to developed successful models of orthogonal metal cutting operation. A better understanding of friction modelling is required in order to produce more realistic finite element models of machining processes to support the goals of longer tool life and better surface quality. The FEM is more accurate due to ability to incorporate more realistic assumptions of material behaviour and the influence of friction. Therefore, this work is intended to compare various friction models and validate the simulation result with experimental data for two conditions; dry and MQL.

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