Plastic deformation and chip formation mechanisms during machining of copper, aluminum and an aluminum matrix composite.

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Plastic Deformation and Chip Formation Mechanisms during Machining of Copper, Aluminum and an Aluminum Matrix Composite

By

Zhang, Hong

A Dissertation
Submitted to the Faculty of Graduate Studies and Research through the Engineering Materials Program in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy at the University of Windsor

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ABSTRACT

The present work aims to study the plastic deformation behaviour of selected workpiece materials during the chip formation process. A 6061 aluminum alloy, a C11000 commercially pure copper and a 6061-10vol.%Al₂O₃ particulate reinforced composite have been chosen to study their machining behaviour under the orthogonal cutting conditions. The following experiments have been performed.

1. For the machining tests, different cutting parameters have been chosen within normal cutting conditions. The cutting speeds were in the range of 20 rpm (0.0245m/sec) and 2000 rpm (2.45m/sec) and the feed rates were in the range of 0.05 mm and 0.3 mm.

2. Detailed metallographic investigations have been conducted on the chip formation areas, including the primary deformation and the secondary deformation zones as well as in the area under the machined surfaces. The microstructure information arising from these investigations have been used to determinate the shear angles and to calculate the strain and stress distributions during cutting. To measure temperatures, an experimental system, with thermocouples, a data acquisition interface card, data collection/analysis software and a personal computer has been designed and constructed.

3. The temperature rise during the cutting process has been measured and analyzed. To measure the temperatures, an experimental system that consists of miniature thermocouples connected to a data acquisition interface card and a personal computer has been designed and constructed.
The following aspects in machining process have been studied;

1. Micromechanisms of the plastic deformation during chip formation
2. Variations of the shear angles and the shear strains in the workpiece materials in front of the tool cutting edge
3. Microhardness variations and hence the local stresses in the workpiece materials in front of the tool cutting edge
4. Estimation of the local strain rates
5. Cutting mechanisms in copper and aluminum in relation to their mechanical properties
6. The effects of hard reinforcements in 6061-10vol.%Al₂O₃ composite on deformation behaviour during cutting
7. Build-up-edge effects
8. Temperature rise during cutting
9. Tool failure mechanisms in cutting 6061-10vol.%Al₂O₃ composite

The main experimental observations/results can be summarized as;

1. The shear angles vary between 0 and 90 degrees in the chip formation areas depending on the location. In secondary shear zone, the shear angle increases, while the newly formed chip moves along the rake face of the cutting tool, at the last chip-tool contact point. Shear angle distribution maps that can be used to describe the plastic deformation behaviour at the onset of chip formation have been developed based on the measurements of the shear angles. The variation characteristics of the shear angles
depend on the mechanical properties of the workpiece materials, in particular their work hardening behaviour.

2. Shear strains are calculated based on the measured values of the shear angles in all interested areas. The shear strains vary with the location in workpiece materials relative to the cutting tool tip, corresponding to the shear angles. The maximum shear strain in chip formation area is at the tool tip for 6061 aluminum alloy. For C11000 copper, the maximum shear strain is at the chip root location. The measurable strains are as high as 20.

The secondary shear strains happened in newly formed chips in the chip-tool contact interface areas. For all studied materials, the maximum shear strains are at the last contact point of chip-tool contact.

The shear strain distribution maps have been constructed based on the shear angle distribution maps.

3. The stresses in the chip formation zone and secondary deformation zone as well as in the machined surface have been estimated by using the data from microhardness measurements. The four different locations have been selected to perform the microhardness measurement; 1) along primary shear plane, 2) across the length of the chip, 3) across primary shear plane and 4) across the machined surface. The microhardness variations with loading have also been studied. The stress maps have been developed in these different locations. The results have shown the stresses vary with the location and that the maximum stress is at a location close to the primary shear plane, but not at the maximum strain location.
4. The shear strain rates have been estimated from the cutting speeds and the widths of the shear bands in the chip formation areas. The values of the strain rates vary with the locations. The strain rates at the chip-tool contact interface and the machined surface in aluminum and copper could be as high as $10^6 \text{ s}^{-1}$.

5. During machining, voids are generated along the strain gradient. The coalescence of the voids leads to the formation of shear cracks near the free surface of the chip. Shear crack propagation leads to the formation of the fracture at the chip free surface.

6. The formation of a built-up-edge has been observed when cutting the 6061-10vol.% Al$_2$O$_3$ composite, but not when cutting Cu and Al. The built-up-edge effects play an important role in determining the plastic deformation behaviour in chip formation process. Under the same cutting conditions, much thinner chips in 6061-10vol.% Al$_2$O$_3$ composite were produced compared with Cu and Al.

7. The rotation of the secondary reinforcement particles in severe plastic deformation areas has been observed. Fracture of the secondary reinforcement particles is hardly ever observed.

8. Temperature rise distribution maps have been created based on the shear strain and the stress data as well as the physical and thermal properties of the workpiece materials. A coefficient of temperature rise (CTR), which is a measurement of the temperature rise capability of workpiece materials, has been introduced to make the temperature rise estimation easier. It has been observed that the highest temperature is at the chip-tool contact interface, where the temperature could be as high as the melting point of the workpiece materials.
9. Tool failure has been observed during cutting of the 6061-10vol.%Al₂O₃ composite. The failure mechanism has been analyzed on scanning electron microscope. The results have shown that the main mechanism for the tool failure may be the delamination, or spallation on the very tip area of the cutting tool, which may be due to the high temperature gradient at the contact interface between the chip-tool rake face.
In memory of my Father; Zhang, Xiu-Feng

Dedicated to my Mother; Long, Shu-Zhi

My wife; Chen

My son; Yi
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$\phi_s$: shear angle, varies with position.
\( \Phi_i \): shear angle, that varies with position, shearing is limited within the grains.

\( \Phi_j \): Grain boundary angles.

\( \Phi_i \) and \( \Phi_j \) very with position, but have the tendency to be parallel to \( \Phi_z \).

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cutting speed, VB = 0.3 mm.

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### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Rake face angle, angle between rake face and the direction perpendicular to the cutting direction, degree</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Complementary angle to shear angle, degree</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Strain, dimensionless</td>
</tr>
<tr>
<td>$\dot{\varepsilon}$</td>
<td>Strain rate, sec$^{-1}$</td>
</tr>
<tr>
<td>$\dot{\varepsilon}_c$</td>
<td>True strain rate, sec$^{-1}$</td>
</tr>
<tr>
<td>$\varepsilon_c$</td>
<td>True strain, dimensionless</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Shear angle, angle between cutting direction and shear direction, degree</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Shear strain, dimensionless</td>
</tr>
<tr>
<td>$\bar{\gamma}$</td>
<td>Equivalent shear strain, dimensionless</td>
</tr>
<tr>
<td>$\dot{\gamma}$</td>
<td>Equivalent strain rate, sec$^{-1}$</td>
</tr>
<tr>
<td>$\dot{\gamma}$</td>
<td>Shear strain rate, sec$^{-1}$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Geometry angle of the build up edge, degree</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Workpiece strength, mm</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Materials constant, less than 1</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Strain angle, equals to $\pi/2 - \phi$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Flow stress, MPa</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Dislocation density, m/m²</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>Density of the annihilated dislocation, m$^{-2}$</td>
</tr>
<tr>
<td>$\rho_e$</td>
<td>Density of the dislocation that escaped through crystal surface, m$^{-2}$</td>
</tr>
</tbody>
</table>
\( \rho_n \)  The density of the newly created dislocation, m/m²

\( \tau \)  Shear stress, MPa

\( \zeta \)  Ratio of the heat dissipated by the chip to the total heat generated

\( \xi \)  The number of the dislocation loops emitted by a source

\( b \)  Burger's vector

\( f \)  Feed rate, mm

\( h \)  Heat convection coefficient,

\( k \)  Boltzamann constant,  \( 1.38 \times 10^{-23} \) kJ/kmol-K

\( l \)  The average slide distance, or radius of dislocation loop

\( n \)  Normal direction of a surface

\( q \)  Heat flux rate, J/mm²·sec or kJ/mm²·sec

\( q \)  The number of lattice parameter separating two active glide planes

\( s_p \)  the length of the primary shear zone, mm

\( t \)  Time, second or hour

\( t_{cut} \)  the thickness of the uncut chip, equals to the feed rate

\( u \)  Velocity vector along y-direction, m/s

\( u_c \)  Shear velocity or chip moving speed, m/s

\( u_p \)  Shear velocity along the primary shear zone, m/sec

\( v \)  Velocity vector along cutting direction, x-direction

\( v_d \)  Dislocation climbing velocity, m/sec

\( w \)  Width of the chip, equals to the contact length of the cutting edge and the workpiece, mm

\( w_l \)  Proportionality factor of geometry
\( x \) Distance away from the shear plane, mm
\( \Delta x \) Increment in the cutting direction, mm
\( \Delta y \) Increment in the direction perpendicular to the cutting direction
\( A \) Materials constant of order of 1
BHN Brinell hardness
\( C_p \) Specific heat, kJ/kg\(^{-\circ}\)C, or kJ/kg-K
\( D \) A material constant determined by the process controlling mechanism
\( F_c \) Cutting force, force measured along cutting direction, kg-f
\( F_p \) Feed force, force measured perpendicular to the cutting direction, kg-f
\( G \) The shear modulus, GPa
HK Knoop's hardness, MPa
HV Vicker's hardness, MPa
\( J \) Mechanical equivalent heat
\( N_{fr} \) Normal load on rake face of the cutting tool, MPa
\( N_{sh} \) Normal force on primary shear plane, MPa
\( \rho \) Density, kg/cm\(^3\) or Mg/m\(^3\)
\( Q \) Heat exchange between system and surroundings, J, or kJ
\( Q \) Thermal activation energy, J or kJ
\( \dot{Q} \) Heat transfer rate, J/sec or kJ/sec
\( S \) System entropy, kJ/kg-K
\( S_n \) Surface
\( S_c \) Length of the secondary shear zone or chip total contact length
\( T \) Temperature, \( \circ \)C or K
\( T_r \) Room temperature, °C or K
\( \Delta T \) Temperature rise, °C or K
\( U \) Internal energy change of a system, J, or kJ
\( VB \) The width of flank wear land, mm
\( V_c \) Cutting speed, m/s, or rpm
\( W \) Work exchange between system and surroundings, J or kJ
\( \dot{W} \) Work rate, J/sec or kJ/sec
CHAPTER I.

INTRODUCTION

1.1. Focus of the Work: Outline of the Problems Studied

Machining is among the most important material shaping processes. The principle of the machining process consists of the removal of the unwanted material from the workpiece by using a cutting tool. To perform a cutting operation energy must be supplied to the tool and this energy is consumed in several ways. The principal ways by which the energy is used are:

i) The kinetic energy imparted by the chip

ii) The shear energy required to produce the chip by plastic deformation

iii) The energy required to move the chip along the rake face of the tool

Among these, the shear energy is the most important. Therefore the study of machining processes should include analysis of plastic deformation at the onset of chip formation and heat generation during the cutting operation.

Prior to examining deformation processes during machining it is useful to summarize the main factors affecting the efficiency of the machining of a workpiece. These are:

1) operation conditions

   • cutting speed (CS)

   • feed rate (FR)

   • depth of cut (DOC)

2) machining tool aspects

   • microstructures and properties of cutting tool materials
• tool tip geometry

• tool failure resistance

3) workpiece aspects

• mechanical, physical and thermal properties

• microstructural changes at high strains and high strain gradients

• shear plane angle and chip thickness, which are influenced by the properties and the microstructure of the workpiece as well as the operation parameters.

Another important consideration is the temperature rise that occurs during the dissipation of mechanical energy. The amount of the heat that causes the temperature rise depends on the operation parameters as well as to the physical, mechanical properties of work-piece and tool materials. The temperature increase affects not only the tool failure, but also the chip formation and the plastic deformation behaviour of the work piece.

The current study is focused on the following areas:

• Plastic deformation behavior of workpiece materials during the chip formation process,

• Temperature rise and the distribution around the tool tip, and

• Cutting tool failure mechanisms.

i) In the work piece materials, the area of interest is the region where the chips initiate. More specifically: The primary shear zone where the chip is formed, right in front of the tool tip,
ii) The secondary shear zone where the newly formed chip is in contact with the rake face of the cutting tool while moving away from the tool and where seizure often occurs due to friction between the tool and the workpiece materials, and

iii) The machined surface where the new surface is formed as a result of removing unwanted materials.

The following events which simultaneously occur in the chip formation areas during the machining process of a workpiece:

1) Accumulation of large strains,

2) Formation of large strain gradients,

3) Generation of high strain rates,

4) Formation of local stress gradients, and

5) Temperature increase and generation of the temperature gradients.

One of the most important parameters that influence the machining process is the shear angle, that is the angle between the direction of the material shearing during chip formation and the cutting direction. In orthogonal machining, the normal direction to the tool cutting edge, the cutting direction and the material shear direction are on the same plane.

The shear angle plays an important role in the determination of local shear strains, strain rates, shear stresses and, thus, on the mechanical work done during cutting. The determination (and the predication) of the shear has been an active research topic for a long time [1-4]. Most of the studies in this field have approached the problem from the point of view of the mechanics of solid bodies, and assumed that the shear plane has a
constant shear angle, on which the chip forms as a result of shear deformation. According to these studies, the typical calculated values of the shear angles range from 10 to 35 degrees for most of the metals.

The present work presents a systematic study of the plastic deformation structures that develop during cutting and the micromechanisms of chip formation. The effect of temperature on the cutting tool and the workpiece has also been considered. In addition the mechanisms of cutting tool failure have also been studied.

1.2. Materials Studied

A 6061 wrought aluminum alloy and a C11000 type commercially pure copper have been selected for their study of the plastic deformation behavior during the machining process. These two relatively simple materials were selected as model materials for studying the mechanisms of deformation and chip formation during the machining process because their fundamental mechanical properties at room temperature and elevated temperature are well documented.

The different work-hardening responses of these materials to the high shear strains and the high shear strain rates generated during machining were investigated by performing compression tests. A particulate reinforced metal matrix composite of 6061-10vol.%Al₂O₃ composite has also been selected for the study of its deformation behaviour during machining and in particular to understand the effect of the alumina (Al₂O₃) particles on the chip formation mechanisms.

The 6061-10vol.%Al₂O₃ composite has an 6061 aluminum matrix and Al₂O₃ particulate reinforcing particles. The presence of the hard second phase particles in the
ductile matrix increases the seizure resistance of aluminum and in most cases results in improved wear resistance, but this beneficial effect is counterbalanced by the difficulty in machining of the composite.

1.3. **The Outline of the Thesis**

The previous research work performed on machining is reviewed in Chapter 2. The literature review concentrates on the existing mechanical models of the chip formation, the temperature increase and its effects on machining. Microstructural models of chip formation are also summarized. The roles of the shear angles and strain distributions are highlighted in relation to the machining parameters.

Chapter 3 describes the design of the experimental set-ups used in the current study and the methods of force, temperature measurements. Details of the metallographic techniques used are also given in this chapter.

The results of the mechanical tests on the workpiece materials performed before the machining tests are presented in Chapter 4. The chapter includes the description of the microstructures, the results of the ring compression tests, and the hardness tests.

Chapter 5 presents the results of the metallographic investigations on the characteristics of the plastic deformation in the primary shear zone, the secondary shear zone and below the machined surfaces. The morphological characteristics of the free surface of the chips are also presented in Chapter 5. The behaviour of the reinforcing particles in the composite materials was analyzed and discussed in Chapter 5. The separation and rotation of the particles in the matrix, and the built-up-edge effects are discussed.
The experimental results are analyzed in Chapter 6. The data was processed in order to determine the local distribution of the shear angles. Further analysis of the shear angles led to an estimation of the shear strains and the strain rates in the primary and secondary shear zones. A relationship has been established between local shear strain and the stresses determined by the microhardness measurements.

Thermal effects play an important role in determining tool life and workpiece integrity. Heat generation and the temperature rise during cutting process are also analyzed in the Chapter 6. The temperature distributions have been discussed based on the shear angle, shear strain and microhardness measurements. The analytical results of the temperature distributions were compared with the experimental. A brief analysis of the cutting tool failure mechanisms has also been presented in Chapter 6.

In Chapter 7, the general conclusions from the present study are summarized and the recommendations for future study in this field are made in Chapter 8.
CHAPTER 2.

LITERATURE REVIEW

Machining is a manufacturing process by which unwanted material is removed to obtain the desired shape of a part. Reducing the machining time and extending the cutting tool life both have great economic significance.

2.1. Basic Types of Machining Processes

Some of the typical machining processes that are most widely used are: 1) Turning, 2) Milling and 3) Drilling. These will be briefly described in this section.

2.1.1. Turning Operations

Turning is a process that uses a single point cutting tool to remove unwanted material to produce a surface by revolution on a rotating apparatus (lathe). The basic operation parameters for a specific work piece and component specification are the cutting speed, the feed rate and the depth of cutting,

The turning processes are normally identified as orthogonal cutting and oblique cutting depending on the way the cutting tool makes a contact with the workpiece material. In practice, the depth of cut is at least five times the feed rate. If the tool cutting edge, cutting direction, as well as the chip moving direction are perpendicular to each other, the orthogonal cutting condition is defined. The orthogonal cutting process can be analyzed as a two dimensional problem. If the cutting direction and tool edges are not perpendicular to each other or the contacting edge of cutting tool with workpiece is not a
straight line, the oblique cutting process is defined and the third dimension has to be considered.

2.1.2. Milling Operations

The milling operation is a process that produces a flat surface or curved surface with either a multi point tool or a multi cutting edge tool. The important variables for the milling operation are the cutting speed, the feed rate and the depth of cut, the same as those in the turning operation. Because the cutting edges of the mill cutter, cutting direction and chip moving direction are not in the same plane, the milling operation is a three-dimension problem. In plane milling operation, if the cutting edge is parallel to the axis of the cutter, an orthogonal problem may be assumed as a first approximation [5-6].

2.1.3. Drilling Operations

In this process, a rotating drill is pressed into workpiece to make a hole. The drilling operation is one of the most complicated oblique cutting processes because of the geometry of the cutting tool-drill. Drills normally have two cutting edges that are not in the plane formed by cutting direction and chip moving direction. Chips were formed on all cutting edges and move out along the tunnel of the drill flutes and the newly formed hole. The rotation speed of the drill and the feed rate play important roles in drilling operations.

In addition to the machining processes mentioned above, there are many other cutting operations including 1) Sawing 2) Reaming, 3) Tapping, 4) Planing, 5) Broaching, 6) Boring, and 7) Threading. Grinding and honing process are also used in
machining processes, but the materials being removed are in the form of fine debris instead of in chip form. These cutting processes also cover a wide range of complexity that is similar to the ones that are encountered in turning, milling and drilling operations [3-7].

2.2. Important Issues in Metal Cutting Operations

In cutting processes, the cutting tool contacts the workpiece material and removes part of the workpiece material. The main study areas in material cutting can be summarized into three groups:

1) Cutting tool aspects, which involve the design of the tool geometry, the properties of the cutting tool materials, the tool failure mechanisms and the tool life prediction.

2) The properties of the workpiece material, which include the mechanical behaviour, the physical, chemical and thermal properties.

3) The operation parameters, which are cutting speed, feed rate and depth of cut.

These aspects in cutting system can be shown clearly in a schematic diagram, see Fig. 2-1 [8]. The interactions between these three aspects of machining decide the efficiency of a given metal cutting process. For example, in cutting a specific workpiece, as soon as the cutting tool is chosen the operation parameter decides the rate of material removal, the quality of the machined surface and the tool life. If a different tool is chosen, (e.g. for different rake angle), the rate of material removal may not change, but the tool life and the quality of the machined surface may change. That is because the material
behaviour changes due to the change of the cutting stress distribution and the plastic strain distribution resulting from the change of the geometry of the cutting tool.

2.3. **Machining Parameters**

The three most important machining parameters that determine the rate of metal removal are i) the cutting speed, ii) the feed rate and iii) the depth of cut. The *cutting speed* is defined as the rotation speed for a rotation tool, or the rotation speed of the workpiece for lathe operations. The *feed rate* is defined as the cutting depth of the cutting edge into the workpiece per cutting edge and per revolution. The *depth of cut* is the normal distance from the previously machined surface to the new surface exposed by the cutting tool.

The optimization of these three parameters results in the minimization of the possibilities of the tool failure, and thus, prolongs the tool life. *Tool life* can simply be defined as the length of time that a cutting tool will cut before becoming dull or before it must be replaced. According to the ANSI standard specification for tool life testing with single point tools [9], the end of tool life is defined as a given amount of wear on the flank face of the tool, normally $V_B = 0.3\text{mm}$, where $V_B$ is the width of flank wear.

The tool life is influenced most significantly by cutting speed, then by the feed rate, and to a lesser degree by the depth of cut. Experiments have shown that when the depth of cut is about ten times greater than the feed rate, a further increase in depth of cut will have no significant effect on the tool life [7]. In practice, the first step is to select the depth of cut based on the tool, workpiece, power and the equipment rigidity. Because depth of cut has the least influence on the tool life, it is advisable to use the heaviest
depth of cut that is possible. The second step is select feed rate, which depends on the specification of the final finishing. Normally the smaller the feed rate the better is the quality of the finishing.

The cutting speed has strong effects on tool life. The mechanical properties of either tool materials or workpiece materials may change significantly with the cutting speed. Higher cutting speeds can increase the rate of removing unwanted materials, but the effects on the tool life vary with the cutting conditions. The reason for this has been recognized as the temperature rise at the contact area between the cutting tool and the workpiece. Increasing the feed rate, thereby increasing the contact stress and the plastic deformation of the workpiece material in the chip formation area, also causes the temperature rise [10].

2.4. Workpiece Materials Behaviour in the Machining Process

Workpiece material behaviour during the cutting process is subjected to severe plastic deformation, which features large strains, high strain rates, and is often accompanied with highly localized plastic deformation. Due to the complexity of the stresses and strains, mechanical analyses of metal cutting processes use simplifying assumptions to obtain tractable solutions [11]. The basic assumptions are:

1) The workpiece material is isotropic and homogeneous.

2) The material does not change its volume. The constant-volume relationship or incompressibility law apply which is expressed as

\[ \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \]  \hspace{1cm} (2-1)
3) Elastic deformation is neglected; only the plastic deformation is considered.

4) Strain hardening is often neglected as a first approximation.

Mechanical analysis of the plastic behaviour of workpiece materials during the cutting process is based on these assumptions. However, in reality, the deformation behaviour of the workpiece is much more complex. The negligible change in the volume of material implies that deformation is shear deformation that involves only deviatoric components. But this assumption is not strictly correct because there should be compressive stresses in the workpiece ahead of the rake face of the cutting tool.

High strain rates (as high as $10^3$ to $10^5$ sec$^{-1}$) deformation processes in metal cutting show considerable similarity with the microstructures produced in heavily cold-rolled metals [12]. The process of the chip formation from the workpiece materials is complicated by the following factors [13]:

i) Large strain plastic deformation process occurring in the chip forming area, formation of localized shear strains.

ii) Large strain gradients extending from machined surfaces to un-machined bulk materials.

iii) High strain rate deformation process occurring in the chip formation area, and in the top layer of machined surfaces,

iv) Temperature rise around the tool tip, and

v) Relative motion between the workpiece material and the cutting tool which may cause seizure at the rake face of the cutting tool and the moving chip.
The economic and technical significance of understanding these issues in the materials removal process have been under extensively active study since the beginning of the century. However many uncertainties still remain.

2.5. **Chip Formation**

The chip formation process involves plastic deformation of the workpiece and a temperature rise that strongly affects the tool performance and the quality of the machined surface.

2.5.1 **Mechanical Models of Chip Formation**

An idealized model of chip formation is proposed by Piispanen [14], see Figure 2-2. According to this model the material is cut as a deck of cards, which move along a constant angle with the cutting direction. In this model, the shear angle is constant, also the width of the sheared material is constant. Thus, the strains are constant. The model is based on the following assumptions:

1) The tool tip is perfectly sharp, thus there is no contact along the clearance face.

2) The shearing is along a flat plane starting at the tool tip and ending at the chip root where a sharp point is formed by the previous machined surface and the free surface of chip.

3) Deformation is in plane strain status: therefore the width of the cut should be much greater than that of the depth of cut.

4) Chip is continuous with no built up edge.
5) Shear stress, strain and strain rates are uniform.

The strain rate \( \frac{dy}{dt} \) is proportional to the \( \frac{V}{\Delta y} \), where \( V \) is the cutting velocity of the relative movement between cutting tool and workpiece, and \( \Delta y \) is the thickness of the shear bands. In ultra high speed machining (UHSM), cutting speeds can be as high as 200 m/min. Assuming that \( \Delta y \) is about one micron, the strain rate, according to the Piispanen model, can be as high as \( 3.33 \times 10^9 \) sec\(^{-1} \) [15].

The concept of the severe plastic deformation zone was introduced by Okushima and Hitomi [16], (see Figure 2-2 b). When the cutting speed is higher than 150 m/min the width of the primary shear zone is only a few microns. Thus, the shear zone takes the form of a plane.

Oxley and Welsh [17], assumed that the primary shear zone is composed of parallel planes, as shown in Figure 2-3 a. It was shown that the flat shear plane concept predicted trends in shear angle, cutting forces with a variation at cutting speed and feed rate, which agree well with the experimental results. The constant shear angle implies that the shear speed is constant across the chip thickness because the materials shear on a straight plane and a constant distance under the constant cutting speed. Thus, the chip should be straight, which is not always the fact in practice.

Based on mechanical analysis, Dewhurst [18] developed a curled chip model that described the shear plane made up of curved parallel planes, (see Figure 2-3 b) to explain the fact that the chips form curved pieces. The curved shear planes lead to the curved chip because of the non-uniformity of the shear on the shear plane [18]. In materials shearing on this particular shear plane, the material in the front area reaching free surface
is subjected to small or no shear stress. The material at the rear area suffers from the secondary shear stresses and high temperatures.

After the chip is formed, it will move along the rake face of the cutting tool, where the chip will suffer from the secondary shear deformation process because the heavy friction between the chip and the rake face of the cutting tool. The ratio of the secondary shear zone thickness to the total chip thickness typically runs into about 0.2 for mild steel [19].

The shear deformation in this zone has been identified as the results of the seizure between the cutting tool and the newly formed chip over the sticking part of the contact length, which has been documented by Trent [20]. The movement of the chip material is retarded due to the seizure that leads to shear between the two adjacent layers of the chip material. The process of the secondary shear is considered to be adiabatic in nature [21].

2.5.2 Mechanics of Chip Formation

1. Cutting Forces

Based on Piispanen model, Ernst and Merchant [22] developed a cutting force diagram, (see Fig.2-4), that has been widely used since then. Since according to his model the chip forms on a single plane and the newly formed chip moves as a rigid body at a constant velocity, the resultant of the forces acting on the chip from the cutting tool and from the workpiece is zero. The relationship between the various forces can be easily derived from the force equilibrium diagram [23] in Fig 2-4:
Shear force: \[ F_{\text{shear}} = F_{\text{cut}} \cos \phi - F_{\text{feed}} \sin \phi \] (2-2)

Normal force on shear plane: \[ N_{\text{shear}} = F_{\text{feed}} \cos \phi - F_{\text{cut}} \sin \phi \] (2-3)

Friction force: \[ F_{\text{friction}} = F_{\text{cut}} \sin \alpha + F_{\text{feed}} \cos \alpha \] (2-4)

Normal force: \[ N_{\text{friction}} = F_{\text{cut}} \cos \alpha - F_{\text{feed}} \sin \alpha \] (2-5)

where \( \phi \) is the shear angle and \( \alpha \) the rake face angle of the cutting tool.

These results are valid for the perfect orthogonal cutting process only, where the radial force is zero, only the cutting force is exerted on the sharp tool, and the forces along the shear plane are uniformly distributed. However, if the tool tip of the cutter is a significant fraction of the depth of cut, restricted cutting, the radial force will be not negligible due to the contribution from the secondary cutting edge. The magnitude of the radial force is determined by the derivation of the chip flow direction for the orthogonal direction, which depends on the ratio of feed rate to the depth of cut [24].

In practice, the worn surface on the flank face of the cutting was developed soon, which introduces additional forces the tool as a result of friction contact between the flank face and the workpiece material. The total forces acting on the tool can be divided into two components: one on the rake face and the other on the flank face. As the flank land that is the width of flank wear increases, the force acting on the flank face increases with a linear relationship. This increases of the force on the flank face during cutting.
process has been considered as the increase of the flank wear [25] and has been utilized in adaptive control for on line measurement of the tool wear [26].

2. **Stresses Generated During Cutting**

According to the stresses analysis from the force diagram in Figure 2-4 the shear stress and the tensile stress on the shear plane, can be represented as follows:

\[
\text{Shear stress: } \tau = \frac{(F_{\text{cut}} \cos \phi - F_{\text{feed}} \sin \phi) \sin \phi}{wt_{\text{uncut}}} \tag{2-6}
\]

\[
\text{Tensile stress: } \sigma = \frac{(F_{\text{cut}} \sin \phi + F_{\text{feed}} \cos \phi) \sin \phi}{wt_{\text{uncut}}} \tag{2-7}
\]

where \(t_{\text{uncut}}\) is the thickness of the uncut chip that equals the feed rate, and \(w\) is the width of chip that equals the depth of cut. The results of the traditional stress analysis are limited in predicting the workpiece material behaviour in cutting process, especially when the strain is higher than 1 and the strain rate is around \(10^3\) to \(10^5\) sec\(^{-1}\). The work hardening and work softening happen simultaneously. As the stress is defined as the force divided by the area of loading, stress would change slightly with cutting speed, but linearly increases with the feed rate and depth of cut [3].

2.5.3. **Shear Angle**

In most studies the value of the shear angle is simply defined as the angle between the straight line originating from the tool tip, extending parallel to the cutting direction
and the line starting again at the tool tip but ending at the intersection of the chip free surface and the previous machined surface. Due to the fact that in practice, it is difficult to define either the tool tip or the intersection of the chip free surface with the previous machined surface it is not always possible to measure the shear angle accurately even it is simply defined as above.

The shear angle plays a dominant role in determining the cutting energy required for machining. Any mechanical model of cutting forces, cutting strains, strain rates, temperature rise and the tool life prediction should take into account the shear angle. Consequently several models based on solid mechanics analysis have been developed to measure the shear angles. These models have been compiled and compared with each other in [27].

Ernst and Merchant (23) first defined the shear angle as \( \phi = \frac{\pi}{4} + \frac{\alpha}{2} - \frac{\beta}{2} \), which is the angle that makes the cutting force along cutting direction minimum. Lee and Shaffer [28] defined the shear angle as \( \phi = \frac{\pi}{4} + \alpha - \beta \), which gave the minimum shear stress according to the slip line field model of chip formation. To account for the build-up-edge (extra material that accumulates at the tool tip) problem, Lee and Shaffer [28] modified the shear angle calculations as \( \phi = \frac{\pi}{4} + \alpha + \eta - \beta \), where \( \eta \) is the geometry angle of the build-up-edge. The value of \( \eta \) varies with the shape of the build-up-edge. The angle \( \beta \) is an effective angle that can be calculated by measuring the cutting force, \( F_c \), and the force normal to this force, \( F_p \), \( \tan (\beta - \alpha) = F_c/F_p \), where \( \alpha \) is the rake face angle of the cutting tool.
In practice, the chip root seldom has a sharp geometry, which makes the measurement of the shear angle complicated. The geometry measurement varies with the clearance of the chip root where the free surface of newly formed chip meets the previously machined surface.

In addition, the built-up-edge makes the exact location of the shear plane hard to determine. Kobayahi et al. [29] performed extensive cutting tests, the shear angle measured from the samples scattered up to 20%, especially for the conditions under which the built-up edge appears and the intersection where the chip free surface and previous machined surface meet assumes a curved geometry.

Oxley [30] has presented an analysis that indicates that, for a given tool material, at low cutting speeds the effective shear angle will be smaller compared to that at higher speeds. This has been attributed to the fact that at higher cutting speeds the temperature is higher at the interface of cutting tool and at the workpiece where the chip formation was initialized. The temperature increase will reduce the cutting force so as to form thinner chip, which will increase the shear angle and reduce the shear stress.

The rate of the plastic deformation work done in the primary shear zone, $W_p$, (assuming a discrete parallel-sided shear zone) can be calculated as follows [31-33]

\[ \dot{W}_p = k \cdot u_p \cdot s_p \]  \hspace{1cm} (2-8)

where $k$, $u_p$ and $s_p$ are the yield strength of the material, the shear velocity along the zone and the length of the primary shear zone, respectively. Similarly, in the secondary shear zone, the rate of the plastic deformation energy is [33]
\[ \dot{W}_s = \lambda \cdot k \cdot u_c \cdot s_c \]  \hspace{1cm} (2-9)

where the shear strength is multiplied by a constant \( \lambda < 1 \) to account for the fact that some sliding occurs at the end of the contact length, and \( u_c \) is the shear velocity or chip formation speed and \( s_c \) is the length of the shear zone (or chip-tool contact length).

Wright [34] has shown that the total power curve \( (\dot{W}_p + \dot{W}_s) \) has a minimum value where the shear angle is located, see Figure 2-5. For commercial machining of steels \( \lambda = 0.9 \) and long contact lengths \( s_c \), promote low values of shear plane angle Wright’s calculations [34] tend to predict that the lowest values of the shear angles, \( \phi \), are found when machining annealed ductile materials, in agreement with the experimental results. But as a general model of shear angles, the predictive power of the model was poor and showed reasonable agreement with the experimental data only for free-machining steels.

Wright [34] modified the model so that the modified calculations were based on the determination of the lowest plastic work rate necessary for initiating the shear instability in severely work-hardened materials and assumed that the process will continue to operate at this work rate while shearing the softer material. The parameter \( k_1 \) used in these calculations is the shear strength of severely work-hardened material (corresponding to ultimate strength in tension/\( \sqrt{3} \)), and \( k_o \) is defined as the shear yield strength along the shear plane angle \( \phi_o \), which is calculated as follows:

\[ \cos(\phi_o - \alpha)\sin \phi_o = k_o / k_1 \left[ \cos(45 - \alpha/2)\sin(45 + \alpha/2) \right] \]  \hspace{1cm} (2-10)
Table 2-1 Comparison of the values of the predicted shear angles with the experimental values [34]

<table>
<thead>
<tr>
<th>Work Piece Materials</th>
<th>Heat Treatment</th>
<th>Shear Yield Strength (MPa)</th>
<th>Shear Strength at UTS (MPa)</th>
<th>Predicted Shear Angles</th>
<th>Experimental Shear Angles (°)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armco Iron</td>
<td>Normalized</td>
<td>97</td>
<td>178</td>
<td>17.9</td>
<td>12-18</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>13-17</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11-17</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15.5</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12.5-16</td>
<td>38</td>
</tr>
<tr>
<td>AISI 1040</td>
<td>Hot-Rolled</td>
<td>234</td>
<td>367</td>
<td>21</td>
<td>23-29</td>
<td>38</td>
</tr>
<tr>
<td>AISI 1040</td>
<td>Cold Rolled</td>
<td>355</td>
<td>404</td>
<td>33</td>
<td>33-34</td>
<td>24</td>
</tr>
<tr>
<td>304 SS</td>
<td>Cold Rolled</td>
<td>303</td>
<td>444</td>
<td>23</td>
<td>21-23</td>
<td>34</td>
</tr>
<tr>
<td>Copper (commercial purity)</td>
<td>Annealed</td>
<td>40</td>
<td>129</td>
<td>9.9</td>
<td>7.5-12.5</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11-13.5</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11-13.5</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6-12</td>
<td>37</td>
</tr>
<tr>
<td>Copper (commercial purity)</td>
<td>Cold Drawn</td>
<td>161</td>
<td>181</td>
<td>34</td>
<td>31</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>33</td>
<td>37</td>
</tr>
<tr>
<td>Brass, 70/30</td>
<td>Cold Rolled</td>
<td>254</td>
<td>307</td>
<td>30</td>
<td>27-35</td>
<td>34</td>
</tr>
<tr>
<td>Nickel (commercial pure)</td>
<td>Annealed</td>
<td>34</td>
<td>186</td>
<td>5.8</td>
<td>11-15</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.1-8.3</td>
<td>32</td>
</tr>
<tr>
<td>Aluminum (commercial pure)</td>
<td>Annealed</td>
<td>20</td>
<td>536</td>
<td>12</td>
<td>9</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9</td>
<td>37</td>
</tr>
<tr>
<td>Aluminum (commercial pure)</td>
<td>Precipitation Hardened</td>
<td>182</td>
<td>238</td>
<td>26</td>
<td>23-26</td>
<td>34</td>
</tr>
</tbody>
</table>

- The experimental shear angle values listed in the table were measured by different methods, see related references.

using \( \phi_r = 45 + \frac{\alpha}{2} \) and \( \alpha = 6 \) degrees (rake angle). The model can be simplified as
\[ 2\phi_0 = \left( \sin^{-1}\left[ \frac{1.104k_0}{k_t - \sin 6}\right] \right) + 6 \quad (2-11) \]

The results of the predictions from equation (2-11) and comparison with experimental results are listed in Table 2-1.

There are still high disagreements of up to 40% between the model and the experiments even though this may be the best agreement between the theoretical work and the experimental work.

2.5.4. Strains and Strain Rates

Strains and strain rates generated during metal cutting were first calculated by Merchant [40], see Fig.2-6. The results of their analysis are as following:

Shear strain: \[ \gamma = \tan(\phi - \alpha) + \cot \phi \quad \text{or} \quad \gamma = \frac{\cos \alpha}{\sin \phi \cos(\phi - \alpha)} \quad (2-12) \]

Shear strain rate: \[ \dot{\gamma} = \frac{\cos \alpha}{\cos(\phi - \alpha)} \frac{V}{\Delta y} \quad (2-13) \]

where \( \Delta y \) is the thickness of the shear band. The values of strain rates strongly depend on the shear angle. For special cutting tool, the rake face angle, \( \alpha \), is constant. \( \Delta y \) depends on the material properties and the stress distribution. The cutting speed, \( V \), is a constant. Under this circumstances, strains and strain rates are monolithic functions of shear angle, \( \phi \) [40]. However the strain and the strain rate remain constant only if the shear angle is
assumed to have a fixed value. In this thesis it will be shown that the shear angles in the chip formation area exhibit a broad distribution from 16 degrees to almost 90 degrees.

Stevenson et al. [41], and Tay et al. [42] have analyzed the effects of temperature rise on the strains generated during machining. The temperature rise will reduce the work hardening effect, therefore increase the shear angle. The strains will increase and the stress will decrease with the temperature increase.

In summary the continuum modeling approach of shear strains in metal cutting yielded results that were mostly compatible with the experimental studies of Black, Ramalingam and Von Turkovich [43-45]. Some of the most salient aspects of metal deformation behaviour during machining can be summarized as follows.

**In the primary shear zone:**

i) The final values of the strain rates depend on the cutting speed and the width of the shear bands that in turn depend on the properties of the work piece materials. According to the equation 2-10 [34] for the shear strain rate, at the cutting speed of 1mm/sec to 3000mm/sec and at the feed rate of 0.001mm to 0.25mm, the strain rates will lie in the range of $2 \times 10^2$ to $8 \times 10^6$/sec [43]. Consequently the thickness of $\Delta y$ is 1μm to 3μm which is in general agreement with the thickness of shear bands in polycrystalline metals [43-45].

ii) For the fcc polycrystalline materials, at the cutting speed of 1mm/sec to 3000mm/sec and at the feed rates of 0.001mm to 0.25mm, high shear strains, typically $\gamma_p = 2 - 5$ can be attained according to the equation (2-12). This indicates that at the
onset of chip formation process these materials lose their capacity to further strain-harden [41], *i.e.* they reach to saturation strength.

**In the secondary shear zone:**

i) The material as newly formed chip will suffer secondary strain along the interface at very high strain rates in the range of \( \dot{\gamma}_p = 10^3 \, s^{-1} \) [40, 45]. The strains can be as high as 20 – 640, (calculated for a sample of nickel alloy at the cutting speed of 35m/min using the model presented in [37, 46]).

ii) The secondary zone approximates an adiabatic shear deformation condition. The temperatures can reach 1100°C – 1200°C when cutting a low-alloy carbon steel at the cutting speed of 250m/sec with the cemented carbide tool [47].

2.5.5. Dislocation Models of Chip Formation

A microstructural description of deformation structure during machining is given by Turley [48] who has shown that in cutting 70/30 brass, there is a highly fragmented zone near the machined surface and below this is a deformed layer. The substructure in this fragmented zone can not be resolved, but a high density dislocation substructure is established in the area that is very close to the machined surface. The natural strain at the machined surface was estimated to be constant in the range of 6 - 7, being independent of rake angle, depth of cut, and the number of passes for the machining conditions. The natural strain at the bottom of the fragmented zone was about \( \sim 2 - 3 \) and hence the strain gradient within the fragmented zone depended upon the thickness of the zone. Machining variables, such as increasing the rake face angle and decreasing the depth of cut, which
reduced the thickness of the fragmented zone, caused a steeper strain gradient in the zone. At the deeper levels in the deformed zone, the strain decreased less rapidly and the strain gradient became shallower as the elastic-plastic boundary between the deformed and the undeformed material was approached. The feature of the strain distribution in machined surface from Turley's work is schematically shown in Figure 2-7.

Von Turkovich [49] has assumed that the dislocation density remains constant within the primary shear plane during the deformation process. The number of new dislocations created during the deformation process is equal to the number of the dislocations that are annihilated within the crystal and those which have escaped through the freshly machined surface. The following dislocation equilibrium equation was suggested:

$$\frac{d\rho}{dt} = 0 = m_t (\rho_c - \rho_a - \rho_e)$$  \hspace{1cm} (2-14)

where $\rho$ is dislocation density, $m_t$ is the proportionality factor, $\rho_c$ is the density of newly created dislocations, $\rho_a$ is the density of annihilated dislocations and $\rho_e$ is the density of dislocations which escape through crystal surface.

Von Turkovich [49] also noted that the average dislocation density can be expressed as

$$\rho = \sqrt{\frac{15\xi}{l^3b}}$$  \hspace{1cm} (2-15)
where the factor \( \xi \) can be estimated from the stress on the leading dislocation in a pile-up [50]

\[
\tau = \frac{\xi G b}{\pi (1 - \nu) l}
\]  

(2-16)

Since \( \tau \) is of the order of \( 5 \times 10^3 \) in metal cutting [51], and \( (1 - \nu) = 0.7 \), it follows that \( \xi = 40 \sim 50 \) for \( l = 10^{-4} \text{cm} \). Therefore, the dislocation density of the work piece in the material being cut can be of the order of \( 1.5 \times 10^{11} \). Then, the shear stress [52-56], the shear strain rate [49] and the shear strain [49] can be obtained from the following equations respectively.

\[
\tau = 10^{-7} AG b \sqrt{\rho}
\]  

(2-17)

\[
\dot{\gamma} = \frac{2
\nu_d}{q^2 b} = \frac{\rho^2 l^2 b \nu_d}{2 \xi^2}
\]  

(2-18)

\[
\gamma = \int_0^t \dot{\gamma} dt \approx \frac{d}{\nu_f} \dot{\gamma}
\]  

(2-19)

where \( q \) is the number of lattice parameters separating two active glide planes. \( b \) is Burgers vector magnitude, \( \rho \) is density of the dislocation, \( l \) is average slide distance, radius of dislocation loop, \( \xi \) is number of loops emitted by a source, \( \nu_d \) is dislocation
climb velocity, \( v_f \) is the chip moving velocity, \( G \) is the shear modulus, and \( A \) is a constant of order of 1. \( t = d / v_f \).

Assuming the following values, \( v_d \geq v_f = 100 \text{ cm/sec}, \rho = 10^{12} \text{ cm}^{-2}, l = 10^{-4} \text{ cm}, \xi = 40, \) and \( b = 2.5 \times 10^{-8} \text{ cm}, \) the strain rate will be \( 8 \times 10^6 \text{ sec}^{-1} \). If the thickness of the shear band is \( d_2 = v_s / \dot{\gamma} \) (\( v_s \) is the shearing velocity). Since \( v_s \approx 2 v_f, d_2 = 2 \times 10^2 / 8 \times 10^6 = 2.5 \times 10^{-5} \text{ cm}. \) The shear strain will then be \( \gamma_2 = \frac{d_2}{v_f} \dot{\gamma} = 2 \). These results give a good estimate for the strain and the strain rate. Black [57], has simulated orthogonal machining of single crystal aluminum, copper and polycrystalline 2024 aluminum alloy using the ultramicrotomy method. TEM examination has shown that the shear front at the free surface of the chip has a lamellar structure. The microstructure of the lamellar structure in the chip was composed of pairs of partial dislocations, triangular nodes and extinction contours. For the aluminum samples, numerous dislocation loops were observed along with dislocation pile-ups in the slip planes of the crystal. It was however suspected that the dislocation structure may have been modified due to the heating effect of the electronic beams of TEM, so that there was some structural relaxation and reorganization of the dislocation structure.

The study [57] has demonstrated the possibility of large numbers of dislocations moving large slip distances, even in the heavily work hardened parts of material being cut, if the rotation of the material at the primary system nearest to the maximum shear strain direction is prevented.

In a study of strain hardening and recovery process during chip formation in cutting \( \alpha \)-brass, Ramalingam et al. [58] have suggested that thin shear front structure was
the result of the balance between the strain hardening by the dislocation movement and dynamic recovery by recrystallization. In general terms they have indicated that the chip formation process was strongly sensitive to the defect structure of the material undergoing plastic deformation. The important variables during chip formation were listed as the number and orientation of operable slip systems, certain characteristic dislocation parameters such as the stacking fault energy, the interaction of dislocations with vacancies and solute atoms or with second phase.

In another study of the chip formation process, Ramalingam et al. [59] developed an equation to estimate the dynamic shear stress accounting for the chip morphology

\[ \tau \cdot f(\tau) \exp(-D/kT) = c \rho \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} \quad (2-20) \]

where \( c \) is the specific heat of workpiece material, \( t \) is the cutting time. \( \rho \) is the density of workpiece material, \( T \) is the temperature at the location of maximum shear, and \( x \) is the distance away from the shear plane.

In fact, after a certain time \( t \) of cutting, the temperature will reach a steady condition. Further cutting will not continue to increase the temperature. The cutting time should not affect the temperature increase, nor therefore the shear stress.

The study [14] has concluded that the shear stress involved in the cutting process can be predicted by assuming that a saturation stress state prevails in the deforming material during the chip formation. The stacking fault energy may alter the shear angle by affecting the dislocation movement.
2.5.6. Shear Bands and Their Role in Chip Formation

An important characteristic of the plastic deformation process in chip formation is the formation of the shear bands. The shear band forming process is associated with the localization of the plastic deformation process at high strains and strain rates, where the rapid rates of dissipation of the plastic work may cause adiabatic heating.

The formation of shear bands is especially sensitive to changes in the stacking fault energy of the material [43]. The higher the stacking fault energy the workpiece has, the higher the strain required to form the shear bands.

The main aspects of previous work on the substructures have been summarized in Table 2-2 [59]. The shear bands are one of the typical characteristics of the substructures.

Shear bands have been classified into two groups, microbands and macrobands. Microbands were observed by Hu (1963) [60], when annealed mild carbon steel was studied under the TEM. He defined the microbands as:

*A microband is a narrow band composed of a number of paralleled elongated segments, it has a high dislocation density and a large orientation difference across.*

Taylor (1973) [61] has defined an orientation factor $M$ as follows:

$$M = \frac{\sum \gamma_i}{\varepsilon} = \frac{\sigma}{\tau}$$  \hspace{1cm} (2-21)

where the value of $M$ was determined by finding the combination of slip systems that minimize $\gamma_i$ (but still satisfy the continuity of slip across the grain boundaries).
<table>
<thead>
<tr>
<th>Material</th>
<th>T/T&lt;sub&gt;m&lt;/sub&gt;</th>
<th>SFE (erg/cm&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Low Strains (&lt;0.3)</th>
<th>Moderate Strains (&lt;2.3)</th>
<th>Large Strains (&gt;2.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100 Aluminum</td>
<td>0.32</td>
<td>166</td>
<td>Dislocation tangles; cell network by ε = 0.1; dynamic recovery and subgrains above 0.2.</td>
<td>Cells and subgrains decrease in size, new ones form, some evidence of microbands in edge-on section.</td>
<td>Structure looks highly &quot;recovered&quot;; more subgrains misorientation between subgrains continues to increase. Only occasional microbands at ε = 2.3</td>
</tr>
<tr>
<td>200 Nickel</td>
<td>0.17</td>
<td>128</td>
<td>Dislocation tangles; cell network by ε = 0.1.</td>
<td>Cells decrease in size, definite recovery at ε &gt; 1 with distinct subgrain boundaries. Cells and subgrains continue to decrease. Structure looks ribbon-like. Some evidence of microbands.</td>
<td>Continues recovery; cells and subgrains continue to decrease in size (edge-on). No evidence of microbands or shear bands.</td>
</tr>
<tr>
<td>Copper</td>
<td>0.22</td>
<td>78</td>
<td>Dislocation tangles; cell network by ε = 0.1; microbands evident by ε = 0.2</td>
<td>Microbands along {111}; rotate toward rolling plane; new microbands form. Much of deformation appears by microband mechanism. Macro shear bands form at ε &gt; 1.</td>
<td>Shear bands assume dominating role in deformation. Dynamic recovery occurs. Dynamic recrystallization at very large strains ( &gt; 4).</td>
</tr>
<tr>
<td>70-30 Brass</td>
<td>0.2</td>
<td>14</td>
<td>Slip by partials; develop planar dislocation array, followed by microbands.</td>
<td>At strains of 0.5 to 1.3, twinning is major deformation mode deformation ode observed; twins form and rotate to align with rolling plane; by ε = 1.6 most of volume is twinned.</td>
<td>Extensive macro shear banding, especially in twinned areas. Subgrains form in shear-band areas, and again deform by slip.</td>
</tr>
</tbody>
</table>
Due to the inhomogeneous nature of slip, latent hardening effects may result [62, 63]. Some slip systems in aluminum and copper monocrystals [64, 65], form dense dislocation walls (DDW) locally.

The width of the microbands is the distance between the dense dislocation walls. Macrobands or the shear bands may run through the large fraction of a grain or may run through multi-grains. Therefore, the shear bands can significantly influence the flow stress anisotropy [66]. Once shear bands formed the subsequent deformation is normally localized within these bands. Such intensive local deformation may lead directly to ductile fracture.

Timothy [67] defined the shear bands as being either “transformed” or “deformed” according to how the prior shear deformation is partitioned between two discrete zones. The transformed shear bands are often partitioned into two distinct regions: a central zone of intense shear deformation is accompanied by significant microstructural modification of the original material. A single phase predominates within the central zone, consisting either of the high density of dislocations with some cells, or cells, sub-grains or grains that are usually equi-axed, and between 0.1μm and 0.5μm in diameter. While the deformed shear bands are thought to be the earlier stage of adiabatic strain localization, in which there is no central zone like transformed shear bands.

In the study of eutectoid steels at high strain rate and different temperatures, Nakkalil [68] suggested that the deformed and transformed shear bands, rather than being two separate phenomena, are only an outcome of the extent of adiabatic strain localization occurring during deformation. The deformed bands form with less localized flow, and the transformed bands form with extensive localized flow.
In the study of Ti-6%Al-4%V titanium alloy, Timothy [69] has shown that the adiabatic shear bands often act as precursor sites for eventual failure of the material. The hardness of the intense deformed shear bands was only slightly higher than the adjacent material. It was suggested [69] that "the thermal recovery within the shear zones could equal or outweigh any hardening effect of the concentrated shear deformation (and/or phase transformation), resulting in an overall absence of hardening, or even softening of the shear band material with respect to the adjacent matrix after cooling to room temperature". The temperature can rise to as high as exceeding the melting point of the titanium alloys in micro-ligaments at the moment of final separation. A study of shock deformation of 6061-T6 aluminum alloy [70] has shown that the temperature could rise to 600°C under the pressure of 11 GPa and the strain rate of 10^7/sec. These conditions are not unlike those encountered in metal cutting operations.

2.5.7. Continuity of Chips

Two types of chips have been observed, depending on the properties of workpiece materials and machining conditions. These are:

- Continuous chips and continuous chips with build-up edge
- Discontinuous chips, which features intense deformation (or shear localized chip, i.e. segmental chips)

The shear localization in the workpiece is the main reason for the formation of discontinuous chips. The discontinuous chip formation process involves plastic instability and strain localization in a narrow area within the primary shear zone leading to catastrophic shear failure along a shear surface. In cutting a hardened steel, Matsumoto
[71] showed the surface originates from the tool tip approximately parallel to the cutting velocity vector and gradually curves concavely upward until it meets the free surface.

The transition from continuous to discontinuous chip formation depends primarily upon the material, its thermo-mechanical condition, and the cutting speed [71-74]. For the AISI 4340 steel, at low speed, continuous chips form [73]. As the cutting speed increased [73], a transition from continuous to segmental chip formation occurred, the latter composed of distinct trapezoidal segments. The deformation of the chip was inhomogeneous on a macroscopic level with two wide regions: one where deformation is very severe (i.e. between the segments) and the other where deformation was relatively low (i.e. within the segments).

With further increases in speed, "the shear-localized instability" was established completely in the primary shear zone, which resulted in concentrated intensive shear between the segments, separated by large areas of relatively less deformed material within the segments [73]. At still higher speeds, the extent of contact between the segments decreased, which resulted eventually in completely isolated segments.

Similarly, Inconel 718 forms relatively continuous chips below 60 m/min, but within the range of 60 – 120 m/min segmentation begins and at higher speeds severe detachment occurs [75]. In titanium alloys, the segmented chips are common [75]. Over a range of speeds from 0.0012 m/min in machining experiments inside a scanning electron microscope [75] to 18,000 m/min in ballistic machining experiments [76], discontinuous chips have been observed to occur. The size and the spacing of the segments in a discontinuous chip depend on the feed rate and the rake angle but appear to be independent of the cutting speed.
Chip segmentation or shear localization is favored by low thermal diffusivity, hexagonal closed packed structure (limited number of slip systems), and high hardness (exhaustion of work hardening). Titanium alloys, nickel-base superalloys, and hardened alloy steels are susceptible to shear localization, but this only happened at certain cutting speed [77-78].

2.5.8. Built-Up-Edge (BUE) and its Effects

At some intermediate cutting speeds, the cutting force decreases to a minimum value and increases again with the increase of cutting speed. The minimum in the cutting forces corresponds to a situation where a layer of material grows on the rake face of the tool ahead of the cutting edge that is known as the built-up-edge. The built-up-edge is composed of layers of the strain hardened material that has accumulated on the rake face to appear as an extension of the tool [79]. At a relative low cutting speed of 15m/min in machining low carbon steel, the built-up-edge can form. The hardness test of the built-up-edge can reach up to 600HV (compared with 200 – 250HV in the body of the chip) revealing the work hardening effect [80].

The built-up-edge induces several effects. It alters the tool geometry thereby reducing the area of contact of the chip with the rake face [20]. This increases the shear plane angle and reduces the cutting and feed forces. The fragments of built-up-edge, which are constantly breaking away, leave a very rough surface finish and if surface finish is important, high cutting speeds must be used [80]. High cutting speeds increase the power used thereby heating up the chip until the metal in the built-up-edge experiences recovery and re-crystallization [79, 81]. This softens it until it is swept away
by the stress on the rake face. The presence of a built-up edge can often protect the tool from wear and, for some materials which have relative poor surface finish due to their heterogeneity, e.g. 6061-10vol.%Al₂O₃ composite material, the formation of a built up edge is encouraged.

In cutting mild steel at the medium cutting speeds of 5.5 m/min to 64 m/min, the thickness of the built-up edge increased as the speed increased from 5.5 m/min to 15 m/min [79]. The size of the BUE was reduced when the cutting speed increased further and disappeared completely at the speed of 64 m/min. The build-up edge did not form at low and high speeds but reached its maximum at a very definite speed of 15 m/min [79]. During the formation of built-up edge, the temperature at the tool rake face must be high enough so that the workpiece material seizure on the rake face is strong enough to form a layer [80-81].

2.6. Temperature Increase and its Effects on Machining

Temperature increase during metal cutting, recognized as early as one century ago, was first mentioned in Taylor’s paper “On the Art of Cutting Metal” in [5]. It is generally accepted that there are three sources of heat generation. These are:

1) Primary shear zone where plastic deformation by shearing occurs.

2) Secondary shear zone where the newly formed chip suffers from secondary deformation by heavy load friction between chip and the tool rake face.

3) Second friction zone where the friction is between the worn surface on the tool flank face and the freshly machined surface.
As a first approximation, the heat produced per unit time, \( Q \), in metal cutting can be determined in the form of product of cutting speed \( v \) and the cutting forces \( f \), based on the operation parameters. Thus the total heat is:

\[
Q = J \cdot v \cdot f
\]  \hspace{1cm} (2-22)

where \( J \) is the equivalent mechanical heat. The total heat will be composed of three heat from different heat sources [6]:

\[
Q = Q_s + Q_f + Q_a
\]  \hspace{1cm} (2-23)

where \( Q_s \) is the heat from shearing in the chip forming area, \( Q_f \) is the heat from the friction between the tool-chip interface at rake face of cutting tool, and the \( Q_a \) is the heat from the friction between the tool-chip at flank face of the tool.

All these heat components may transfer away from the heat sources, either by the moving chip, by conduction into the bulk of the workpiece, or into the cutting tool. Brackenburg and Meyer [79] carried out the tests to study the heat generation in metal cutting. They used the principle of mechanical work transferring to temperature increase of water during a cutting process in an isolated system. At the cutting speed of 3.3 m/min, 61 per cent of the total generated heat was carried away by the moving chip. At the cutting speed of 25 m/min, the percentage of the heat carried away by the moving chip was 78 percent. Therefore, they concluded that the amount of the heat carried away by the moving chip was proportional to the cutting speed.
According to [83] the parameter that should be used in the analysis of the heat generation and dissipation by chip was $\zeta$ that is the ratio of the heat dissipated by the chip, $H_c$, to the heat generated, $H_e$. This ratio can be expressed as follows:

$$\zeta = \frac{H_c (\text{heat dissipated by chip})}{H_e (\text{total generated heat})} \quad (2-24)$$

The typical energy (heat) distribution in metal cutting at conventional speeds is shown in Figure 2-8 [83]. The figure also indicates that most of the heat generated in metal cutting was dispersed by the moving chip. The heat that remains in the cutting tool, however, is usually only 10 – 20 percent of the total heat generated, against 80 percent in the chip at present day’s cutting operations [83].

The total heat generated in metal cutting depends on the cutting operation parameters. The heat transferred and dissipated from the cutting tool, the chip and the workpiece depend on the physical and thermal properties of the tool and the workpiece such as the density, $\rho$ and the specific heat, $C_p$.

There are several temperatures of importance in metal cutting. The shear plane temperature $T_s$ is important for its influence on the tool rake face temperature $T_R$ and on the flank face temperature $T_f$, which are main concerns to crater wear and flank wear development respectively. $T_s$ is also important because it determines whether adiabatic shear bands will form or not in certain materials such as stainless steel and Ti-alloys. The temperature on the tool rake face plays a major role on determining the size and the stability of the build-up-edge effects. The workpiece temperature, $T_o$, is also important since it directly affects $T_s$, $T_f$ and $T_R$ [6].
2.6.1. Temperature Measurements

Because of the difficulty of making direct measurements of the temperature at the contact interface different indirect methods of temperature measurement developed. These methods can be classified into four groups:

1) Tool-Workpiece thermocouple measurements,
2) Direct embedded of thermocouple measurements,
3) Infra-red radiation photography focused on the tool tip,
4) Thermosensitive paints or coatings on tool or side of workpiece close to the tool tip.

The tool-workpiece thermocouple technique that was first used by Herbert [84] is shown in Figure 2-9 a). The temperature is measured by tool-workpiece thermocouple method is answered by analyzing the electrical potential distribution in a cutting tool due to the distributed interfacial *emf*. The calibration of this set-up is explained later by Roeser [85]. This measurement technique has shown that the equilibrium values of temperatures are reached almost instantaneously at the start of cutting. However the method is strongly influenced by the setting up of the thermocouple system, the tool wear patterns, the formation of the built-up-edge and the contact surface roughness. The accuracy range is below 760°C [86].

The idea of using the embedded thermocouple was also proposed by Herbert, see Figure 2-9 b) [84]. But, because of the difficulty of making a small hole in hard tool, it was not used at that time. This is no longer a problem at the present time and this technique is being widely used to measure the temperatures on the tool side close to the
interface on the rake face of the cutting tool. The thermocouple can be placed in any location. The measurement results have shown that the maximum temperature occurred on the rake face some distance away from the cutting edge, see Figure 2-10 [87]. This method has been adapted in present work to measure the temperature distribution in the interface between the rake face of the cutting tool and the moving chip.

The indirect (non-contact) temperature measurement method was also used in the study of temperature distribution. Infrared radiation photography techniques were first used by Boothroyd [88]. The temperature distribution at the interface of tool rake face-moving chip was determined as the result of tedious experimental results analysis, as shown in Figure 2-10, which has been verified by Burkes [89] using a hi-tech infrared radiation photography instrument. The maximum temperature is about one-third away from the cutting edge along the tool-chip interface. This can be considered as a general pattern of temperature distribution in cutting tool.

The difficulty of using infrared radiation photography technique is tedious work and the accessibility to the measured surface. A “drilling-a-hole” technique developed by Bickel [90] improved the accessibility of the area where the temperature distribution is supposed to be measured. The application of this technique is limited because of its accuracy and the high cost of the instrument.

Thermal sensitive paintings were used by Birkel et al. [91] and Kato et al. [92] and others. This method is limited to the accessible surfaces under the steady state conditions. The value from this method is limited to the estimation of the relative tool temperatures and is not useful for the accurate temperatures at actual contact surfaces.
2.6.2. Theoretical Calculations

Theoretical analyses have been performed to establish general models that can be used to predict the temperature distribution. In general, three methods have been used:

1) Heat transfer analyses,

2) Mechanics analyses,

3) Dimensional Analyses.

Heat transfer models are based on the fact that heat generation and heat transfer occurred during metal cutting. The phenomenon occurring during orthogonal machining may be governed by the following partial differential equation [93]:

\[ k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \rho C_p \left( \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) + \dot{Q} = 0 \]  

(2-25)

by considering heat transfer and heat convection. This equation has been used from early time, Weiner [94], Rapier [95], Muraka [96] and Smith [97] to current time, Ramanujachar et al. [98], Ding, et al. [99], Chu, et al. [100], and Chang, et al. [101]. The boundary conditions for the equation are:

i) \( T = T_b \) on part of boundary \( S_T \)

ii) \( -k \frac{\partial T}{\partial n} = q \) on part of boundary \( S_q \)

iii) \( -k \frac{\partial T}{\partial n} = \kappa (T - T_o) \) on part of boundary \( S_h \)

where the surfaces of \( S_T, S_q \) and \( S_h \) are defined as shown in Figure 11 [102].

In addition to these boundary conditions, the assumptions regarding the allocation of heat sources are required to solve the heat transfer problems. For example, Chao [93]
and Rapier [95] assumed that the heat sources in both the primary and secondary shear zones are planar and uniform. The maximum temperature along the tool-tip interface was found to be at the end of the planar heat source.

Rapier [95] has shown that the most of the heat generated in the frictional heat sources was carried away by the moving chip and thus, the thermal properties of the cutting tool had little influence on the temperature increase at the tool-chip interface.

Boothroyd [88] found the experimental values of temperature were considerably lower than the values predicted by Chao [93] and Rapier [95] models. He attributed this discrepancy to the fact that the heat sources were along the contact length rather than being of planar form. The temperature distribution should be shown as a function of the size and shape of the heat sources.

Finite element analysis methods were first successfully applied by Tay et al. [103] to calculate the temperature field in the workpiece, chip and the tool during orthogonal machining. This was achieved by solving the Equation (2-25) with the boundaries mentioned above.

Finite element methods enable workpiece material properties, cutting parameters and tool geometry to be included in the analysis. The results will be only as good as the properties employed in the analysis. The typical temperature distribution field obtained by finite element method matches well the results from the experiment ones. The variation is due to the boundary condition and the meshing methods.
2.6.3. Mechanics Analysis

Trigger [104] carried out a mechanics analysis of temperature increase. By considering the deformation energy and mechanical equivalent heat, the temperature rise may be expressed as:

$$\Delta T = T - T_o = \frac{A \cdot \{ F_c \cdot V_c (l - B_f) - F \cdot V_f \}}{J \cdot C_p \cdot (V_c \times 12) \cdot t \cdot w} \quad (2-26)$$

where \( C_p \) is specific heat of workpiece material. \( F_c, V_c, V_f \) are cutting force, cutting speed and feed rate respectively. \( J \) is mechanical equivalent heat, \( A \) is dimensional coefficient, \( t \) is the chip thickness, \( w \) is the width, and \( I \) and \( B_f \) are the geometry factors of the chip formation area. Even though these results from mechanical analysis give a good average value of the temperature rise, they can not be used to locate the temperature at the point of interest.

In addition to these boundary conditions, the assumptions regarding to the allocation of heat sources are required to solve the problems. Chao [93] and Rapier [95] assumed that the heat sources in both the primary and secondary shear zones are planar and uniform. The maximum temperature along the tool-chip interface was found to be at the end of the planar heat source. Rapier has shown that most of the heat generated in the frictional heat source was carried away by the moving chip and thus, the thermal properties of the cutting tool had little influence on the temperature rise generated at the tool-chip interface.

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discrepancy to the fact that the heat source is along the contact length rather than being in planar form. The temperature distribution should be shown as a function of the size and shape of the heat source.

2.6.4. Dimensional Analysis

Reasoning that the mean temperature rise is related to material properties and operating parameters, Kronenberg [105] applied a dimensional analysis to the tool face temperature problem. Four dimensionally independent quantities were related to each other in the following form:

$$\frac{T_{\text{surface}}(\rho C)}{u} = \varphi \left( \frac{AV^2(\rho C)^2}{k^2} \right)$$  \hspace{1cm} (2-27)

This form was improved by considering the $(k\rho C)$ as a single variable instead of including both $k$ and $\rho C$, and involving the uncut chip thickness $t$, giving the following form:

$$\frac{T_{\text{surface}}}{u} \left[ \frac{k\rho C}{Vt} \right]^{1/2} = \text{constant}$$  \hspace{1cm} (2-28)

Dimensionless analysis lead to very interesting investigations of the tool life-cutting speed relationship as disclosed in the Equation (2-28). It suggests that the temperature at tool-chip interface be proportional to the square root of the cutting speed and the cutting time, but inversely proportional to the properties of workpiece material.

Even though when only 10 percent of the total heat is available for the cutting tool, we can expect the cutting tool to have a higher temperature rise than the chip that
carries 80 per cent of the total heat. The reason is 75 per cent of the total heat dispersed in the chip is carried away by chip removal.

In addition, the cutting tool has the higher density and higher specific heat than workpiece material, which allows the cutting tool to retain more heat per unit volume than the workpiece does. Therefore, the cutting tool will suffer from higher level of temperature rise.

2.7. Tool Wear and Tool Life Prediction

Tool wear on the rake face and on the flank face of cutting tool is the dominant cause of the failure of the cutting tool. Flank wear is normally measured in terms of the width of the worn area on the tool flank face. Flank wear results in a loss on the clearance face of the tool, which leads to an increase in friction. As indicated in Section 2-6, the highest temperature within the contact area is located at the cutting edge of the tool [105]. The typical form of the tool life, according to the Taylor equation [5], is:

$$TV = C \quad (n < m < l) \quad (2-29)$$

where $T$ is tool life, $V$ is cutting speed, and $n$, $m$, and $l$ are material constants.

Based on the Taylor’s equation, Woxen [106] and Colding [107] have shown that tool life is a simple function of temperature, which may be written approximately as follows:

Woxen [106]  \hspace{1cm} \text{Tool Life} = c(T - T_o)^{-\beta/\alpha} \quad (2-30)
Colding [107]  \[ \text{Tool life} = \text{constant} \times \exp\left(\frac{u}{2RT}\right) \]  

(2-31)

These simple models imply that the tool life is shortened with the temperature rise. While Kronenberg [105] gives a opposite result by applying dimensional analysis, which shows that the tool life varies with the eighth to twenty-third power of the temperature. It was expressed in the form of

\[ \text{Tool Life} \propto T_{\text{tool face}}^{\frac{1}{(0.5-2m)}} \]  

(2-32)

where \( m \) has a value between 0.188 and 0.228. The result from dimensional analysis was confirmed with Schallbroch [108].

Crater wear is measured in terms of the depth of crater on the rake face with a profilometer. At the contacting area between the moving chip and the tool rake face the temperature and the pressure are high. The location of maximum wear is at the middle of the contact area that suffers from the highest temperature rise. Taylor’s equation can also be applied to the crater wear.

The general form of the tool life model proposed in the literature and the most commonly known equations for predicting tool life are listed in Table 2-3.

Some important concerns can be identified from the previous work. Almost all the expressions are based on flank wear (VB) and/or crater wear (KT) criterion.
### Table 2-3. Most commonly known equations for predicting tool life

<table>
<thead>
<tr>
<th>No.</th>
<th>Tool life equation ((t, \text{ tool life (min)}))</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Taylor’s basic equation: (V t^n = C)</td>
<td>[79-106]</td>
</tr>
<tr>
<td></td>
<td>where (V = \text{cutting speed}) and (t = \text{tool life}).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- C and (n) are experimentally determined and currently available from many</td>
<td></td>
</tr>
<tr>
<td></td>
<td>reference sources.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Most widely used equation, however, (C) and (n) apply only to particular tool</td>
<td></td>
</tr>
<tr>
<td></td>
<td>workpiece combination.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Taylor’s reference-speed-based equation: (\left(\frac{V}{V_R}\right) = \left(\frac{t_R}{t}\right)^n)</td>
<td>[100,110]</td>
</tr>
<tr>
<td></td>
<td>where (V) is the reference cutting speed for reference tool-life (T_R = 1) min.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- (N) is experimentally determined and currently available from many reference</td>
<td></td>
</tr>
<tr>
<td></td>
<td>sources.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- (N) applies only to particular tool-workpiece combinations.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Taylor’s extended equation: (t = \frac{C_2}{V^p f^q d^r})</td>
<td>[109,111-114]</td>
</tr>
<tr>
<td></td>
<td>where (f = \text{feed rate}) and (d = \text{depth of cut}).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- All constants ((C_2, p, q \text{ and } r)) are experimentally determined.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Gives better accuracy than Taylor’s basic equation, but more tool-life tests are</td>
<td></td>
</tr>
<tr>
<td></td>
<td>required.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Temperature based tool life equation: (T t^n = C_3)</td>
<td>[110,115-116]</td>
</tr>
<tr>
<td></td>
<td>where (T = \text{tool temperature}).</td>
<td></td>
</tr>
</tbody>
</table>
- N is found between 0.01 and 0.1 and C is experimentally determined.

- Although the equation is set only on an empirical basis, it is not convenient for practical use in the shop floor environment.

| 5 | Colding's equation based on ECT (equivalent chip thickness):

\[ y = k \frac{(x - H)^2}{4M} - \left( N_0 - L_x \right)z \]

where \( x = \ln \text{ECT} \), \( y = \ln V \) and \( z = \ln t \)

- 5 constants (\( K, H, M, N_0 \) and \( L \)) are empirical determined; feed, depth of cut, lead angle and nose radius are integrated into a single parameter ECT.

- It is claimed that the accuracy can be -50% - 100%; tool life prediction is inconsistent.

| 6 | Taylor's basic equation including rake angle and clearance angle:

\[ C \alpha \left[ (\cot \beta - \tan \alpha)^n F(\alpha, \beta)^{1/r} \right]^{-1} \]

where \( F(\alpha, \beta) \) is a function of \( \alpha \) and \( \beta \).

- The influence of \( \alpha \) and \( \beta \) can be theoretically determined as a part contribution to Taylor's constant \( C \).

- A complicated relationship between tool-life and rake/clearance angles.

| 7 | Taylor's extended equation including cutting conditions and tool geometry:

\[ t = C_4 V^n f^m d^p r^q s^t j^z \]

- Requires excessive tool-life tests to determined all constants (\( C_4, n, m, p, q, t, u \), and \( x \)).

- It is claimed that the data for setting up the equation are general from both
| 8 | Taylor’s extended equation including cutting conditions and workpiece hardness:  
\[ V = \frac{C_t}{t^m f^n d^n (BHN/200)^n} \]  
- All constants \((C_t, m, y, x, \text{ and } n)\) are experimentally determined.  
- It is claimed to be a good approximation for tool life ranges of 10-60 min. | [122, 123] |

A list of critical flank wear (VB) and crater wear (KT) values for tool failure is given below.

- \(VB = 0.3 \text{ mm regularly worn or} 0.6 \text{ mm unevenly worn as specified by the ASME standard [124];} \)
- \(VB = 0.2 \text{ mm for light,} 0.35 \text{ mm for normal and} 0.5 \text{ mm for large wear in ISO/DIS 8688 standard [125];} \)
- \(KT = 0.06 + 0.3f \) (\(f = \text{feed in mm/rev}\) in ASME standard [128] and ISO/DIS 8688 standard [125].

However, most often the tool failure depends on a combination of different tool wear criteria, with one or more wear mechanisms playing a dominant role. In fact, different cutting tool manufacturers have formed their own combined tool wear standards based on experience, although no universally accepted standard is available.

The main types of cutting tool failure are summarized below:
2.7.1. Abrasive Wear

If the material to be cut contains hard particles, the abrasive wear may occur between the tool face and the hard particles or hard inclusions in the matrix. Abrasion can be also caused by the entrapment of hard particulate or its debris between two softer surfaces [125]. The sizes of hard particles or inclusion have an effect on the abrasive wear. According to [126], small hard particles with the size of less than about 5 microns have little influence on the rate of tool wear, but large particles or concentrated aggregates of small particles may greatly increase the wear rate.

Because of the presence of the ceramic particles SiC and Al₂O₃, the tool wear in cutting metal matrix composite has been attributed to the abrasive wear [127, 128]. The main factors affecting tool life have been identified as the cutting speed, feed rate and the tool hardness.

2.7.2. Dissolution Wear

When the temperature at the tool-workpiece interface is high enough, some of the tool material may diffuse into the workpiece. In other words, the tool surface material is dissolved by the workpiece material flowing over it. The basic requirements for diffusion controlled dissolution wear are: i) metallurgical bonding of the two, ii) temperatures high enough to cause rapid diffusion, and iii) some solubility of the tool material in the work material. Diffusion controlled dissolution wear is considered as the dominant mechanism of the wear on the tool rake face when high enough temperatures are generated. Quantitative measurements of the diffusion wear on the crater face have been done by neutron activation analyses [129]. For a carbide tool during cutting a free machining
steel, 66.4% of the total crater wear was due to the diffusion wear [129] at the cutting speed of 150 m/min, and this increased to 93.4% at the cutting speed of 240 m/min. The total crater wear was due to the diffusion wear.

The local equilibrium concentration of solute and the square root of the diffusion coefficient are the key material parameters that determines the diffusion tool wear, which decreases with the decrease of the temperature at the interface [130]. The grain size is another concern that affects the diffusion wear rate. For a tungsten carbide cobalt tool, as the WC grain size increases, the tool wear rate decreases, in spite of a reduction in tool hardness [131].

Crater wear occurs under the conditions that depend on the cutting speed and feed rate. The relationship can be shown as Figure 2-12, for medium carbon steel cut by a WC-6%Co tool [126]. Crater wear is not observed below the lower line and becomes so severe that it destroys the tool very rapidly above the upper line. The position of the crater wear starting line and the rapid crater wear line depends upon the tool material.

2.7.3. Tool Fracture

Cutting tools are susceptible to fracture by cracking and chipping, which form at the tool tip and lead to tool failure. The toughness of carbide tools is strongly influenced by the binder composition [132]. For polycrystalline diamond tools, the graphitization of the diamond by the catalytic function of cobalt at elevated temperatures, above 700°C, reduces the hardness of the tool, which facilitates chipping [133].
2.7.4. Deformation Induced Failure

The shape of the tool tip may be changed by plastic deformation resulting from the high stress and temperature near the cutting edge during cutting. Especially when the temperature is high at the interface of the tool and the chip, the moving chip can drag the tool material from the crater area. The deformation causes accelerated wear on the tool flank face or rake face with sudden collapse of the tool. The upper limit to the rate of metal removal may occur when the tool is no longer able to resist the stress and temperature near the edge. Tool deformation may, therefore, initiate the wear processes that terminate tool life [134].

2.8. Factors Influencing Tool Wear in Machining Metal Matrix Composites

Due to the existence of the hard reinforcing particles in the metal matrices, tool wear is more severe. The factors that significantly affect tool wear can be summarized as follows:

2.8.1. Tool Hardness

Brun et al. [135] have shown that the hardness of the cutting tool does not always have a linear relationship with the wear rate of tool. There is a clear difference in the performance of tools harder than reinforcements and that of tools softer than the reinforcement in composite materials.

All the tool materials harder than the hard reinforcements, other than sintered cubic BN, fell on a straight line, indicating that the wear rate shows an approximately
inverse linear dependence on the hardness. Tool materials softer than hard reinforced particles did not show such a simple trend.

2.8.2. Cutting Speed and Feed Rate Effects

Monaghan et al. [136] observed that with a ceramic tool coated with silicon nitride, flank wear decreased with the increase of cutting speed in the range of 25 to 170 meters per minute. At lower cutting speed ranges, this fact was not significant.

In cutting an aluminum matrix composite with 14vol.%SiC [136], tool wear increases with the cutting speed for a given time. Similarly, Line et al. [137] has shown that the tool life decreases with increases of the speed and the feed rate.

2.8.3. Temperature Effects on Cutting Tool Wear

The temperature rise in the chip formation area may lead to the following possible results:

i) Significant reduction in the hardness and the strength of workpiece material at the front of the cutting edge;

ii) Slightly molten workpiece material at the interface on the tool rake face. This may reduce the rake face wear of tool, and also the abrasive wear on the flank face by wrapping the particles;

iii) Thermal shock may increase the risk of microcracking of the tool tip;

iv) Increasing seizure on tool tip may worsen the integrity of the machined surface.
2.8.4. Surface Quality

Particles can severely damage the surface integrity in three ways, as observed while cutting an aluminum alloy with 10vol.%Al$_3$O$_2$:

i) particles can fracture producing sharp angularity appearing on the machined surface;

ii) particles may be pressed forward into the matrix leaving the backside of the particles torn apart from the matrix. These defects reduce the surface integrity of the machined parts.

The surface finish strongly depends on the feed rate. In test [138], at the large feed rate of 0.48 mm per revolution, the surface finish decreases with the increase of the cutting speed up to 75 meters per minute.

A further increase of the cutting speed will not affect the surface finish. At the smaller feed rate of 0.24 mm per revolution, the surface finish will not be affected with the increase of the cutting speed. The surface integrity may be improved with tool wear increase, but may worsen with the seizure and the build-up-edges [139].
Fig. 2-1. A metal cutting system that includes cutting tool aspects, workpiece properties and operation parameters [8]. Tool life in the cutting process is dominated by cutting tool, operation parameters and workpiece material. As soon as any of the three aspects has been chosen, the tool life depends on the aspects that form the interaction.
a) Piispanen idealized model of cutting process [10].

b) Severe plastic deformation zone [16]. When cutting speed is higher than 150 m/min the width of the primary shear zone is only a few microns. Thus, the shear zone approaches a shear plane.

Fig. 2-2. Idealized shear model by Piispanen [14] and severe deformation zone model by Okushima et al. [16].
a) Parallel sided shear zone model [17]

b) Curled chip model [18]

Fig. 2-3. Parallel shear model by Oxley et al. [17] and curved shear model by Dewhurst [18].
Fig. 2-4. Schematic diagram of composite forces by Ernst and Merchant [23]. Shear is constrained on a single plane, which leads to the uniformity of forces, thus the shear.
Fig. 2-5. Rowe and Spick's simple model of plastic energy rate vs. shear angle: if $\alpha = 6$ degrees, the minimum power of primary shear, $W_P$ arises when $\phi$ is 48 degrees, provided that the tool is frictionless, i.e. $W_s = 0$. However as $W_s$ is increased as schematically shown, the minimum in the total power curve $(W_P + W_s)$ moves to lower $\phi$ values [34].
Fig. 2-6. Schematic representation of the physical significance of shear strain in metal-cutting process [40].
Fig. 2-7. Strain distribution and dislocation substructures in the fragmented and deformed zones beneath a machined surface. Single cut 0.0050 inches (0.127mm) deep, 0 degree rake angle on a 70/30 brass [48].
Fig. 2-8. Energy (heat) distribution in metal cutting at conventional cutting speeds [83].
a) Setup of Tool-Workpiece thermocouple technique [84]

b) Setup of direct measurement of temperature distribution [84]

Fig.2-9. Schematic diagram of setup of tool-workpiece technique and embedded thermocouple technique. a) calibration required for tool-workpiece technique and b) simple thermocouple in hole technique [84]
Fig. 2-10. Schematic diagram of temperature distribution in cutting tools. a) temperature distribution in a new tool and b) temperature distribution in a worn tool [87].
Fig. 2-11. Problem region showing thermal boundary conditions [102]
Fig. 2-12. Schematic diagram showing relationship of crater wear with the feed rate and the cutting speed [126]
CHAPTER 3.

EXPERIMENTAL PROCEDURES AND MATERIALS

3.1 Introduction

A 6061 aluminum alloy, a C11000 commercially pure copper and a 6061 aluminum alloy based metal matrix composite reinforced by 10vol.%Al₂O₃ particulate have been selected to study micromechanisms of plastic deformation behaviour during chip formation process.

In this chapter the experiment set-up used in measuring the temperature is described. The temperature measurements conducted are explained in detail.

Details of compression tests and the micro hardness measurements are given. The chapter ends with the description of the methods used for metallographic sample preparation and the analytic techniques used for material characterization.

3.2 Machining Experiments

Chip formation studies were conducted at various cutting speeds and feed rates under orthogonal cutting conditions using a standard lathe (Gemico) equipped with quick stoppers. Thermocouples inserted into the cutting tool were used for the measurements of the temperature changes embedded at the tool tip during the machining.

A photograph of the experimental set up is given in Figure 3-1. A schematic drawing of the experimental set up is shown in Figure 3-2. The experimental set up was designed to enable measuring and recording temperature data. This was achieved by using a data acquisition interface with multi channel capability that collected and

66
digitized analogue input signals from the thermocouples. Data acquisition and analysis were carried out using the LabView software.

3.3 Temperature Measurements

The temperature variations in the cutting tools were measured using K-type (Chromel-Alumel) thermocouples. Three thermocouples were mounted at different locations on the cutting tool insert to measure the temperatures at the tool tip, and near the rake face area. They were placed as shown in Figure 3-3. The grooves on the tool inserts where the thermocouples were installed were cut by low speed diamond saw. The standard variation of the measured temperature during the constant cutting process is ±2%. A typical temperature change versus cutting time data set is given in Figure 3-4.

During the tests the data collected as a function of time were simultaneously displayed on four windows on the computer screen (see Figure 3-1). The first three display areas were for the force measurements and the fourth window was for the temperature measurements.

3.4 Machining Parameters

Cutting speeds of 20 rpm (0.025 m/sec), 60 rpm (0.074 m/sec), 400 rpm (0.49 m/sec), 490 rpm (0.6 m/sec), 1000 rpm (1.23 m/sec), 1500 rpm (1.84 m/sec) and 2000 rpm (2.45 m/sec) were used. The feed rates were 0.05 mm, 0.10 mm, 0.15 mm, 0.20 mm, 0.25 mm and 0.30 mm. The rake angle was kept constant at negative five degrees.
3.5 Cutting Tool Materials

The two types of cutting tool inserts used in this study had both flat surfaces without chip breakers, and the dimension is 12.5 mm by 12.5 mm by 5 mm. The "ceramic insert" was sintered Al₂O₃ (supplier: ADAMAS) and the cemented carbide inserts were cobalt bonded tungsten carbide (supplier: KORLOY). Some important properties of the insert materials are listed in Table 3-1.

3.6 Workpiece Materials

Materials chosen to study their chip formation characteristics were as follows:

a) A wrought aluminum 6061(Al-Mg-Si) aluminum alloy,

b) An aluminum matrix composite: Al6061 alloy matrix reinforced with 10vol.% Al₂O₃ particulates (Duralcan W6A.10A),

<table>
<thead>
<tr>
<th>Properties</th>
<th>Ceramic Insert</th>
<th>Cemented Carbide Insert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point, °C</td>
<td>2050</td>
<td>2800</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion, μm/m.K</td>
<td>8.4</td>
<td>28</td>
</tr>
<tr>
<td>Thermal Conductivity, W/m.K</td>
<td>5</td>
<td>120</td>
</tr>
<tr>
<td>Transverse Rupture Strength, MPa</td>
<td>600–850</td>
<td>1250–2100</td>
</tr>
<tr>
<td>Fracture Toughness, MPa√m</td>
<td>3.5–4.5</td>
<td>10.0–13.5</td>
</tr>
<tr>
<td>Hardness, HV (1000g)</td>
<td>2250 @ RT</td>
<td>1700 @ RT</td>
</tr>
<tr>
<td></td>
<td>1850 @ 200°C</td>
<td>1600 @ 200°C</td>
</tr>
</tbody>
</table>

c) A Commercial purity single phase polycrystalline C11000 type copper.
The chemical compositions of these materials are listed in Table 3-2.

The 6061Al-10vol.%Al₂O₃ was supplied by Alcan International (Kingston, Ontario Canada) as hot extruded tubes with an extrusion ratio of 20:1. The Al6061 and C11000 were also hot extruded with the same extrusion ratio of 20:1. The tubular samples had an inside diameter of 21.43 mm and an outside diameter 25.40 mm. The thickness of the tube wall is 1.99 mm. The cutting tests on the 6061Al-10vol.%Al₂O₃ were performed on the samples in the as-received condition.

The same metallographic polishing preparation procedures were used for all the materials. After rough polishing to 1200 grid polishing, the final polishing procedures was as followings: A diamond suspension was used in the 6 μm and 1μm polishing steps to polish the 6061Al-10vol.%Al₂O₃ samples.

**Table 3-2 Chemical composition of the materials studied**

<table>
<thead>
<tr>
<th>Weight %</th>
<th>6061 aluminum [140]</th>
<th>6061-10vol.%Al₂O₃ composite [141]</th>
<th>C11000 copper [140]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg, %</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Si, %</td>
<td>0.6</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Cu, %</td>
<td>0.3</td>
<td>0.3</td>
<td>99.95</td>
</tr>
<tr>
<td>Zn, %</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Cr, %</td>
<td>0.2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Fe, %</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Ti, %</td>
<td>0.15</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Mn, %</td>
<td>0.15</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃, Volume %</td>
<td>0.0</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Balance</td>
<td>Aluminum</td>
<td>Aluminum</td>
<td>Fe, S, Se, Te, Bi, Pb, Cd, As, Sb</td>
</tr>
<tr>
<td>Material condition</td>
<td>Hot Extruded (20:1)</td>
<td>Hot Extruded (20:1)</td>
<td>Hot Extruded (20:1)</td>
</tr>
</tbody>
</table>
Table 3-3  Properties of the study materials (at room temperature)

<table>
<thead>
<tr>
<th></th>
<th>Al6061 [140]</th>
<th>Al6061-10vol.%Al₂O₃ [141]</th>
<th>C11000 [140]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>275</td>
<td>324</td>
<td>69</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>2.80</td>
<td>2.91</td>
<td>8.89</td>
</tr>
<tr>
<td>Tensile Strength, MPa</td>
<td>310</td>
<td>365 [141]</td>
<td>220</td>
</tr>
<tr>
<td>Work hardening exponent (n)</td>
<td>0.35</td>
<td>0.26</td>
<td>0.54</td>
</tr>
<tr>
<td>Shear Strength, MPa</td>
<td>207</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Hardness, HK (1000g)</td>
<td>119</td>
<td>121</td>
<td>117</td>
</tr>
</tbody>
</table>

The final polishing was performed using 0.05 µm alumina suspension. The etching reagents used were as follows: i) Keller's reagent (2 ml of HF-48%, 3 ml of HCl-concentrated, 5 ml of HNO₃-concentrated and 190 ml H₂O) that was used for the 6061 Al-alloy and 6061Al-10vol.%Al₂O₃, and ii) A 10 ml HNO₃ and 90 ml H₂O solution that was used for etching the C11000 Cu samples.

The properties of the materials studied are listed in the Table 3-3. The tabulated values are compiled from the existing data in the literature [140-141].

3.7 Mechanical Property Measurements

3.7.1 Compression Testing

Compression tests were carried out [141] to generate stress data at strains larger than can be obtained with the tensile loading, thus to obtain stress-strain data more relevant to metal cutting conditions. The compression tests were performed in the temperature range of 25°C to 400°C, again to obtain stress-strain data at high
temperatures representative of those generated during machining. The ring compression type test samples with an outside diameter of 25.4mm, an inside diameter of 21.4mm and a height of 6mm were cut from the as received extruded tubes. The specimens were compressed between two hardened steel platens that were machined from M2 type tool steel, and heat treated (oil quenched from 850 °C and tempered for 30 minutes at 350 °C) to obtain the hardness of 51 Rc. The plates were lubricated with high temperature grease to minimize the effect of friction.

Compression tests were carried out on a microprocessor controlled servo-hydraulic Instron (model 8562) test machine. A high temperature furnace with three heating zones, and a water cooling system, was used to heat the compression samples. The variation in the test temperatures was kept within ±0.5 °C during the tests. Prior to the test, the specimen was kept for one hour at the test temperature to achieve thermal equilibrium.

For a cylindrical sample of initial height $h_0$ compressed to $h$, the axial compressive strain is:

$$\varepsilon = \int_0^h \frac{dh}{h} = \ln\left(\frac{h}{h_0}\right) = -\ln\frac{h_0}{h} \quad h_0 > h$$

(3-1)

True strain rate:

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = -\frac{dh}{h_0} \cdot \frac{I}{dt} = -\frac{v}{h_0}$$

(3-2)

where negative sign indicates compressive strains and $v$ is the cross-head speed of the compression tester. It is common practice to reverse the sign convention so that compressive stresses and strains are defined as positive. Thus,
True strain: \[ \varepsilon_c = \ln \frac{h_0}{h} \] \[ h_0 > h \]  

True strain rate: \[ \varepsilon'_c = \frac{v}{h_0} \]  

(3-3)  

(3-4)

where the subscript \( c \) designates the reverse sign convention. If a constant cross-head velocity of 0.4 mm/sec (= \( v \)) was set at the beginning of the test corresponding to a strain rate of 0.067 sec\(^{-1}\), according to equation 3.4, this would increase to 0.13 sec\(^{-1}\) at the end of the compression test when the sample height is reduced by 50%. The load and the strain data were recorded to a PC computer using a data acquisition interface card.

Since the volume remains virtually constant during plastic deformation

\[ \frac{1}{4} D_0^2 h_0 = \frac{1}{4} D^2 h \quad \text{or} \quad D_0^2 h_0 = D^2 h \]  

(3-5)

where \( D_0 \) and \( D \) is the initial and instantaneous diameters of the compression test specimen; thus, the true compressive stress can be calculated from

\[ \sigma = \frac{P}{A} = \frac{4P}{\pi D^2} = \frac{4Ph}{\pi D_0^2 h_0} \]  

(3-6)

where \( D_0 = \frac{(D(\text{outside diameter}) + D(\text{inside diameter}))/2}{2} \) for the ring type compression specimens.
3.7.2 Microhardness Tests

Vickers and Knoop hardness tests were performed on all the materials prior to machining studies. Different loads were applied during the hardness tests to study the effects of load on the hardness values. The hardness values were calculated using the following two equations:

Vickers Hardness: 
\[ DPH = \frac{2P \sin(\theta / 2)}{L^2} = \frac{1.854P}{L^2} \] (3-7)

where \( P \) is the applied load (in kg), \( L \) is average length of diagonals (in mm) and \( \theta \) is the angle between the opposite faces of the diamond (136°) indenter.

Knoop Hardness: 
\[ KHN = \frac{P}{A_p} = \frac{P}{L^2C} \] (3-8)

where \( P \) is the applied load (kg), \( A_p \) is the projected area of indentation (mm\(^2\)), \( L \) is the length of the long diagonal (mm) and \( C(=0.95) \) is a constant for each indenter supplied by the manufacturer.

Knoop hardness was used for the hardness measurements of the chips and the small volume of subsurface material below the machined surfaces. The special shape of Knoop indenter (with a ratio of 7:1 between the long diagonal length and the short diagonal length) makes it possible to place several indenter impressions on small areas such as the chip and subsurface zones beneath the freshly machined surfaces. The long
diagonal of the indenter was placed, parallel to the machined surfaces at regular intervals of 10 μm, on the polished cross-sections. Microhardness tests were performed using Buehler Micromet II type microhardness tester at different loads, ranging from 15 grams to 1000 grams.

3.8 Metallographic Analyses

A comprehensive understanding of material behaviour during chip formation requires a thorough characterization of the nature of the plastic deformation in the chip forming areas. This includes the microstructural analyses and the examination of the state of the plastic deformation in the chip formation area (primary and secondary shear zones), the seizure area and the subsurfaces below the machined surfaces. The topographic features of the machined surfaces and the morphologies of the “free surfaces” of the chip have also been investigated.

The metallographic sections were prepared using standard metallographic procedures. All samples, after wet grinding on 240, 320, 400 and 600 grit SiC papers, were polished with 6 μm and then 1 μm diamond suspension. The final polishing was made with 0.5 μm and 0.05 μm Al₂O₃ particle suspension. At the end of each step, samples were ultrasonically cleaned before moving to the next polishing step.

To reveal the details of the deformed microstructures developed during cutting process, the sectioned samples were etched with the same reagents mentioned in section 3.5. The microstructural investigations and chemical analyses on the areas of interest were performed using scanning electron microscopy (SEM, Jeol 5400-LV) with energy
dispersive spectroscopy (EDS-Kevex) and optical microscopy (Leitz Laborlux 12 ME metallographic microscope).
Fig. 3-1    Photograph of the experimental set-up
Fig. 3-2 Experimental set-up for the measurement of temperatures
Fig. 3-3  Layout of temperature measurements
Fig. 3-4 Typical temperature rise profile on the rake face of cutting tool. 0.4 mm, 1.0 mm and 1.6 mm are the distances from the tool tip, or cutting edge. Sample is 6061 aluminum cut at a cutting speed of 0.6 m/sec and a feed rate of 0.3 mm.
CHAPTER 4.
EXPERIMENTAL RESULTS I:
MICROSTRUCTURES AND MECHANICAL PROPERTIES

4.1. Quantitative Characterization of the Microstructures of the Materials Studied

All the materials studied were hot extruded to an extrusion ratio of 20:1. During the machining experiments the cutting direction was kept perpendicular to the extruding direction. The microstructures of the three materials studied are shown in Figure 4-1, Figure 4-2 and Figure 4-3, for 6061 aluminum, 6061Al-10vol.%Al₂O₃ and commercial purity copper C11000 respectively. The planes on which grain size measurements were made in the direction parallel to the extrusion direction at the center of the thickness of the samples. The deformation structures induced by the cutting operation are also evaluated on the same plane locations.

The grain size measurements were performed in directions both parallel and perpendicular to the extrusion direction. The average value of grain size, \( \bar{x} \), was calculated by

\[
\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}
\]  (4-1)

where \( x_i \) is the size of the \( ith \) grain, \( n \) is the total number of grains. Therefore, \( \sum_{i=1}^{n} x_i \) is the total length measured on the micrograph using a linear intercept method. The number of the grain boundaries intercepted by a constant linear marker length (2000µm) were counted. A total of twenty measurements, ten in the horizontal and ten in the vertical direction were done.
The standard variation equation,

\[ \Delta x = \left[ \sum_{i=1}^{n} (x_i - \bar{x})^2 / (n - 1) \right]^{1/2} \] (4-2)

has been used to calculate the error in grain size measurements.

Histograms showing the grain size distributions of the 6061 aluminum, the 6061Al-10vol.%Al₂O₃, and the C11000 copper are given in Fig.4-4, Fig.4-5 and Fig.4-6 respectively. The average grain sizes were 119 ± 40μm for the 6061 aluminum alloy, 18.08 ± 5μm for the 6061Al-10vol.%Al₂O₃ composite and 47.39±15μm for the C11000 copper.

The particle size distribution in the 6061Al-10vol.%Al₂O₃ composite was determined using the same statistical method discussed above. The total number of particles measured was more than 50, and the measurements were randomly repeated three times. The results of the particle size measurements in the longitudinal direction and in the transverse direction are shown in Fig.4-7 and Fig.4-8.

### Table 4-1  Microstructural characteristics of the materials studied

<table>
<thead>
<tr>
<th>Microstructural Features</th>
<th>6061</th>
<th>MMC</th>
<th>C11000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain size, μm</td>
<td>119 ± 40</td>
<td>18.1 ± 5</td>
<td>47.4 ± 15</td>
</tr>
<tr>
<td>Grain size ratio</td>
<td>1.2 ± 0.2</td>
<td>1.1 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>Particulate reinforcement size, μm</td>
<td>6.7 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle size ratio</td>
<td>1.71 ± 0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Al₂O₃ particles in 6061Al-10vol.%Al₂O₃ composite had an average size of 11.22 μm in the longitudinal direction, 6.68 μm in the transverse direction and thus an aspect ratio of 1.71. Grain size and particle size measurements are summarized in Table 4-1.

4.2. Mechanical Properties of the Materials Studied

4.2.1. Compression Test Results

Compression tests were carried out in the temperature range of 25°C to 400 °C. The true strain and the true axial stress values from compression testing were calculated by using Equations (3-3) and (3-4):

The stress-strain relationships at different testing temperatures are plotted in Figure 4-9, Figure 4-10 and Figure 4-11 for the 6061 aluminum, the 6061Al-10vol.%Al₂O₃, and the C11000 copper respectively.

Considering that the alumina particles in 6061Al-10vol.%Al₂O₃ composite do not deform, the true plastic strain in matrix was corrected using the following equation [142]

\[ \varepsilon_p^m = \varepsilon_p^c (1 - f_v) \]  \hspace{1cm} (4-3)

where \( \varepsilon_p^c \) and \( \varepsilon_p^m \) are the plastic strains of the composite and its matrix, \( f_v \) is the volume fraction of the reinforcing phase; here it equals 0.1.
4.2.2. Flow Curves of 6061 Aluminum and 6061Al-10vol.%Al₂O₃ Composite

At a true strain of 0.1, the room temperature flow strength of the 6061Al-10vol.%Al₂O₃ is about 70MPa higher than that of the matrix alloy 6061Al, (see Figure 4-12). The flow strengths of both materials decrease, as expected, with the increase of the test temperature. At $\varepsilon = 0.10$, the highest rate of decrease occurs at a temperature range of about 200°C and 240°C.

Similarly, at the true strain of $\varepsilon = 0.20$, the room temperature flow strength of the 6061Al-10vol.%Al₂O₃ is higher than that of the 6061Al, but at this strain the temperature has a stronger effect on the rate of drop in the flow strength of 6061Al-10vol.%Al₂O₃, so that at temperatures above 250°C there is no significant difference in the flow strengths of both materials (see Figure 4-13).

The rate of change of strength with temperature, i.e. $|d\sigma/dT|$ vs. T curves are given in Figure 4-14 and Figure 4-15 for $\varepsilon = 0.10$ and $\varepsilon = 0.20$ respectively. At $\varepsilon = 0.10$, the rate of decrease in the flow strength is clearly higher for the 6061-10vol.%Al₂O₃ at temperatures up to 220°C, so that the strengthening advantage provided by the Al₂O₃ particulate is lost. The maximum in $|d\sigma/dT| = 3$ is reached in the 6061-10vol.%Al₂O₃ at 220°C while this is delayed to a slightly higher temperature in the 6061Al ($|d\sigma/dT| = 2.6$ at 225°C).

At $\varepsilon = 0.20$, the decrease in the flow strength for 6061-10vol.%Al₂O₃ and 6061Al are similar to that at $\varepsilon = 0.10$. For 6061-10vol.%Al₂O₃, $d\sigma/dT$ can reach up to 3.5 at 220°C, while this is delayed to a higher temperature of 260°C for the 6061Al ($|d\sigma/dT| = 2.8$).
4.2.3. Flow Curves of C11000 Copper

The flow curves of C11000 copper exhibit a similar dependence to the temperature as those for 6061-10vol.%Al₂O₃ and 6061 aluminum alloy. At both strain levels of $\varepsilon = 0.10$ and $\varepsilon = 0.20$, the strength decrease of C11000 with the increase of temperature is less than 20 MPa, when the test temperature increases from room temperature to 220°C (see Figure 4-12 and Figure 4-13). The significant decrease of the flow strength occurs when the temperature goes beyond 220°C, but still at a lower decrease rate than those of 606Al-10vol.%Al₂O₃ and 6061 aluminum in the range of 220°C to 300°C.

When the temperature is lower than 260°C, C11000 copper has a lower true compression strength than those of 606Al-10vol.%Al₂O₃ and 6061 aluminum. Due to the lower decrease in the rate of flow strength with the temperature increase, C11000 exhibits higher true compression stress compared to those of 606Al-10vol.%Al₂O₃ and 6061 aluminum when temperature is higher than 280°C at low strain of $\varepsilon = 0.10$ and 260°C at high strain of $\varepsilon = 0.20$.

4.2.4. Strain Hardening in Compression Tests

Consider that the flow curve in the region of uniform plastic deformation, (e.g. in the range of $\varepsilon = 0.10$ to $\varepsilon = 0.20$) can be described by the following equation:

$$\sigma = K\varepsilon^n \quad \text{or} \quad \ln \frac{\sigma_{0.2}}{\sigma_{0.1}} = n \cdot \ln \frac{\varepsilon(=0.2)}{\varepsilon(=0.1)} \quad (4-6)$$
where \( n \) is the work hardening exponent. \( K \) is the strength coefficient. From equation (4-6), \( n \) can be calculated (at a specific temperature) as follows:

\[
n = \frac{1}{0.693} \cdot \ln \frac{\sigma_{0.2}}{\sigma_{0.1}} \tag{4-7}
\]

The results of work hardening coefficients at different temperatures under the compression stress are listed in Table 4.2.

It noted that, C11000 copper has higher work hardening coefficients than 6061 aluminum alloy with the increase of test temperatures while the 6061-10vol.%Al\(_2\)O\(_3\) has very low values, but, this remains constant.

<table>
<thead>
<tr>
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<tr>
<td>C11000 Copper</td>
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<td>0.25</td>
<td>0.29</td>
<td>0.21</td>
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4.3. Microhardness Tests Results

For both types of microhardness tests (Vicker and Knoop) performed the sensitivity of the hardness values to the applied load have been investigated. It was important to find the optimum indentation loading conditions because the microhardness tests were extensively used to determine the flow strength of the machined surfaces and the chips. The results have shown that the microhardness values are sensitive to the load
at the low loading range. The results are shown in Figure 4-16 and Figure 4-17 for the Knoop hardness and the Vicker hardness tests respectively. It is clear that for the Knoop hardness, when test load is greater than 200 grams the value of the hardness is not affected by the level of the load applied. When the load is smaller than 100 grams, the hardness value increases exponentially with decreasing test load. For the Vicker's hardness tests, when the test load is greater than 100 grams, the hardness values decrease linearly with the test load. For test loads less than 100 grams, the hardness values also increase exponentially.
Fig. 4-1  Microstructure of 6061 aluminum alloy

Fig. 4-2  Microstructure of 6061-10vol.%$\text{Al}_2\text{O}_3$ particulate reinforced metal matrix composite.
Fig. 4-3  Microstructure of C11000 commercial pure copper
Average grain size = 119 μm

Grain size distribution of 6061 Aluminum alloy, hot extruded with the extrusion ratio of 20:1.
Fig. 4-5  Grain size distribution of 6061Al-10vol.%Al₂O₃, hot extruded with the extrusion ratio of 20:1
Fig. 4-6  Grain size distribution of C11000, hot extruded with the extrusion ration of 20:1.
Fig. 4-7  Size distribution of Al₂O₃ particles in 6061-10vol.%Al₂O₃ metal matrix composite, measured in longitudinal direction
Fig. 4-8  Particle size distribution of Al₂O₃ particles in 6061Al-10vol.%Al₂O₃ metal matrix composite, measured in transverse direction.

Average particle size in the transverse direction = 7 µm

Particle size in transverse direction, µm
Fig. 4-9  True compression stress-true strain plots for 6061 aluminum alloy obtained at the strain rate of 0.067 s⁻¹. The test temperatures are indicated on each curve.
Fig. 4-10  True compression stress-strain plots for 6061-10vol.% Al₂O₃ composite at the strain rate of 0.067 s⁻¹. The test temperatures are indicated against each curve.
Fig. 4-11  Compression stress-strain plots for C11000 copper at the strain rate of 0.067 s\(^{-1}\). The test temperatures are indicated against each curve.
Fig. 4-12  True compression stress versus test temperature at a strain of 0.10
Fig. 4-13  True compression stress versus test temperature at a strain of 0.20
Fig. 4-14  Change in the rate of flow strength in compression stress with test temperature at a strain of 0.10
Fig. 4-15  Change in the rate of flow strength in compression stress with test temperature at a strain of 0.20
Fig. 4-16  Knoop's hardness of study materials vs. the testing load
Fig. 4-17  Vicker's hardness of study materials vs. the testing load
CHAPTER 5

EXPERIMENTAL RESULTS II:
METALLOGRAPHY OF CHIP FORMATION AND
DETERMINATION OF TEMPERATURE DISTRIBUTION

5.1 Metallographic Examination of Deformation Patterns in the Workpiece

Machined workpiece samples were sectioned for metallographic examination of their microstructures and deformation patterns that were developed during machining. Metallographic samples were sectioned as shown in Figure 5-1.

5.1.1 6061 Aluminum Alloy

Figure 5-2 shows the general view of the cross-section of the material ahead of the tool tip. The material is 6061 aluminum cut at a feed rate of 0.30 mm and a cutting speed of 0.6 m/sec. The extent of plastic deformation is revealed by the significant shape change of the grains that became elongated in the cutting direction. The grains that have an almost equiaxed shape in the bulk material assume a “tear drop” shape as they approach the root of the chip.

There are two basic deformation zones that can be seen in the chip (see Figure 5-2). In the first, the chip is entirely deformed as it meets the tool. This is the "primary shear zone", as shown in Figure 5-3. In this zone, the grain boundaries have become almost indistinguishable from each other. The grains have reduced into microstructural features resembling shear bands with average thickness ranging from submicrometer to 5µm.
A classical mechanics analysis based on this micrograph would suggest that the shear plane angle is 14 degrees. The average shear strain in the primary shear zone is about 4.4 [40]. However, it is clear, from the cross-sectional micrograph presented, which as the material flows into the primary shear zone the shear strains increase drastically. The shear strains and the variation in the shear angles are calculated and their distribution will be presented in section 6.3.1.

There is also a deformation zone along the rake face of the cutting tool where material is even more heavily sheared. This zone, called the "secondary shear zone", occurs during friction at the rake face. Seizure of the tool to the workpiece material within the secondary shear zone is very common. A careful investigation of the material adjacent to the rake face of the cutting tool reveals the presence of the secondary shear zone in 6061 aluminum as shown in Figure 5-2. The microstructural difference (dotted morphology structure) within a strip of material of about 0.5 ~ 5μm in thickness makes up the secondary shear zone.

A higher magnification SEM micrograph of the section of a newly formed chip, from around the tool tip, in 6061 aluminum alloy is shown in Figure 5-4. The periodic lamellar structures observed in the primary shear zone demonstrate the heterogeneous nature of the deformation.

It is difficult to distinguish between the grain boundaries and the shear bands formed within the grains, but clearly the deformation is located in the periodic features giving rise to a serrated deformation microstructure (lamellar morphology). Detailed strain analyses will be given in Section 6.4, but it is appropriate to comment here briefly
on the magnitude of the local shear strain rates \( \dot{\gamma} \) generated during cutting. Local values of \( \dot{\gamma} \) can be estimated using the following equation by Ramalingam et al. [43]

\[
\dot{\gamma} = \frac{0.5v_s}{d} \tag{5-1}
\]

where \( d \) is the distance between the shear bands, and \( v_s \) is the cutting speed. Since \( d \) is on the order of 0.5 mm (Figure 5-4), then for the cutting speed used \( (v_s = 0.6 \text{ m/sec}) \), the average shear strain rate is about \( 5 \times 10^5/\text{sec} \). This simple calculation confirms that metal cutting is a high strain rate deformation process. In fact, the rate calculated is close to those obtained in shock loading experiments [143].

Therefore, it is not surprising to find the microstructural elements leading to damage accumulation within the primary shear zone, such as the voids extending in the direction of the strain gradients as shown in Figure 5-4. Near the free surface, the voids coalesce and initiate cracks seen in Figure 5-5.

The cracks resulting from the coalescence of voids cause formation of shear facets and cracks at the free surface of the chip (opposite to the rake face), see Figure 5-6. Figure 5-7 shows that the average distance between the shear bands at the chip free surfaces is 2–5 \( \mu \text{m} \) consistent with the morphology observed on the cross-sectional plane as depicted in Figure 5-4. The periodic nature of the crack fronts forms at the free surface are also shown at a lower magnification optical cross-sectional micrograph in Figure 5-8.

Void coalescence and growth events can also be clearly observed at several locations. The depth of the cracks on the free surface in this micrograph runs 100 \( \mu \text{m} \) into
the width of the chip. The fracture may be due to the accumulation of the strain in the shear bands meeting the free surface. During cutting one of these cracks become unstable and causes complete separation of the chip from the workpiece. The high magnification secondary electron SEM image, in Figure 5-9, shows details of the void coalescence process. As seen by examining Figure 5-4 and Figure 5-5, the voids have been formed in chip formation areas.

The number of the voids increases with proximity to the free surface of the chip. Fine details of the microstructure that develops within the cracks on the free surface are given in Figure 5-9. At the chip root, cracks did not form, but the micrograph reveals the existence of a set of deformation fronts (shear bands), see Figure 5-10, that are approximately oriented at about 90 degrees to the first set of shear band, e.g. those shown in Figure 5-8.

Once the chip is formed, it moves away by sliding along the rake face of the cutting tool. Due to the severe frictional contact between the chip and the rake face of the cutting tool, chip material suffers from the secondary shear deformation, see Figure 5-11.

Only the material along the cutting line, i.e., the line along which the tool tip moves in the cutting process, experiences the secondary plastic deformation. There is evidence that the severe wear or seizure occurred in secondary shear zone. At the onset of seizure in aluminum alloys, the friction induced local temperature normally exceeds half the melting point of the material. Thus, the material in the secondary shear zone not only suffers from high strains but also subjected to thermally activated processes that induce microstructural changes as shown in Figure 5-11.
The strain in secondary shear zone could be four and half times as great as the strain in the primary shear zone (~20). Cracks and voids are not observed in secondary shear zone. The ability of the materials to withstand such high shear strains in the secondary shear zone without fracture should be attributed to the high compressive stresses in this zone. The high compression stress could inhibit the initiation of cracks and the formation of voids. Also the high compression stress could cause the re-welding of small cracks as may be started or already existed in the workpiece materials before machining [31].

5.1.2 Commercially Pure Copper, C11000

The deformation microstructure of commercially pure copper at the chip formation area is shown in Figure 5-12. The cutting conditions are similar to those used for cutting the aluminum sample. The thickness of the copper chip is about one and half times of that formed in aluminum.

In commercial machining conditions, the approximate power requirements (or power consumption) for machining copper alloys range from 1.1 to 2.7 MJ cm⁻³-min⁻¹, while for machining aluminum alloys the power required in machining is between 0.8 and 1.4 MJ cm⁻³-min⁻¹ [3]. This can be partly attributed to the formation of larger primary and secondary deformation areas in copper.

The total power consumed in machining is the sum of the work done that is proportional to the size of the shear zone, the materials strength and the shear angle. On the primary shear plane, the work rates can be expressed as [34]:

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\[ \frac{dW}{dt} = V \tau = (wl \tan \phi) \tau = (wv) l \tau \tan \phi \] (5-1)

where \( w \) is the width of the cut, \( l \) is the length of contact length, \( v \) is the cutting speed, \( \tau \) is materials strength and \( \phi \) is the shear angle. Under the same cutting speed and sample dimension, the work rate is proportional to the shear angles. The C11000 copper shows the longer shear plane and bigger shear angle. Similarly in the secondary shear zone, the work rate is proportional to the shear angle and the contact length. Therefore, higher machining work is required to perform the cutting operation of the C11000 than that required in cutting aluminum alloy.

Higher cutting forces have been measured in cutting C11000 copper. Also the local temperature increase during the cutting of copper is higher compared to the aluminum samples, as will be discussed in the following chapters.

It can be suggested that because the primary and secondary deformation areas are larger, the distribution area of cutting energy is more uniform in copper. The heavily etched areas in the primary shear zone have indicated presence of voids within the shear bands (Figure 5-13).

Microcracks appear to form by the coalescence of these voids in the shear flow direction. As shown in Figure 5-14, the cracks are along the grain boundaries and shear bands and become more conspicuous towards the free surface of the chip. The high magnification view of the microstructure shown in Figure 5-15 has given the details of the grain boundary cracks and separation of the faces of shear bands. The figure also appears to indicate that the grain boundaries are struggling to rotate in order to orient themselves parallel to the material's flow direction.
Figure 5-16 shows the morphology of the free surface of the chip. The shear fracture facets are clearly seen. The average distance between the shear cracks is about 50μm. This is larger than the average shear crack spacing in aluminum (Figure 5-8). It is also noticed that the shear cracks in copper form a straight or a planar pattern. This is in contrast to aluminum where a wavy crack pattern is formed.

There is clear evidence for secondary shear (light features extending parallel to each other) perpendicular to the plane of shear cracks in Figure 5-17. These shear bands are normal to the first set of shear bands close to the free surface of the chip. At the chip root area where the materials can keep the continuity, like 6061 aluminum, no cracks have been observed, see Figure 5-18. The shear front has a smaller dimension than that of the distance of the fracture separation (1 to 2 μm).

A schematic model of shear band formation is conceptualized in Figure 5-19. Under high magnification SEM, it was observed that shear bands were formed in the direction of elongation of grain boundaries, which tend to rotate toward the materials flow direction. At the "microscopic" level, the shear directions of microbands can be randomly orientated. But overall the bands are oriented towards the direction of maximum shear stress, and the grain boundaries tend to elongate and rotate in the same fashion.

The characteristics of plastic deformation in the secondary shear deformation area in C11000 copper are similar to those in the 6061 aluminum alloy. The thickness of the server deformation zone in C11000 copper is about 20 to 50 μm, much thicker than that in 6061 aluminum alloy (5 to 10 μm). It may be due to the fact that the yield strength of the C11000 copper is much lower than that of 6061 aluminum alloy.
5.1.3 6061Al-10vol.%Al₂O₃ Composite

The addition of secondary hard particles has resulted in significant differences in the morphologies of the cutting zones compared to the non-reinforced matrix aluminum. One significant difference from the non-reinforced aluminum matrix was the formation of a built-up-edge in the composite material ahead of the tool tip; a layer of material has grown on the rake face of the tool ahead of the cutting edge (Figure 5-20).

A close examination of Figure 5-20 indicates that the build-up-edge is composed of layers of highly deformed (and extremely strain hardened) material which builds up on the rake face to act as an extension of the tool. The built-up-edge has significantly reduced the severity of plastic deformation in the secondary shear zone that is no longer in direct contact with the cutting tool.

The built-up-edge shown in Figure 5-20 was formed when the 6061Al-10vol.%Al₂O₃ composite was cut at a feed rate of 0.30 mm and a cutting speed of 0.6 m/sec. It appears that during the cutting process a dynamic equilibrium was reached between the rate of deposition of the material and the rate at which material was broken off to produce a build-up-edge of dynamically constant size.

The built-up-edge is a common phenomenon in the machining of commercial alloys. The build-up-edge formation affects the machinability in several ways, the most significant being the reduction in cutting and feed forces. For most materials this occurs at a certain range of cutting speeds [80].

For 6061Al-10vol.%Al₂O₃ build-up-edge was formed under all the cutting conditions used in this work. The size of the built-up-edge is about the same as the size of
the chip thickness in current cutting conditions. Unlike cutting 6061 aluminum alloy and C11000 copper, 6061Al-10vol.%Al2O3 composite lost its continuity when the serration is initiating; see Figure 5-21.

The shear cracks formed on the free surface of the chip have similar morphology to 6061 aluminum *i.e.*, the cracks form on the surface a wavy morphology. The average distance between the cracks is about 10 μm (see Figure 5-22). A high magnification micrograph of the shear cracks is given in Figure 5-23. The high magnification SEM image of the cross section of Figure 5-23 has shown the fracture pattern that disclosed the particles have physically separated from the matrix, see Figure 5-24.

The debonding (decohesion) of the particles from the matrix occurred in the primary shear zone shown in Fig 5-25. Most particle /matrix separation processes occurred at ten and four o’clock positions (along the shear direction). It appears that these are the regions of high hydrostatic tension.

Details of damage accumulation processes around the particles and within the aluminum matrix are shown in the higher magnification micrograph in Figure 5-26. It is also worth noting that the matrix deformed in the same way as 6061 aluminum alloy *i.e.*, deformation bands extending parallel to the deformation direction is seen. The average distance between the shear bands (deformed grain boundaries) is about 5μm. Matrix voids can also be seen.

The debonding increases with increased feed rate. The fracturing of the particles can not be observed at high feed rate of 0.3 mm, see Figure 5-27. At low feed rate of 0.05 mm, the debonding is hardly observed, see Figure 5-28.
No particle debonding or particle cracking has been observed in the secondary deformation area either. The temperature rise that reduces the yield strength of the materials must play an important role here to lower the magnitude of the matrix constraint. Also as mentioned earlier the frictional drag in the secondary shear zone is reduced by the formation of the build-up-edge.

5.2 Deformation Patterns on the Machined Surfaces

The patterns of plastic deformation on machined surfaces are reminiscent of those observed in dry sliding wear (reference). The severe deformation is within a thin layer of material with a thickness of about 100 μm for C11000 copper, and about 50 μm for 6061 aluminum alloy.

A subsurface deformation zone thickness of about 20 μm for 6061-10vol.%Al₂O₃ composite is observed. For 6061 aluminum and C11000 copper, the strains decrease exponentially with the distance away from the machined surface. The typical deformation structures in the subsurfaces below the machined surfaces are shown in Figure 5-29 for the 6061 aluminum and in Figure 5-30 for C11000 copper.

For 6061-10vol%Al₂O₃ composite, the deformation in the subsurface zones is less severe and the depth of the deformed zone is less than the non-reinforced aluminum, see Figure 5-31. It is because part of the machining energy is consumed in particle debonding and crack formation. The SEM microstructures showing in Figure 5-27 and Figure 5-28 show the particle debonding and subsurface cracks.
5.3 Temperature Distribution

Temperature distributions on the rake face of the cutting tool have been measured with thermocouples directly. The results have shown that the temperature distribution strongly depends on the location on the rake face, the cutting speed and the workpiece materials.

5.3.1 Temperature Rise Varying with Location and Cutting Speed

Cutting speed has strong effect on the temperature distribution on the tool rake face. The variation of the temperature with the cutting speed are given in Figure 5-32, Figure 5-33 and Figure 5-34 for 6061 aluminum, 6061-10vol.%\( \text{Al}_2\text{O}_3 \) composite and C11000 copper respectively. For 6061 aluminum and C11000 copper, the tool temperature increases exponentially with the cutting speed, while for the 6061-10vol.%\( \text{Al}_2\text{O}_3 \) composite, the temperature rises almost linearly with cutting speed.

As indicated on these figures tool temperatures are measured at three points starting from 0.4 mm from the tool tip. The temperature decreases with increasing the distance from the tool tip along the rake face of cutting tool. The temperature profiles measured at the same locations of the tool for the three work pieces are given in Figure 5-35, Figure 5-36 and Figure 5-37 for the measurement locations of 0.4, 1.0 and 1.6 mm from the tool tips.

5.3.2 Variation of the Tool Temperature with the Workpiece Materials

As shown in Figure 5-35, Figure 5-36 and Figure 5-37, the temperature of the tool depends on the workpiece material. The tool temperature increase was the highest
when cutting the copper samples. The lowest tool temperature increase occurred when the 6061-10vol.%Al₂O₃ composite was cut. The difference in the tool temperatures is small when the materials are cut the low cutting speeds (0.25 m/sec) but the difference becomes large at higher cutting speeds. A lower cutting speed the temperature rise is not significant even though the differences of the physical and thermal properties of the workpiece materials are significant. Therefore, the temperature rise in the workpiece materials has less effect on the temperature rise of the cutting tool. With the increase of the cutting speed, the physical and thermal properties of the workpiece materials play important role in the temperature rise, thus the temperature rise of the cutting tool.
Fig. 5-1  Schematic diagram showing the metallographic sections taken from tubular workpiece after machining. The plane of sectioning is perpendicular to and at the middle of the cutting edge of the cutting tool.
Fig. 5-2. Optical micrograph of 6061 aluminum alloy, cut at a feed rate of 0.30 mm and a cutting speed of 0.6 m/sec. Intensive shearing in the chip forming area causes the formation of shear bands.
Fig. 5-3  Schematic diagram identifying different zones in the chip and the workpiece
Fig. 5-4 SEM micrograph of shear bands in 6061 aluminum alloy, cut at a feed rate of 0.30 mm and a cutting speed of 0.6 m/sec. Intensive shearing in the chip forming area causes the formation of shear bands. Notice the voids extending in the direction of strain gradient.
Fig. 5-5  SEM image showing the microstructure of chip. Grains are not resolvable. The lines are made up of grain boundaries. Voids line up to form cracks while approaching the free surface. Sample is 6061 aluminum cut at a speed of 0.6 m/sec and at a feed rate of 0.3 mm.
Fig. 5-6  SEM image showing the fracture on the free surface of chip. The fracture forms the serrations on the free surface of the chip. The secondary shear zone parallel to the rake face of the cutting tool. The primary shear direction is also shown. Sample is 6061 aluminum alloy cut at a speed of 0.6 m/sec and at a feed rate of 0.3 mm.
Fig. 5-7  SEM micrograph of serrations on the free surface of the chip in 6061 aluminum alloy, cut at a feed rate of 0.30 mm and a cutting speed of 0.6m/sec.
Fig. 5-8  Low magnification optical cross section morphology of shear cracks on the chip free surface close to the chip root. 6061 aluminum alloy, cut at a feed rate of 0.50 mm and at a cutting speed of 0.6m/sec. Intensive shearing in the chip forming area causes the formation of shear bands.
Fig. 5-9  SEM image showing the cross section of a band of serrations on the free surface of the chip. The depth of the serration, or the fracturing, is about 100 μm. This value is about constant. This implies that as soon as the fracture forms no more propagation occurs. Sample is 6061 aluminum cut at a speed of 0.6 m/sec and at a feed rate of 0.3 mm.
Fig. 5-10  SEM image of 6061 aluminum alloy at the chip root, where the shear deformation is initialized. No cracks observed, but the serration is initializing. Sample is cut at a speed of 0.6 m/sec and at a feed rate of 0.3 mm.
Fig. 5-11 SEM micrograph of secondary deformation zone where the newly formed chip seizes the rake face of the cutting tool while moving away. 6061 aluminum alloy sample, cut at a speed of 0.6 m/sec and a feed rate of 0.3 mm. The top surface is the surface contacting with the rake face of the cutting tool.
Fig. 5-12. Optical microphotograph of C11000 copper, cut at a feed rate of 0.30 mm and a cutting speed of 0.6m/sec. Intensive shearing in the chip forming area causes the formation of shear bands.
Fig. 5-13  SEM image of C11000 copper in chip the formation area. The shear traces have a width of sub-micro millimeters. The heavy etching has disclosed the weakening of grain boundaries and the deformation direction. Sample is cut at a speed of 2.45m/sec and at a feed rate of 0.3 mm.
Fig. 5-14  SEM image of C11000 copper in the area approaching the chip root area. The voids at the grain boundaries line up to form cracks. Sample is cut at a speed of 2.45 m/sec and at a feed rate of 0.3 mm.
Fig. 5-15  High magnification SEM image of Fig. 5-14 shows the micro bands within the grains and the grain boundaries.
Fig. 5-16. SEM micrograph of serrations on the chip free surface of C11000 copper, cut at a feed rate of 0.3mm and a cutting speed of 0.6m/sec.
Fig. 5-17  High magnification SEM image of a serration of C11000 copper at the chip free surface. Sample is cut at a speed of 2.45 m/sec and at a feed rate of 0.3 mm.
Fig. 5-18 SEM image of C11000 copper at the chip root where the shear deformation is initiated. Sample is cut at a speed of 2.45 m/sec and at a feed rate of 0.3 mm.
Fig. 5-19  Schematic hand drawing that shows the shearing mechanism.

$\Phi_\alpha$: shear angle, varies with position.
$\phi_i$: shear angle, that varies with position, shearing is limited within the grains.
$\Phi_j$: Grain boundary angles.
$\phi_i$ and $\phi_j$ very with position, but have the tendency to be parallel to $\Phi_\alpha$. 
Fig. 5-20.  Optical micrograph of 6061-10vol.%Al₂O₃ metal matrix composite, cut at a feed rate of 0.30 mm and a cutting speed of 0.6m/sec. Intensive shearing in the chip forming area causes the formation of shear bands.
Fig. 5-21 SEM image of 6061-10vol.%Al₂O₃ composite at the chip root where the shear deformation is initialized. The serration is initializing. The serration is initializing. Sample is cut at a feed rate of 0.30mm and a cutting speed of 0.6m/sec.
Fig. 5-22  SEM micrograph of the serration on the chip free surface of 6061-10vol.%Al₂O₃ composite, cut at a feed rate of 0.30 mm, and at a cutting speed of 0.6m/sec.
Fig. 5-23  High magnification SEM image of the serrations in the 6061-10vol.%Al₂O₃ composite.
Fig. 5-24  SEM image of the cross section of a serration, in Fig. 5-23, showing that when approaching the free surface, the particles have physically separated with the matrix. 6061-10vol%Al$_2$O$_3$. Sample is cut at the speed of 0.6 m/sec and at the feed rate of 0.3 mm.
Fig. 5-25 SEM image showing the severe debonding of reinforced particles in 6061-10vol.%Al₂O₃ composite in the chip formation area. The particles are preferentially lined up in the long direction to the shearing. Fracture of particles occurred. Sample is cut at a speed of 2.54 mm/sec and at a feed rate of 0.05 mm.
Fig. 5-26 SEM micrograph of shear bands of 6061-10vol.%Al₂O₃ composite cut at a feed rate of 0.30 mm and a cutting speed of 0.6m/sec
Fig. 5-27 SEM image showing the severe debonding of reinforced particles in 6061-10vol.%Al₂O₃ composite on the machined surface. The particles are preferentially lined up in the long direction to the shearing direction. No fractured particles are observed. Sample is cut at a speed of 2.54 mm/sec and at a feed rate of 0.3 mm.
Fig. 5-28  SEM image showing no debonding of reinforced particles in 6061-10vol.%Al$_2$O$_3$ composite in machined surface at low feed rate of 0.05mm. The particles are lined up only at the very top surface. The fracture of particles can be observed. Sample is cut at a speed of 0.6 m/sec and at a feed rate of 0.05mm.
Fig. 5-29 Optical micrograph of the plastic deformation of the machined surface of 6061 aluminum alloy, cut at a feed rate of 0.30 mm and at a cutting speed of 0.6 m/sec., x 50. Intensive shearing deformation was concentrated in the top layer of the machined surface.
Fig. 5-30 Optical micrograph of plastic deformation in machined surface of the C11000 sample, cut at a feed rate of 0.30 mm and a cutting speed of 0.6 m/sec., x50. Intensive shearing deformation was concentrated in top layer of the machined surface.
Fig. 5-31 Optical micrograph of plastic deformation in machined surface for 6061-10vol.%Al₂O₃ composite sample, cut at a feed rate of 0.30 mm and at a cutting speed of 0.6m/sec., x 50. Intensive shearing deformation was concentrated in the top layer of the machined surface.
Fig. 5-32  Temperature distribution at different distances from the tool tip on the rake face of the cutting tool versus the cutting speed. 6061 aluminum was cut with a feed rate of 0.3 mm and VB = 0.3 mm.
Fig. 5-33  Temperature at different distances from the tool tip on the rake face of the cutting tool versus the cutting speed. 6061-10vol.%Al₂O₃ composite was cut with a feed rate of 0.3 mm and VB = 0.3 mm.
Fig. 5-34  Temperature at different distance from the tool tip on the rake face of the cutting tool versus the cutting speed. C11000 copper sample was cut with a feed rate of 0.3 mm and VB = 0.3 mm
Fig. 5-35 Temperatures at 0.4 mm away from the tool tip on the rake face versus the cutting speed, VB = 0.3 mm.
Fig. 5-36  Temperatures at 1.0mm away from the tool tip on the rake face versus the cutting speed, VB = 0.3mm.
Fig. 5-37 Temperatures at 1.6mm away from the tool tip on the rake face versus the cutting speed, VB = 0.3mm.
CHAPTER 6

ANALYSIS AND DISCUSSION OF
EXPERIMENTAL RESULTS

6.1 Introduction

In mechanical analyses of metal cutting processes, the shear angle, \( \phi \), is commonly defined as the angle between the cutting direction and the primary shear plane where the shear stress is at the maximum level and material shears along the primary shear plane to form chip. The shear angle defined in this way represents the situation that the shear resistance of the workpiece material is at its minimum. The work expended in cutting tool is also at its minimum [40].

According to the following equation proposed by Merchant [40],

\[
\gamma = \tan(\phi - \alpha) + \cot \phi \quad \text{or} \quad \gamma = \frac{\cos \alpha}{\sin \phi \cos(\phi - \alpha)} \quad (2-12)
\]

The value of the shear strain is a function of the shear angle, \( \phi \), and the tool rake face angle, \( \alpha \).

The relationship between the shear strain and the shear angle based on the equation (2-12) is shown in Figure 6-1. For a given tool, the rake face angle of the cutting tool is constant. The shear strain varies with the shear angle only. The shear strain decreases as the shear angle increases until the shear angle reaches a minimum value, about 45 degrees.
The minimum value of the shear angle is not a strong function of the rake face angle of the cutting tool. At lower shear angles, the shear strain strongly depends on the shear angles. When shear angles are greater than about 15 degrees the dependence of the shear strain on the shear angle is not significant. With the increase of the shear angle greater than the minimum value, the relationship appears to be a symmetric feature.

The results presented in Chapter 5 indicate that along the primary shear plane, the shear direction of the material changes starting from near the tool tip, progressively towards the free end of the chip. Therefore, contrary to the predictions of the traditional mechanical analyses, the strains along the primary shear plane are not constant, but vary with the locations. Consequently, the strain rates within the primary shear zone are not constant but again vary from point to point.

6.2 Analysis and Comparison of Deformation Microstructures

The geometries of the deformed grains and the deformation bands have been studied by investigating the optical micrographs of the cutting areas as presented in Chapter 5. The direction of the shear deformation have been estimated by studying changes in the orientation of the typical microscopic features, namely grain boundaries during cutting as will be explained in this section.

Figure 6-2 is a manual drawing of the grain structure of the 6061 aluminum sample. In this figure the morphology of the grain boundaries of the 6061 aluminum is redrawn from the deformation microstructure of the alloy presented Figure 5-2. The drawing of Figure 6-2 helps to clarify the severity of deformation during cutting and show the extent of grain elongation and bending during the cutting process. Examination
of several cross-sectional micrographs of the chips similar to Figure 5-2 led to the conclusion that the deformation pattern shown in Figure 6-2 is typical and this remains constant at any given time during the cutting process (provided that the machining conditions do not change).

An idealized picture of the deformation microstructure of the 6061 aluminum alloy during cutting is given in the computer generated image of the microstructure as shown in Figure 6-3. Similarly, the computer generated typical deformation structure of the 6060-10vol.%Al₂O₃ composite is given in Figure 6-4 which is reproduced from the actual metallographic cross-sections, like the one shown in Figure 5-20. Figure 6-5 is the typical deformation microstructure of C11000 copper reproduced from Figure 5-12.

The deformation microstructures of copper and aluminum are fairly similar to each other under the present experimental conditions (i.e., at the cutting speed of 0.6 m/sec and the feed rate of 0.3mm per cut). The 6060-10vol.%Al₂O₃ composite exhibits a considerably different deformation structure during cutting.

A detailed analysis of the deformation geometry will be provided later in this chapter but it is first of value to compare the characteristic features of the deformation geometries of aluminum and copper. It can be seen from Figure 6-3 (and Figure 5-2) and Figure 6-5 (and Figure 5-12) that;

1) The average thickness of the chip in copper is longer

2) The average width of the primary shear zone is narrower in aluminum compared to copper
3) The grain boundaries become straight and remain so within the shear zone of aluminum. However in copper the grain boundaries remain curved, thus it continues to deform within the shear zone.

These differences arise from the differences in the deformation behaviour of the copper and aluminum and reflect primarily the fact that strain localization occurs more readily in aluminum alloys compared to copper (which typically has a higher work hardening coefficient $n$, see Table-3-3. The discussion of the different work hardening effects of the 6061 aluminum alloy and C11000 copper based on the differences in stacking fault energy is given in section 6.11.5.

6.3 Determination of the Shear Angles

The shear direction of the materials in plastic deformation areas is defined by the shear angles. The shear angles can be estimated from the slopes of the deformation bands. More specifically the shear angle is the angle between the cutting line and the tangent line at any point of the shear line (as determined by the grain boundary, shear band morphologies depicted in Figures 6-5, 6-6 and 6-7. Therefore, the shear angle, $\phi$, can be computed as shown in Figure 6-6. The direction of the shear deformation at any point in the plastic deformation areas during cutting can be estimated from the angles between the tangential line at the point and the cutting direction from the following equations,

$$\tan \phi = \frac{\Delta y}{\Delta x} \quad \text{or} \quad \phi = \tan^{-1} \left( \frac{\Delta y}{\Delta x} \right) \quad (6-1)$$
where $\phi$ is the shear angle, and $\Delta x$ and $\Delta y$ are the absolute values of the intercepts of the tangential line at the point $P$ along the $x$ and $y$ axes.

This method provides an easy way to determine the shear angles at any point in the chip formation area where the plastic deformation occurred. The shear angle measurements were taken in the following areas that have been defined in Figure 6-7.

1) Near primary shear zone (chip formation area), the area $ABDO$, in which the materials deform at the onset of chip formation.

2) In the chip, the area marked as $ODEF$, where the newly formed chip moves along the rake face of the cutting tool. The materials closed to the rake face of the cutting tool in the area suffer from secondary shearing deformation.

3) Machined surface, the surface below $OG$.

6.3.1 Distribution of the Shear Angles in 6061 Aluminum Alloy

Figure 6-8 shows the distribution of the shear angles in the chip formation area of the 6061 aluminum alloy. The $x$-axis in Figure 6-8 is the distance below the cutting line in $\mu m$. The cutting line is defined as the line starting from the tool tip and going along the cutting direction. The line $OC$ indicates the position of the cutting line, positive numbers indicate distances of the locations that are above the cutting line, and negative numbers are the locations below the cutting line. The $y$-axis shows the values of the shear angles whose values vary with the location in the deformation areas.

For example, the shear angles along the cutting line, line $OC$ in Figure 6-7, vary from 10 degrees which represents a maximum amount of deformation at point $O$ to 84
degrees at the point $C$. Along this line the values of the shear angles have widest variation. The variation of the shear angles along the primary shear line, $OD$, is the minimum. At minimum deformation area on the line $AB$ in Figure 6-7, the materials shear in the direction almost perpendicular to the cutting line. Therefore all the shear angles at any points on the line have the same shear angle values close to 90 degrees.

6.3.2 Distribution of Shear Angles in C11000 Copper

Compared with the 6061 aluminum alloy, C11000 copper has shown a different distribution of shear angles as shown in Figure 6-9. The smaller variation of the shear angle range indicates that the plastic deformation during cutting of copper has been more uniform. It is also noted that the area bonded by the chip root line and tool tip line (plastic deformation zone) is wider compared to that in aluminum, providing compelling evidence to the more localized nature of deformation in aluminum.

The average width of the deformation zone in copper is 700 μm into the uncut area, compared to 400 μm in 6061 aluminum alloy. In copper, the maximum variation range of the shear angles does not occur on the cutting line like that in aluminum alloy, but at 100 μm to 200 μm below the cutting line. This fact has proven that the plastic deformation area during chip formation in copper is larger than that in aluminum.

6.3.3 Distribution of Shear Angles in 6061-10vol.%Al₂O₃ Composite

The distribution of the shear angles in 6061-10vol.%Al₂O₃ composite is significantly different than those of the 6061 aluminum alloy and the C11000 copper. Primarily, there is a built-up edge effect during cutting of 6061-10vol.%Al₂O₃ composite
as shown in Figure 6-10. The built up edge on the tool rake face has changed the plastic deformation pattern in the chip formation area. The shear angles change is the largest at one-third of the feed rate that is 100 μm under the cutting line in the cutting conditions used (at the cutting speed of 0.6 m/min and the feed rate of 0.3 mm).

The shear angles do not vary much along the cutting line. It may be plausible that symmetrical shear angle distribution pattern in 6061-10vol.%Al₂O₃ composite may be due to the built up edge and this might be a typical pattern in other materials in which a build up edge forms during machining.

The variation of the shear angle in chip formation areas for the three studied materials is summarized in Table 6-1. It is clear the distribution of the shear angles strongly depends on the properties of the workpiece materials.

6.3.4 Distribution of Shear Angles in the Chips

When the chip is formed it will move away from the base materials along the rake face of the cutting tool. At the contact area, the secondary shear zone, between the newly formed chip and the rake face of the cutting tool the material will suffer from a secondary plastic deformation under the contact stress between the chip and the tool.

Table 6-1. The variation ranges of the shear angles in materials studied

<table>
<thead>
<tr>
<th>Materials/Location</th>
<th>Cutting line</th>
<th>-100 μm</th>
<th>-200 μm</th>
<th>-300 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-Al</td>
<td>76°</td>
<td>68°</td>
<td>37°</td>
<td>9°</td>
</tr>
<tr>
<td>C11000-Cu</td>
<td>33°</td>
<td>42°</td>
<td>42°</td>
<td>32°</td>
</tr>
<tr>
<td>6061-10vol.%Al₂O₃</td>
<td>14°</td>
<td>65°</td>
<td>41°</td>
<td>0°</td>
</tr>
</tbody>
</table>
Figure 6-11 and Figure 6-12 show the distribution of the shear angles in the newly formed chip for 6061 aluminum alloy and C11000 copper respectively. The measurement of the shear angle is relative to the primary shear plane. The x-axis is the primary shear plane, the straight line OC in Figure 6-7. The top curve, EO (or DO), with equation is the boundary line in the chip. Starting from that line the chip leaves the rake face of the cutting tool stress-free. The other curves between the OD and EO (or DO) stand for the shear angle values in different location in the corresponding area ODEFO, see Figure 6-7.

The general variation of the curves has shown that the plastic deformation in secondary zone is limited within the area close to the contact area.

It is interesting to note that the "The top lines" in copper and aluminum are different, which are expressed in different equations, see Equation (6-2) and (6-3) for aluminum and copper respectively. But these equations have the same pattern, which may explain that the secondary shear deformation in chip have same pattern for metals.

\[
\phi = \arctan[2.68\exp(-0.0095 \ x)] \quad (6-2)
\]

\[
\phi = \arctan[3.55\exp(-0.055 \ x)] \quad (6-3)
\]

where \(\phi\) is shear angle, \(x\) is the distance from the contact surface.
where \( \phi \) is shear angle, \( x \) is the distance from the contact surface.

Comparing Figures 6-11 and 6-12 and Equations 6-2 and 6-3, it is shown that C11000 copper has wider deformation area in secondary shear zone (900 \( \mu \)m wide for copper and 500 \( \mu \)m for aluminum).

Due to the large built up edge on the tool tip, the plastic deformation in the 6061-10vol.\%Al\_2O\_3 composite was less severe. Figure 5-20 has shown that there is a built-up material staying between the chip and the rake face of the cutting tool. When the chip moves away along the rake face of the cutting tool, the secondary plastic deformation in the chip did not form because there is no direct contact between the chip and the tool. Because the amount of the plastic deformation is small the measurements of the shear angles are not possible.

6.3.5 Distribution of Shear Angles Below the Machined Surface

The distributions of the shear angles below the machined surface for each of the three materials studied have similar patterns (see Figure 6-13). The values of the shear angle increase exponentially as the location approaches to the machined surface. Copper shows the largest deformation depth, about 150 \( \mu \)m, in all three materials studied.

With the cutting tool worn the deformation area in newly machined surface increases. It may be because the tool flank face area was increased, which would increase the contact area between the tool flank face and the newly machined surface. As result, the temperature and contact stress all increased at the contact area. The general trends of the effects of cutting speed and the feed rate on the size of the deformation area in machined surface are shown in Figure 6-14.
6.4 Determination of Shear Strains and Shear Strain Distribution

The variation on the shear angles in the areas around the tool cutting edge clearly indicate the non-uniform nature of the shear during cutting of 6061 aluminum, C11000 copper and 6061-10vol.%Al₂O₃ composite. The equivalent strains $\bar{\gamma}$ that form during cutting can be estimated from the measured values of shear angle using the following equation;

$$\bar{\gamma} = \frac{\sqrt{3}}{3} \cot \phi = \frac{\sqrt{3}}{3} \cdot \frac{\Delta x}{\Delta y} \quad (6-4)$$

where $\phi$ is the shear angle as defined in Section 6.2.

6.4.1 Distribution of Shear Strains in the 6061 Aluminum Alloy

The distribution of the equivalent shear strains in the region ahead of the cutting tool edge in the 6061 aluminum alloy are shown in Figure 6-15. At the tool tip where the chip starts to form the strain has a value of about 4.0. The strains increase along the rake face of the cutting tool where the secondary plastic deformation zone is formed. This can be seen by following the tool tip line above the tool tip point (in Figure 6-15) where the strains can reach the values as high as 8.

On the cutting line $OC$, the strain at its maximum at the tool tip, point $O$, and at its minimum at the chip root, point $C$, where there is almost no strain. This fact indicates that the plastic deformation in the 6061 aluminum alloy is highly localized to the area close
to the tool tip. When moving along the "primary shear plane" the strains decrease from
the tool tip, at the value of 4 to about 2 at chip root.

The further increase of the strain after the chip has formed is due to the contact
stress between the rake face of the cutting tool and the chip, which is defined as
secondary shear deformation in literature. The microstructure examination has shown that
the plastic deformation in secondary shear zone is the most severe.

6.4.2 Distribution of the Shear Strains in C11000 Copper

Distribution of the shear strains in C11000 copper is shown in Figure 6-16. On
the cutting line OC, the strain is at its maximum at the tool tip, point O, and at its
minimum at the point C on the chip root line, which indicates that the plastic deformation
in copper has wider region than that in 6061 aluminum alloy in chip formation area.
When moving along the "primary shear plane" the strains decrease at the tool tip with a
value of 2.4 and at the chip root with a value of 0.6.

Comparing Figure 6-16 with Figure 6-15, it is clear that the strain variation range
is smaller for copper than for aluminum. Starting at about 200 μm below the cutting line,
the strains in the direction upward to the primary shear plane at any locations in chip
formation area increase in a way parallel to each other in C11000 copper, which indicates
that the strains in copper was more uniform than that in aluminum. The plastic
deformation in copper was not limited to a narrow zone along the primary shear plane
like that in aluminum, instead it spreads over a wider zone.

Another interesting fact is that along the primary shear plane, strains increase
from the tool tip, point O, i.e. from 2.4 to 3.8 at the point D in copper.
6.4.3 Distribution of the Shear Strains in 6061-10vol.%Al₂O₃ Composites

The built-up-edge on the tool tip and the rake face of the cutting tool is a dynamically stable phenomenon. The tool tip becomes blunt due to the accumulation of the materials built-up on the rake face of the cutting tool during cutting process. The maximum strain in chip formation area is not at the tool tip, instead at the tool "nose". Therefore, there is no primary shear plane observable, see Figure 5-20.

When a chip was formed, it moves without contacting the rake face of the cutting tool due to the existence of the built-up material on the rake face of the cutting tool, which makes the strain too small to measure in secondary shear zone. Unlike aluminum and copper, the most severe plastic deformation occurred at 100μm below the cutting line and concentrated around the tool tip with the built-up edge; see Figure 6-17.

6.4.4 Distribution of the Shear Strains in the Chip

The strains are also measured in the chips relative to the rake face of the cutting tool to study the strain distribution in the secondary plastic deformation zone and the region ahead of it. At the contact point where the chip leaves the rake face of the cutting tool, the strain decreases exponentially across the chip and away from the contact area; see Figure 6-18 and Figure 6-19.

The strain in contact area increases while the chip moves away along the rake face of the cutting tool until the chip leaves the rake face. The minimum secondary strain is at the very beginning of the chip forming at the location of tool tip, point O in Figure 6-7.
The maximum secondary strain is at the point where the chip leaves the contact with the tool rake face, point $F$ in Figure 6-7.

The significant strain in secondary shear zone in chip is about 200 $\mu$m away from the contact area for aluminum and 300 $\mu$m for copper. The equations shown in Figure 6-18 and Figure 6-19 represent well the maximum secondary strain in the chip for aluminum, Equation 6-5, and copper, Equation 6-6, except at the locations, about 50 $\mu$m, very closed to the rake face.

$$\gamma = 1.55 \exp(-0.0095\, x) \quad (6-5)$$

$$\gamma = 2.05 \exp(-0.55\, x) \quad (6-6)$$

where $x$ is the distance from the rake face of the tool. The constants in the equations depend on the property or the workpiece materials. These equations poorly represent the strain in the area within 50 mm to the contact interface. It may be due to the fact that the materials in that area are highly softened and deformed. Therefore, the strains can not be described with the general methods.

The strain in the chip formed in 6061-10vol.%$\text{Al}_2\text{O}_3$ composite is very small as discussed above. It could not be measured. The built up edge has prevented the newly formed chip from suffering from the secondary plastic deformation.
6.4.5 Distribution of the Shear Strains below the Machined Surfaces

The three materials studied have similar shear strain distribution patterns below the machined surfaces; see Figure 6-20. The strains increase slowly toward the machined surface. When approaching to 50 µm away from the top surface for 6061-10vol.%Al₂O₃ composite, 80 µm for 6061 aluminum alloy, and 150 µm for C11000 copper, the strains increase sharply in a high order exponential manner.

Similar to the strains in secondary shear zone, the strains in machined surface may be expressed with the following form of equation,

\[ \gamma = A \exp (-B x) \] (6-7)

where \( A \) and \( B \) are materials constants. \( x \) is the distance from the machined surface. For all materials studied, \( A \) is larger than 1 and \( B \) is smaller than 1. This equation could not be used to represent the strains in the area very close to the machined surface because the materials properties change in the top layer are quit different from the area below that, 50 µm away from the top layer.

6.5 Determination of the Strain Rates and Its Distribution

If the cutting tool passes through the length of the chip formation area, \( l \) (the length of line \( OC \) in Figure 6-7), in \( t \) seconds, the average strain rate can be estimated by the following equation

\[ \dot{\gamma} = \frac{\gamma}{t} = \frac{\gamma \cdot v_{cut}}{l} \] (6-8)
where $\dot{\gamma}$ is the average strain rate, $l$, is the length of chip formation area, and $v_{cu}$ is the cutting speed along the cutting line. For the chip shown in Figure 6-2, $l = 2.2$ mm, and $v_{chip} = 1.6$ m/sec. At the maximum strain, from the strain map of Figure 6-8 and 6-15, $\dot{\gamma} = 4.0$. Thus, the maximum strain rate is about $1.0 \times 10^3$ sec$^{-1}$ in the chip formation region.

Strain rates vary with the position in the material, as shown in Figure 6-21. The strain rate can be as high as $10^6$ sec$^{-1}$ in the material very near the machined surface where the maximum temperature rise occurred, or at the contact surface where the newly formed chip suffers from severe secondary plastic deformation at elevated temperature.

The equivalent strain rates in the cutting areas can be obtained from the equation for the equivalent strains. The strain rates in cutting direction are:

$$
\dot{\gamma} = \frac{d\gamma}{dt} = \frac{\sqrt{3}}{3} \frac{l}{d\gamma dt} = \frac{\sqrt{3}}{3} \frac{l}{d\gamma v_{cu}}
$$

(6-9)

where $v_{cu}$ is the cutting speed. The above equation indicates that the strain rates are proportional to the cutting speed and sensitive to the distance away from the cutting line.

The cutting speed is the velocity of the workpiece relative to the cutting tool in the cutting process. The maximum velocity of $v_{cu}$ is along the cutting line. At high speed cutting the cutting speed can be as high as $10^6$ mm/min. If the shear band is $10^3$ mm the strain rate can be expected to be $10^7$ sec$^{-1}$, using Equation 6-9.

Below the machined surface, with the increase of the distance away from the top surface, $(d\gamma$ increased) the strain rate decrease. That is because the plastic deformation decreases with the distance increase.
6.6 Isostrain Contour Maps and Constant Shear Angle Maps

Figure 6-22, Figure 6-23 and Figure 6-24 show the iso-strain contour maps in the chip formation areas for 6061 aluminum alloy, C11000 copper and 6061-10vol.%Al₂O₃ composite respectively. For the 6061 aluminum alloy, the strains increase towards the tool tip; while for the C11000 copper, the strains increase with increasing distance from the tool tip. For 6601-10vol.%Al₂O₃ composite the strains increase toward the tool tip like its matrix material.

The aluminum has a straight-concave primary shear line. The intensive shear deformation zone is narrow, about 50 μm, and located close to the primary shear line. The shear angles increase along the cutting line and towards to the chip root along the primary shear plane. Therefore, the strain decreases with the location away from the tool tip along the primary shear plane.

Copper has a convexly curved “primary shear plane”. The shear angles decrease in the cutting direction and towards the chip root along the primary shear plane. Thus, the strains increase with the location away from the tool tip.

6061-10vol.%Al₂O₃ composite did show a primary shear plane. It may be due to the built-up-edge that has change the geometry of the rake face of the cutting tool.

6.7 Variation of Microhardness in the Chip Formation Areas of the Workpiece

Microhardness measurements have been carried out at four different locations (see Figure 6-25) as described below:
Along the primary shear planes, or line OD, starting from the tool tip and ending at the chip root; see Figure 6-26;

Along chip center lines crossing the primary shear planes; see Figure 6-27;

Across the thickness of the chips, starting at the contact surfaces with the rake face of cutting tools, 400 μm above the cutting line, see Figure 6-28, and

Below the machined surfaces, see Figure 6-29.

Two conflicting factors influence the hardness of the workpiece materials. In general, hardness is expected to increase due to work hardening. However, the results of the hardness measurements have shown that the areas where the strains are the highest have the lowest hardness, especially in the secondary shear zone in contact with the tool.

At the contact area between the rake face of cutting tool and the chip, the temperature reaches to its highest value, which causes softening of the material in this region. Consequently the hardness decreases to a lower value. Due to the same reason, similar decreases in the Knoop's hardness are observed in the material layers very close to the machined surfaces.

The maximum hardness occurs at certain distance below the machined surfaces where the work hardening effect is stronger than the thermal softening effect. In the machined surfaces, the C11000 copper has the thickest and the most severely deformed top layer, compared with the 6061 aluminum alloy and 6061-10vol.%Al₂O₃ composite.

The thermal softening effect seems to be limited to 20 μm in the copper. The work hardening effects can be detected to occur within 80 μm or 180 μm for 6061 aluminum and C11000 copper respectively.
Under the severe secondary shear strains, the hardness of 6061 aluminum alloy increases to higher values compared to those for the C11000 copper. This could be attributed to the fact that the 6061 aluminum has a thermal conductivity of 167 W/m-K while C11000 has a value of 391 W/m-K. Therefore, temperature gradient in a 6061 aluminum chip decreases more gradually than that in a C11000 copper chip, as will be discussed in section 6.9.2.

An interesting observation (see Figure 6-27) regarding the hardness measurements made on a line crossing the primary shear plane along the central line of the chip is that the hardness increase occurred as the measurement location approached the primary shear plane.

For C11000 copper, the hardness peak was wide and spread over a range of 400 μm at both sides of the primary shear plane. The minimum hardness of the materials was about 22 percent higher than the materials under OD.

For the 6061 aluminum alloy, the hardness increases about 17 percent, but over a narrower range of 250 μm. The hardness peak was above the primary shear plane. In 6061-10vol.%Al₂O₃ composite the hardness increase was limited to only 5 percent. The hardness increase occurred when crossing the primary shear plan along the center of the chip.

Softening of the materials occurred at the contact areas, either at the chip-tool interface or at the tool-machined surface interface. The significant softening effects were limited to be within 40μm from the chip-tool contact interface. Within this softening layer, the temperature can be expected to be as high as the melting point.
Figure 6-30 shows the morphology of a naturally fractured (i.e., during the cutting process) cross surface of a chip of the 6061-10vol.%Al₂O₃ composite. The fractured surface exhibits the features indicating that the material at this location was probably melted (Figure 6-30 b). The material at the location close to the free surface shows the usual shear fracture morphology (Figure 6-30 a).

6.8 Flow Stresses (Estimated from Hardness) and Strains

Flow stress varies with strain from location to location in cutting areas. The stress in a cutting area is not directly measurable however can be estimated from the hardness measurements. A generally accepted method of relating hardness to the strength of the materials has been developed by Meyer (1908) [144]. The relation between the Meyer hardness and the uniaxial flow stress may be expressed as follows:

\[ H_M = C \sigma \]  \hspace{1cm} (6-10)

where \( C \) is called the constraint factor for the hardness test. Experimentally, \( C \) is approximately equal to be three for the Brinell, Vickers, and Knoop hardness tests. The Meyer method have been adopted by many researchers [145-147] to estimate materials strength under conditions where tensile or compressive tests are not practical.

In the current study, a load of 25 grams has been employed for the Knoop hardness test in order to place indentation in small areas. According to the microhardness measurements, the three \( C \) values were estimated as 3.19, 3.52 and 2.19 for 6061 aluminum alloy, 6061-10vol.%Al₂O₃ composite and C11000 copper, which were
calculated by comparing the stress and microhardness of the materials studied with the Equation 6-10.

The values of constant C have been used to estimate the local flow stresses in the cutting areas of the 6061 aluminum alloy, 6061-10vol.%Al₂O₃ composite and C11000 copper respectively.

In the chip formation area (see Figure 6-31), along the primary shear plane, the flow strength of the 6061 aluminum alloy increases with the strain. Flow strength has its lowest value at the tool tip and increases to a maximum value at the chip root.

For C11000 copper, the stress increases with strain to a maximum value at about half of the chip thickness, then decreases to a level as the same as that at the tool tip. For 6061-10vol.%Al₂O₃ composite, because the strain changes non-monotonically with the location in the area, the relationship between stress and strain could not be determined accurately. The hardness test load was too small to overcome the reinforcement effects. The built-up-edge effect also caused additional uncertainty.

Along the central line of the chip, crossing the primary shear plane (see Figure 6-32), stress increases with strain for 6061 aluminum alloy. For C11000 copper, the stress increases with the strain to a maximum value of 390 MPa at the strain of 3.5, then starts to decrease. At the strain of 4.7, the stress drops sharply. It may be due to that the thermal softening effect is stronger than that of the work hardening at this strain level.

The stress-strain relationships under the machined surfaces are shown in Figure 6-33. Here the hardness variations in the 6061-10vol.%Al₂O₃ composite could be measured with higher accuracy and included in the figure. All the materials exhibit
strength increase with the strain increase to a maximum level then a decrease due to thermal softening.

The strength is significant for 6061 aluminum alloy and C11000 copper, but not for the 6061-10vol.%Al_{2}O_{3} composite. It may be that under the thermal softening effects the hard reinforcement particles can still keep the microhardness, thus the strength, at a higher level.

6.9 Comparison of the Results of Metallographic Analysis with Merchant’s Model

According Merchant’s model, the minimum shear angle should be about 45 degrees. When the shear angle is greater than the minimum, the strains increase again, which shows a symmetric feature, see Figure 6-1. In fact, as shear angle increase the strain should decrease. Therefore, Merchant’s model is valid only when the shear angles are less than 45 degrees because this will imply a reversal in the shear direction. The present study shows that the shear angles may increase to the values of about 90 degrees, see Figure 6-34.

When the shear angles are small, the Merchant model and the results of the equivalent strain method are compatible. The strain change with the shear angle is as in the Merchant model. At low shear angle less than 10 degrees, the equivalent strain method well compile with Merchant model when the tool with the rake face angles of 0 degree and 10 degrees.

In Merchant’s model, the rake face angles and the shear angles are the only factors that determine the shear strain, see Equation (2-12). The role of the shear angles
has been shown in Figure 6-1. At low shear angles, the rake face angles of 0 and 10 degrees give the same strains. While the rake face angle of –5, 5 and 15 degrees give also the same strains. This variation is not due to the different properties of the workpiece materials, but appears to be a shortcoming of the analysis method.

The Merchant model is based on the trigonometric analysis of the primary shear plane. Therefore it does not work well for the materials that do not show a localized primary shear plane like 6061-vol.%Al2O3 composite. The metallographic method gives the local values of the shear angles and the strains at each point in the chip forming areas.

6.10 Comparison of Deformation Characteristics of Cu and Al: a Stacking Fault Energy Perspective

The differences in the shear strain and the shear angle variations between the 6061 aluminum alloy and the C1000 copper can be related to the work hardening abilities of these two materials. This may be explained by the differences in stacking fault energies (SFE) between the two work piece materials.

6061 aluminum has a higher SFE (~ 200 mJ/m²) [15], therefore, the width of the area between two partial dislocations is smaller, which makes the cross-slip of screw dislocations easier. The work hardening rate is reduced by the escape of dislocations from the obstacles like dispersed particles [16]. Thus, the strain localization is easy. The strains become concentrated to a narrower shear primary zone.

C11000 commercial purity copper has a lower SFE (~80 mJ/m²) [15]. The area between the partial dislocations is much wider than that in 6061 aluminum. The cross slip
of dislocations is difficult. The work hardening rate, therefore less extensive strain localization, makes the primary shear zone wider.

6.11 Particle Rotation and Fracture in 6061-10vol.%Al₂O₃ Composite

The interfacial voids between particles and matrix appear to be formed while the particles attempt to rotate and orient themselves in the strain gradient, see Figure 6-35. Consider a particle, shielded area, embedded in an element of matrix ABCD. Under the shear stress, the shape of the matrix element changed from ABCD to A'B'C'D'. The upper part of this element BC is subjected to higher shear strains than the lower part AD.

In the machined surface and the chip formation area of 6061-10vol.%Al₂O₃ composite, the shear strain at the upper part of the particle can be as high as two times that of the lower part of the particle, see Figure 6-35.

The particle embedded in the matrix element is rigid, therefore cannot change its shape together with the deformation of the matrix element. The only way for the particle to respond to the strain is by rotation towards the shear direction. The voids around the particles were generated during this process especially at 5 and 11 o’clock positions shown in Figure 5-25. The connection of the voids will lead to the physical separation of the particles from the matrix.

Some particle fracture is seen, but compared to matrix decohesion events this is rare. The plastic deformation of the matrix material probably was not sufficient to provide the high tensile stress needed to cause the particle fracture. The large majority of the particles remain intact.
For the particulate reinforced composite, the total strain,

\[ \varepsilon_f = \varepsilon_n + \varepsilon_g \]  \hspace{1cm} (6-11)

may be required to cause the fracture of the matrix material and the particle debonding [148]. Where \( \varepsilon_f \) is the strain required to cause the fracture, \( \varepsilon_n \) is the strain required to nucleate the voids and \( \varepsilon_g \) is the strain required to allow the voids to grow. When the total strain is greater than that the \( \varepsilon_f \) at the matrix-particle interface the debonding occurs.

Considering the stress conditions at the matrix-particle interface, if the strain is not high enough to cause the debonding the particle would keep intact with the matrix. But if the stress acting on the particle exceeds the fracture strength of the particle the particle could fracture.

If defining the \( \sigma_h \) the hydrostatic stress around the particle, \( \sigma_{loc} \) the local stress at the matrix-particle interface, the critical stress, \( \sigma_c \), required to cause the particle fracture may be expressed as [149]:

\[ \sigma_c = \sigma_h + \sigma_{loc} \]  \hspace{1cm} (6-12)

Due to the extreme non-uniformity of the strain and stress distribution and the random distribution of reinforcing particles in 6061-vol.%Al₂O₃ composite material, at some locations, the strain and stress may meet the requirement of Equations (6-11) and (6-12) cause particle fracture. Figure 5-28 has shown the particle fracture, but is rare in current study conditions.
6.12 Prediction of Temperature Rise in the Workpiece Materials

As shown in Figure 6-36, there are three heat sources in the work piece. The first one is due to the material shearing to form the chips at the shear plane. The second one is due to the friction in the contact area between the chip and the rake face of the cutting tool. The third one is due to the friction in the area between the tool flank face and the machined surface.

By considering the physical and thermal properties of the workpiece materials, the temperature rise at specific area where the shear strain occurred under the shear stress can be simply expressed as [56, 148, 149];

$$\Delta T = T - T_o = \frac{1}{\rho C_p} \int_{r_o}^{r} \pi d\gamma$$  \hspace{1cm} (6 - 13)$$

where $T$ is the temperature after the work $\int_{r_o}^{r} \pi d\gamma$ has been input into the workpiece materials at the location where $d\gamma$ is occurred. $T_o$ is the room temperature, $\rho$ is the density and $C_p$ is the specific heat of the workpiece materials. Therefore the value of $T - T_o$ is the temperature rise due to the work $\int_{r_o}^{r} \pi d\gamma$.

In the cutting process, the temperature rises to a steady state in less than one second and remains constant afterwards. Hence, it is reasonable to focus on the steady state temperature. On the other hand, the temperature varies depending on the position. Therefore, Equation (6 - 13) can be rewritten as follows:
\[ dT(x, y) = \frac{\tau(x, y)}{\rho[T(x, y)]C_p[T(x, y)]} \cdot dy(x, y) \]  
\hfill (6 - 14)

where, \((x, y)\) represent the location that defines the area interested.

**Equation (6-14)** has shown that the temperature rise at any points in the deformation areas of the workpiece materials depends on the values of the stress, the density, the specific heat, and the strain at the location.

The discussion above is somewhat intuitive. A detailed discussion on temperature rise in cutting can be found in [10, 152, 153], which derived the same formula as **Equation (6 - 14)**.

### 6.12.1 Coefficient of Temperature Rise (CTR)

Furthermore, if assuming that the density and specific heat are materials constants, then the temperature rise can be simplified as follows:

\[ \Delta T(x, y) = C \cdot [\sigma(x, y)\gamma(x, y)] \]  
\hfill (6 - 15)

where, \(C\) is the coefficient of temperature rise (CTR) defined below:

\[ C = \frac{1}{\rho[T(x, y)]C_p[T(x, y)]} \]  
\hfill (6 - 16)
The physical and thermal properties of three types of materials used in the study are shown in Table 6-2. Based on these data, the CTR values of these studies materials can be found as shown in Table 6-3.

**Table 6-2  Physical and thermal properties of the study materials**

<table>
<thead>
<tr>
<th></th>
<th>Al6061</th>
<th>10vol.%Al₂O₃</th>
<th>C11000 Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, Mg/m³</td>
<td>2.8</td>
<td>2.91</td>
<td>8.89</td>
</tr>
<tr>
<td>Tension Strength, MPa @20°C</td>
<td>310</td>
<td>351 [152]</td>
<td>220</td>
</tr>
<tr>
<td>Tension Strength, MPa @370°C</td>
<td>58 [152]</td>
<td>69 [152]</td>
<td>-</td>
</tr>
<tr>
<td>Shear Strength, MPa</td>
<td>275</td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>Specific heat, J/kg·°C</td>
<td>896</td>
<td>905</td>
<td>380</td>
</tr>
<tr>
<td>Thermal conductivity, W/m·°C</td>
<td>167</td>
<td>152</td>
<td>388</td>
</tr>
<tr>
<td>Stacking fault energy, MJ/m²</td>
<td>200 [14]</td>
<td></td>
<td>80 [14]</td>
</tr>
<tr>
<td>Surface energy, MJ/m²</td>
<td>1080 [149]</td>
<td></td>
<td>1720 [149]</td>
</tr>
<tr>
<td>Thermal expansion, 10⁻⁶°C</td>
<td>23.6</td>
<td>21.9 [152]</td>
<td>17.7</td>
</tr>
<tr>
<td>Melting point, °C</td>
<td>660°C</td>
<td>660°C</td>
<td>1065°C</td>
</tr>
</tbody>
</table>

**Table 6-3  Coefficients of temperature rise of study materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (Mg/m³)</th>
<th>Specific heat (J/kg·°C)</th>
<th>CTR (m³·°C/J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061 Aluminum</td>
<td>2.8</td>
<td>896</td>
<td>0.40 x 10⁻⁶</td>
</tr>
<tr>
<td>6061-10vol.%Al₂O₃</td>
<td>2.91</td>
<td>905</td>
<td>0.38 x 10⁻⁶</td>
</tr>
<tr>
<td>C11000 Copper</td>
<td>8.89</td>
<td>380</td>
<td>0.30 x 10⁻⁶</td>
</tr>
</tbody>
</table>
Hence, the models of temperature rise for three materials are as follows:

\[
6061 \text{ Aluminum: } \quad \Delta T(x, y) = 0.40 \cdot [\sigma(x, y) \cdot \gamma(x, y)] \times 10^{-6} \quad (6 - 17)
\]

\[
6061-10\text{vol.\%Al}_2\text{O}_3: \quad \Delta T(x, y) = 0.38 \cdot [\sigma(x, y) \cdot \gamma(x, y)] \times 10^{-6} \quad (6 - 18)
\]

\[
\text{C11000 Copper: } \quad \Delta T(x, y) = 0.30 \cdot [\sigma(x, y) \cdot \gamma(x, y)] \times 10^{-6} \quad (6 - 19)
\]

From the equations above, the following observations can be made: First, C1000 copper will have the smallest temperature increase. Second, the temperature rise of 6061 aluminum is 25% more than that of C11000 copper. This is due to the fact that 6061 aluminum has higher material density and thermal conductivity, resulting in a higher CTR. Third, the CTR of 6061-10\text{vol.\%Al}_2\text{O}_3 composite is between C11000 copper and 6061 aluminum. This may be attributed to the existence of secondary hard particles. These secondary hard particles cause the increases in the shear strength, the density and the specific heat. However, it may reduce the strain. Consequently, its CTR value is not as high as aluminum 6061, though it is higher than C11000 copper.

The \(\tau(x, y)\) and \(\gamma(x, y)\) values can be obtained using the microhardness and the shear angles values determined at each position in the workpiece material as given in previous sections. Temperature rise in any location in chip formation areas can be simply obtained by measuring the shear angle and the microhardness at the location of interest. The temperature rise at any location can be obtained as in the following steps:
1. Obtain strain values at each location by measuring the shear angle at the location then applying **Equation (6-2)**.

2. Obtain stress at the location by measuring the microhardness at the location, then applying **Equation (6-5)**.

3. The temperature can be calculated from **Equation (6 - 15)**.

Based on the data available from the present experiments mentioned in Chapter 5 and analyzed in previous sections, four areas are chosen for the further study: i) the primary shear plane; ii) near the bottom of the chip; iii) the center of chip, and iv) the machined surface.

### 6.12.2 Temperature Distribution along Primary Shear Plane

The temperature distribution along the primary shear plane is shown in **Figure 6-37**. From the figure, it is seen that the temperature reaches the maximum at the tool tip and decreases to a minimum at the root of the chip for 6061 aluminum alloy. The result for C11000 copper is just the opposite. The temperature reaches a minimum at the tool tip where the maximum strain occurred, and increases to a maximum at the chip root.

This fact may be due to the different work hardening behavior. 6061 aluminum alloy has less work hardening effect that leads to a straight-concave primary shear plane. Cu has high work hardening effect that leads to a convex primary shear plane. Geometrically, along the primary shear plane the stress and strain vary differently, which leads to the opposite trends, see **Figure 6-37**.

For 6061-10vol.%Al₂O₃ composite, the built-up-edge effect make it impossible to measure the stress and strain along the primary shear plane.
6.12.3 Temperature Distribution near Chip-Tool Contact Interface

As pointed out in the previous section in this chapter, after a chip was formed, it would undergo secondary shear deformation. At this stage the chip will be reheated because of the shear deformation. **Figure 6-38** shows the temperature rise distribution along the line of cross chip, marked in **Figure 6-25**. It is seen that the temperature can be as high as 60% of the material’s melting points at the first 10 µm in the chip-tool contact areas. It may be reasonable to conclude that at the chip-tool contact surface the temperature can reach as high as the melting point. In fact, the molten workpiece materials on the rake face of ceramic insert have been observed from a 6061-10vol.%Al₂O₃ composite sample at a cutting speed of 2.4m/sec and at a feed rate of 0.3 mm, as shown in **Figure 6-39**.

6.12.4 Temperature Distribution along the Center of the Chip

The central line of the chip starts from within the workpiece, crosses the primary shear plane, and ends in the chip. Its temperature distribution is shown in **Figure 6-40**. The temperature increases sharply when approaching the primary shearing plane where the intensive shear occurs. Above the primary shearing plan, the materials are heavily deformed. Neglecting the secondary shearing deformation, the materials no longer experience the deformation. Therefore, the temperature can keep a constant level until leaving the tool rake face.

Even though C11000 copper has a higher strain level, its product of stress and strain is smaller than that of 6061 aluminum. In addition, its CTR is 3/4 of that of 6061
aluminum. These all lead to the lower level of temperature rise for C11000 copper compared to 6061 aluminum.

The temperature rise of 6061-10vol.% Al₂O₃ composite cannot be calculated from the microhardness measurements and the shear strain data. The secondary hard particles and the voids around the particle makes the microhardness value measured too random to be constant. The built-up-edge effects make the shear angle measurement difficult. Thus, the shear strain value in the temperature calculations is approximate.

6.12.5 Temperature Distribution in Machined Surface

When the cutting tool passes the machined surface the friction between the tool tip (flank face) and the workpiece causes the temperature of the machined surface to rise further. Similar to friction wear, the temperature rise is also caused by the strain in machined surface.

Figure 6-41 has shown the temperature distribution in the machined surface due to shear deformation. As mentioned above, the level of temperature rise depends on the stress, strain and CTR. It is noted that the temperature decreases exponentially with respect to the distance to the machined surface, similar to the temperature rise in chip in secondary shearing area.

6.13 Tool Failure in Machining 6061-10vol.% Al₂O₃ Composite

Although the main focus is not on the tool failure the following observations have been made. The tool wear in cutting Cu and Al materials is not significant because the hardness of the cutting tool is much higher than that of the workpiece materials, Cu and
Al. In cutting 6061-Al₂O₃ composite, due to the hard Al₂O₃ reinforcing particles, the tool wear is significant. The main types of mechanisms of the wear can be summarized.

1. Particles with sharp angles (due to the fracture of particles) act as micro cutting elements on the tool material; see Figure 6-42. The photo is taken on the machined surface. The freshly fractured particles have very sharp angular points that would cut the tool materials. It also implies that the contact of cutting tool with workpiece material be mainly between the particles and the tool, which could reduce the friction and thermal effects.

2. Debris trapped in the machined surface abrades against the tool face; see Figure 6-43. The fine particles of hard reinforcement are highly abrasive and have less effect on the friction and thermal effects.

The un-fractured particle is shown in Figure 6-44. The smooth surface of particles moving against the tool face is less abrasive than the fractured particles and the debris because it has less sharpness.

The delamination and spallation of tool materials at the cutting edge (tool tip) also play an important role in tool failure during the cutting of the composite. The failure happened at the very tip of the cutting tool on the rake face; see Figure 6-45, 46 and 47.

This kind of failure only happened on the Al₂O₃ ceramic tool, but not in WC insert, which may be due to the fact that the particles in composite have the same hardness as that of the alumina ceramic cutting tool.
Fig. 6-1 The relationship between the shear angles and the shear stains, based on the Merchant model [3], at different rake face angles of the cutting tool.
Fig. 6-2  Schematic drawing of plastic deformation of grains in chip formation areas of the 6061 aluminum alloy sample from the micrograph in Figure 5-2. Cut at the cutting speed of 2.4m/sec and the feed rate of 0.3 mm.
Fig. 6-3 Plastic deformation geometry of 6061 aluminum alloy in the chip formation area during machining.
Fig. 6-4 Plastic deformation geometry of 6061-10vol.%Al₂O₃ composite in chip formation area during machining
Fig. 6-5 Plastic deformation pattern of C11000 copper in chip formation area during machining.
\[
\therefore \quad \theta = \frac{\pi}{2} - \phi = \arctan \left( \frac{\Delta x}{\Delta y} \right)
\]

\[
\therefore \quad \phi = \frac{\pi}{2} - \theta = \frac{\pi}{2} - \arctan \left( \frac{\Delta x}{\Delta y} \right) = \arctan \left( \frac{\Delta y}{\Delta x} \right)
\]

Fig. 6-6 Schematic graph for the determination of shear angles
Fig. 6-7  Schematic diagram representing the areas around the tool tip in metal cutting. 1) the chip formation area $OABD$, 2) in the chip – newly formed chip moving along the rake face of the cutting tool, above the primary shear plane, $OD$, and 3) the machined surface below the lines $OG$ and $DH$. The area closed to the $OF$ is the secondary shear zone. The line $OC$ is the cutting line. $\phi$ is the shear angle. $\delta$ is the feed rate, or the thickness of the uncut chip.
Fig. 6-8  Shear angle distribution in the chip formation area for 6061 aluminum alloy sample, cut at a cutting speed of 0.6m/sec and a feed rate of 0.3mm with VB = 0.3mm
Fig. 6-9  Shear angle distribution in the chip formation area for C11000 copper sample, cut at a cutting speed of 0.6mm/sec and a feed rate of 0.30mm with $V_B = 0.30$mm
Fig. 6-10  Shear angle distribution in the chip formation area for 6061-10vol.%Al₂O₃ composite, cut at a cutting speed of 0.6m/sec and a feed rate of 0.3mm with VB = 0.3mm
\[ \phi = \tan^{-1}[2.68 \exp(-0.0095 \, x)] \]

Fig. 6-11  Shear angle distribution in chip for 6061 aluminum alloy
Fig. 6-12 Shear angle distribution in chip for C11000 copper
Shear angle distribution in machined surface for all study materials. Cutting speed is 0.4 m/min and feed rate is 0.3 mm with the new tool, VB = 0.0 mm.
Fig. 6-14 Shear angle vs. feed rate in machined surface for all study materials.
Fig. 6-15 Strain map representing the shear strains in the cutting area. Sample is 6061 aluminum alloy, cut at a feed rate of 0.3mm and a cutting speed of 0.6m/sec with VB = 0.3mm.
Fig. 6-16  Shear strain map, in the chip formation area, representing the shear strains in the cutting areas. Sample is C11000 copper, cut at a feed rate of 0.30mm and a cutting speed of 0.6m/sec
Fig. 6-17 Strain map representing the shear strains in the cutting areas. Sample is 6061-10vol.%Al₂O₃ composite, cut at a feed rate of 0.30 mm and a cutting speed of 0.6m/sec with VB = 0.3mm.
Fig. 6-18  Strain map representing the shear strains in chip. Sample is 6061 aluminum alloy, cut at a feed rate of 0.30 mm, and a cutting speed of 0.6m/sec.
Fig. 6-19 Strain map representing the shear strains in the cutting areas. Sample is C11000 copper, cut at a feed rate of 0.30 mm and a cutting speed of 0.6m/sec.
Fig. 6-20 Strains in machined surface, Samples were cut at a feed rate of 0.30 mm, and a cutting speed of 0.6 mm/sec.
Fig. 6-21  Strain rates in machined surface versus depth for various cutting speeds
Fig. 6-22 Isostrain contour around the cutting tool tip. The sample is 6061 aluminum alloy, cut at a cutting speed of 0.6 m/sec and a feed rate of 0.3 mm with VB = 0.3 mm.
Fig. 6-23  Iso-strain contour around the tool tip. The sample is C11000 copper, cut at a cutting speed of 0.6m/sec and at a feed rate of 0.3mm with VB = 0.3mm.
Fig. 6-24  Iso-strain contour around the tool tip. The sample is 6061-10vol.%Al₂O₃ composite, cut at a cutting speed of 0.6m/sec and at a feed rate of 0.3mm with VB=0.3mm.
Fig. 6-25  Schematic diagram showing the locations of Knoop hardness measurement in cutting area
Fig. 6-26  Knoop hardness along primary shear plane. Work hardening and work softening are not very significant.
Fig. 6-27  Knoop hardness measured along central line of chip crossing the primary shear plane
Fig. 6-28  Knoop hardness across the chip, starting from chip-tool interface and ending at chip free surface. Work softening occurred at chip-tool interface.
Fig. 6-29  Knoop hardness in machined surface. The hardness value disclosed the work hardening and softening of workpiece materials in cutting areas.
a) Approaching the free surface of chip

b) Initializing at chip-tool contact interface

Fig. 6-30 Natural fractured surface of 6061-10vol.%Al₂O₃ composite chip. The melting of workpiece material at the chip-tool contact interface may have occurred.
Fig. 6-31  Stress-Strain in chip formation area. The hardness is measured along the line starting from the tool tip and ending at the chip root.
Fig. 6-32  Stress-strain along the chip central line crossing the primary shear plane
Fig. 6-33  Stress-Strain relationship in the machined surfaces
Fig. 6-34  Comparison of Merchant model [3] and the metallographically determined strains at the different rake face angles of the cutting tool
Fig. 6-35  Rotation of particles in the matrix during the deformation process in machining. The formation and the growth of the voids around particles result in separation of the particles from matrix.
Fig. 6-36  Schematic diagram of heat sources around the cutting tool tip. Heat generated in the chip forming area is due to the material shearing. Heat produced in the friction area is by friction between the newly formed chip and the rake face of the cutting tool. The second friction area between the worn surface on the tool flank face and freshly machined surface is identified as the third heat source. In cutting hard particulate reinforce composite material, due to the presence of the second hard particles the secondary friction area is identified as the abrasive area.
Fig. 6-37  Temperature rise along primary shear plane starting from tool tip.
Fig. 6-38  Temperature rise along the line across the chip marked in Figure 6-25
Fig. 6-39 SEM image of the molten matrix materials of 6061-10vol.%Al₂O₃ on the rake face of cutting tool. Cut at a speed of 2.4m/sec and at a feed rate of 0.3mm with tungsten carbide insert. The molten material is 6061 aluminum matrix material of the composite.
Fig. 6-40 Temperature rise along central line of chip cross primary shear plane
Fig. 6-41  Temperature rise below machined surface
Fig. 6-42 SEM image of freshly fractured particles on machined surface. Sample is 6061-10vol.%Al₂O₃, cut at a speed of 0.6m/sec, and at a feed rate of 0.05mm
Fig. 6-43  SEM image of debris trapped in machined surface. Sample is 6061-10vol.%Al₂O₃, cut at a speed of 0.6m/sec, and at a feed rate of 0.05mm
Fig. 6-44  SEM image of undamaged particle trapped in machined surface. Sample is 6061-10vol.%Al$_2$O$_3$ composite, cut at a speed of 0.6m/sec, and at a feed rate of 0.05mm
Fig. 6-45  SEM image of adhesive failure of the rake face of Al$_2$O$_3$ ceramic tool after cutting 0.5 second. The area is close to the tool tip. Sample is 6061-10vol.%Al$_2$O$_3$ composite, cut at a speed of 0.6m/sec and at a feed rate of 0.05mm.
Fig. 6-46 SEM image of delamination failure of the rake face of Al₂O₃ ceramic tool after cutting 0.5 second. The area is close to tool tip on the rake face. Sample is 6061-10vol.%Al₂O₃ composite, cut at a speed of 0.6m/sec and at a feed rate of 0.05mm.
Fig. 6-47  SEM image of spallation and fracture failure of the rake face of Al₂O₃ ceramic tool. The area is at the tool tip after cutting 0.5 second. Sample is 6061-10vol.%Al₂O₃ composite, cut at a speed of 0.6m/sec and at a feed rate of 0.05mm
CHAPTER 7.

CONCLUSIONS

The current study has been focused on the plastic deformation behavior in the chip formation area, chip-tool contact interface area and machined surface during machining. The 6061 aluminum alloy, C11000 copper and 6061-10vol.%Al₂O₃ composite materials have been selected as study materials.

The conclusions of the experimental results are as follows.

1. **Microstructures**

   Microstructures of workpiece materials in the chip formation area during the machining process feature the intensive localization of plastic deformation. Metallographic techniques were used to observe the microstructural changes. The grain boundaries deformed in the chip forming process have been recognized to be the material shear direction.

   During machining, voids are generated along the strain gradient. The coalescence of the voids leads to the formation of shear cracks near the free surface of the chip. Shear crack propagation leads to the formation of the fracture at the chip free surface.

   The voids formed around the reinforcement particles in 6061-10vol.%Al₂O₃ composite, but particle fracture was less commonly observed.

2. **Determination of Shear Angles**

   A method to measure the shear angles has been given. The shear angle is the angle between the cutting direction and the material’s shear direction. The shear angles
vary between 0 and 90 degrees in the chip formation areas depending on the location. In the secondary shear zone, shear angles increase along the contact area to a maximum value at the last chip-tool contact point. Shear angle distribution maps have been developed to describe the variation of the shear angles in the workpiece materials during machining.

3. **Shear Strains and the Distribution Map**

Shear strains were estimated from the measured values of the shear angles in the primary and secondary shear zones and below the machined surface. Shear strains varied with the location in the workpiece materials relative to the cutting tool tip. The maximum shear strain in the chip formation area was at the tool tip for the 6061 aluminum alloy.

For the C11000 copper, the maximum shear strain was at the chip root location. The strains were as high as 20. The secondary shear strains were generated in newly formed chips in the chip-tool contact interface areas.

For all materials studied, the maximum shear strains were at the last contact point of the chip-tool contact interface.

Shear strain distribution maps were constructed based on the shear angle distribution maps.

4. **Strain Rates**

Shear strain rates have been estimated based on the cutting speeds and the widths of the shear bands. The analysis show that the strain rates at the cutting speed of 2.4 m/sec in cutting 6061 aluminum alloy could be as high as $10^6 \text{ s}^{-1}$ in machined surface.
5. **Flow Stress**

Stress in the chip formation area can not be tested directly, but may be estimated by the microhardness that reflects the work hardening effects and the stress level at the location. The stress is proportional to the microhardness, not proportional to the shear strain.

Four different locations have been selected to perform the microhardness measurement; 1) along primary shear plane, 2) across the length of the chip, 3) across primary shear plane and 4) across the machined surface. The maximum microhardness are at the locations close to the primary shear plane areas, but not at the location where the maximum strains are.

The relationship between the stress and strain is complex. The thermal softening effects could reduce the work hardening effects. Therefore, the high strain would not increase the stress level at a high temperature area, such as the chip-tool contact area.

6. **Machining 6061-10vol.%Al₂O₃ Composite**

The formation of a built-up-edge has been observed when cutting the 6061-10vol.%Al₂O₃ composite, but not when cutting the C11000 copper or 6061 aluminum. The built-up-edge effects have played an important role in determining the plastic deformation behaviour in chip formation process. Thinner chips in 6061-10vol.%Al₂O₃ composite was produced compared with C11000 copper and 6061 aluminum.

The built-up-edge was formed between the newly formed chip and the rake face of the cutting tool. Therefore the secondary severe plastic deformation is hardly observed.
The rotation of the secondary reinforcement particles in severe plastic deformation areas has been observed to occur, and this was due to the strain gradient around the particles.

7. **Temperature Rise**

**Temperature Rise measurement:** The temperature rise right at the tool-workpiece interface can not been obtained with direct measurement, but the direct thermal couple measurement provides a good approximation. The temperature rise estimation model is required to understand the temperature rise distribution at the tool-workpiece interface, especially on tool faces.

**Temperature Rise:** Temperature rise depends on the physical, thermal and mechanical properties of the workpiece materials and the cutting parameters. The coefficient of temperature rise (CTR) that contains the physical and thermal properties of the workpiece materials has been defined. The temperature rise is proportional to the strain and stress. It has been observed that the highest temperature is at the chip-tool contact interface, where the temperature could be as high as the molten point of the workpiece materials.

**Temperature Rise Distribution:** A temperature rise distribution pattern similar to that of the strain distribution has been obtained.

8. **Tool Failure in Machining 6061-10vol.%Al₂O₃ Composite**

Tool failure has been observed in machining 6061-10vol.%Al₂O₃ composite. The failure mechanism has been analyzed on SEM. The results have shown that the main
mechanism for the tool failure may be the delamination, or spallation on the very tip area of the cutting tool. It may be due to the high temperature gradients at the contact interface between the newly formed chip and the rake face of the cutting tool.
CHAPTER 8.

SUGGESTIONS FOR FUTURE WORK

Plastic deformation of workpiece materials plays important role in metal cutting process. The plastic deformation behaviour of workpiece materials affect the temperature rise and its distribution during the chip formation process and in the cutting tool, thus the tool life and the quality of the machined surface. A substantial amount of work has been done in these areas, but there are still certain topics that are not clear. The following are some suggestions for future work that may lead to better understanding of machining or cutting processes have been given.

8.1 On the Materials Aspects

1. The emphasis of further research should be on the area where the newly formed chip seizes against the rake face of the cutting tool. The microstructural changes that occur at the contact interface are still not clear. Combining thermal effects with the plastic deformation behaviour in this area, better models should be developed for tool failure analysis.

2. The area below the machined surface is another important issue. The ways by which the plastic deformation behaviour of the workpiece materials, machining parameters and tool conditions affect the quality of the machined surface is hardly reported. Further study should be carried out to clarify these items.

3. Metal matrix composite materials as advanced engineering materials have found more and more applications in industries, but the study of mechanical behaviour, especially the effects of the hard reinforced particles, in the chip formation process and
tool failure mechanisms are not well studied. The relationship between the built-up-edge and the tool life is not clear. How the material softening in the seizure area affects the tool life needs further investigating.

4. Due to the difficulty in directly measuring stress, strain, and temperature distribution in the cutting areas, finite element analysis should be further developed to supply more accurate data required for machining studies.

8.2 On Cutting Tool Aspects

1. Even though a specific width of flank wear has been standardized to define tool failure, measuring the flank wear is a daunting work. New standards or methods should be developed for monitoring tool failure on line.

2. In cutting soft materials with a hard cutting tool, the cutting tool may never get worn. Therefore, the \( VB = 0.30 \text{ mm} \) standard can not be used to determine the end of tool life because even \( VB \) is larger than \( 0.30 \text{ mm} \), the cutting tool can still produces good surface, which means that the tool does not reach the end of service life. This situation varies strongly with workpiece materials. The cutting tool could still fail not by wear but by other mechanisms like tool tip fracture.

3. Further investigation of bonding materials in tool inserts is needed. Because the current study has shown that the tool failure was initialized at the very beginning of the cutting. The sharp drop of the mechanical property due to the high rate of temperature rise may be the main reason that leads to tool failure at the very beginning of the cutting.
8.3 On Operation Parameters Aspects

Temperature rise is most sensitive to the cutting speed and, then to the feed rate (or depth of cut), and the least width of cut. The combined effects of these three operation parameters on tool failure or tool life are still not clear. Optimization of these operation parameters should be related to the thermal, physical and mechanical properties of workpiece materials to reduce the probability of cutting tool failure.
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LIST OF PUBLICATIONS AND PRESENTATIONS
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