A study of micro-machining thin workpieces

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**NANYANG
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**A STUDY OF MICRO-MACHINING THIN
WORKPIECES**

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**SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING
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A STUDY OF MICRO-MACHINING THIN WORKPIECES

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ABSTRACT

Thin sheet molds with micro-features are needed in the hot roller embossing process to mass produce cheaper and disposable polymer microfluidic devices. Fabrication of thin molds using mechanical micro-machining techniques has some advantages over lithography and MEMS based processes: capability to manufacture 2D, 2 ½D and 3D features, and ability to process a wide range of workpiece materials. However, several challenges remain in using the machining process where the micro-feature dimensions created in the surface of a thin mold can be comparable to mold thicknesses. This thesis examines micro-machining of thin ($< 100\text{ }\mu\text{m}$) workpiece materials, a topic rarely discussed in the literature.

A significant difference in machining thin workpieces compared to thick ones is the ratio of depth of cut to the workpiece thickness; in the former this ratio is very small (~ 1) whereas in the latter it is very large (~ 1000). Hence, the machining induced mechanical and thermal loading can be significant on the machined workpiece material. This thesis studies four specific issues in machining such thin workpieces:

- Effect of the reduced workpiece thickness on the cutting process.
- Machining induced residual stress and warping due to the reduced workpiece thickness and substrate elastic properties.
- Microstructural changes in the workpiece material.
- Burrs reduction.

The approach taken includes both experimental and simulation based investigations. Orthogonal cutting is used to study the effect of workpiece thickness reduction and machining induced warping. Oblique cutting, in the form of single point diamond turning process, is conducted to study the microstructural changes, while a micro-milling process is used to study burr reduction. Finite element simulations are utilized to understand the machining induced stress and the effect of the substrate properties.

Some significant findings of the thesis are as follows. The limitation to achieve very thin workpieces fixtured using adhesive is mainly due to workpiece material peel-off (adhesive fracture mode) that occurs during initial tool engagement. There are significant changes to the machined workpiece material as the workpiece thickness is

reduced. Workpiece curvatures are larger as thickness is reduced due to the effect of the machining induced stresses. The stress profiles across the thickness of the machined workpiece are broader as the ratio of the depth of cut to the machined workpiece thickness is increased, especially for a compliant substrate while a stiffer substrate produces less variation in stresses. Grain refinement and grains orientation modification are seen to occur due to the significant plastic deformation in the form of localized large strains in the shear zone experienced by the thin workpiece. The top burrs are successfully reduced using an edge angle strengthening method achieved by increasing both the side edge angle and tapered micro-milling tool angle.

A thin mold with a thickness of about 160 μm and with ratio of the feature height to the machined thickness of about 0.625 was successfully produced using the micro-milling process. The results prove the capability of the mechanical micro-machining process to create features necessary for a thin embossing mold.

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List of Publications

Journals

1. K. Saptaji and S. Subbiah, 2010, "*Microstructural changes in machining of thin substrates*", Key Engineering Materials, Vol. 447-448, pp. 76.
2. Kushendarsyah Saptaji, Sathyan Subbiah and Jaspreet Singh Duphia, "*Effect of Side Edge Angle and Effective Rake Angle on Top Burrs in Micro-Milling*", Precision Engineering, 36 (2012), 444 – 450.
3. Kushendarsyah Saptaji and Sathyan Subbiah, "*Study of the Micro-cutting Thin Workpiece*", ASME Journal of Manufacturing Science and Technology, submitted in July 2011, in review.

Conferences

1. K. Saptaji and S Subbiah, 2009, "*Burr Removal in Micro-milling Aluminium Alloys*", Symposium T, 5th International Conference on Materials for Advanced Technologies (ICMAT) 2009, Singapore.
2. K. Saptaji and S Subbiah, S, 2010, "*Challenges in Precision Machining of Thin Substrate*", 13th International Conference on Precision Engineering (ICoPE), Singapore.
3. K. Saptaji and S. Subbiah, 2011, "*Orthogonal Cutting Study of the Micro-cutting Thin Workpiece*". Proceedings of 2011 ASME International Manufacturing Science and Engineering Conference (MSEC) Volume 2, June 13-17, 2011, Corvallis, Oregon, USA.

Chapter 1.

INTRODUCTION

1.1 Background and Motivation

Polymer microfluidic devices are micro analyzer tools in the area of micro total analysis system (μ TAS). Micro total analysis system or “Lab on Chip” is an integration of monitoring and analysis of chemicals, such as sample collection, pretreatment, amplification and detection, all to be performed in one easy to handle as if in a standard laboratory. The integration offered by the μ TAS, especially polymer microfluidic devices, is advantageous in that it can reduce the consumption of the chemical samples that may be rare and expensive, provide faster and more accurate analysis, offer simplicity of use, provide higher sensitivity, and offer lower cost compared to conventional devices [1-3]. Hence, these devices have been used widely in many areas such as in genetic analysis, drug discovery, clinical diagnostics, environmental monitoring, biomedical and biochemical industries, and also in the field of chemistry [1, 3-4].

Different fabrication processes have been developed to produce such polymer microfluidic devices, namely injection molding, hot embossing, and thermoforming [3, 5]. Of these, the hot embossing is a simple process that provides several advantages such as low cost and the ability to process a wide range of workpiece materials [5-6]. Hot embossing employs an embossing mold (also referred to as a replication tool, master mold or mold insert) that replicates a positive relief pattern onto the polymer surface at a temperature above its glass transition temperature [7-8].

In the current trend of usage polymer microfluidic devices are used once after which they are discarded. A continuous manufacturing process is thus necessary in order to reduce cost while providing flexibility to make different types of microfluidic devices. One example of such a continuous process is the hot roller embossing process (Figure 1-1). The continuous hot roller embossing process needs a thin flexible embossing mold to transfer the micro-features patterns onto the

polymer material. The thin embossing mold is wrapped and mounted around onto the cylinder roller and as the polymer sheet is passing through; it will transfer the micro-features patterns onto the polymer material. The thin mold has to be strong enough to withstand high pressure and temperature while transferring the micro-features patterns onto the polymer material. Several manufacturing processes to produce thin embossing mold have been proposed in the literature such as dry etching [9], lithography [10], electroplating [11-12], and *UV-LiGA (Ultraviolet - Lithographie Galvanoformung Abformung)* [13]. These processes have successfully fabricated molds with thicknesses down to 50 μm [9, 13]. However, these processes are expensive, involve hazardous chemicals and have a long series of stages including creating custom masks that require tight tolerance control [14].

Figure 1-1. Continuous hot roller embossing concept.

Alternatively, the thin embossing mold can be manufactured by the mechanical micro-machining process. Micro-milling, which is a flexible mechanical machining process, has some advantages such as the ability to manufacture 2D, 2 $\frac{1}{2}$ D and 3D features, to process a wide range of work materials and to produce faster and cheaper molds when compared with lithography and MEMS based processes [15-16]. In addition, the mechanical micro-machining process can avoid the use of hazardous chemicals, reducing operational and investment costs. It has been shown that micro-milling process has the capability to produce workpiece features as thin as 8 μm over small areas [17]. Roller embossing molds require large areas to be micro-cut while being fixtured appropriately.

Application of micro-milling with uniform fixturing on the surface area of the sheet is a new method to produce features on a thin mold to be used for roller embossing. The application of this method requires a fundamental study of micro-cutting thin workpieces. There are several challenges involved in creating micro-features using micro-milling process to produce embossing molds especially in thin workpieces, such as reducing burrs, fixturing method and its effects, reducing workpiece deformation and warping, and possible microstructural changes induced by the mechanical and thermal loading of the tool.

1.1.1 Challenges of Micro-cutting Thin Workpieces

Machining Basics. Cutting or machining is a mechanical material removal process in which the cutting action is performed by a tool with higher hardness than the workpiece material. In the simplest form of cutting viz. orthogonal cutting (Figure 1-2), the cutting edge is perpendicular to the cutting velocity (v_c) and as the tool moves towards the workpiece with constant depth of cut (t_0), the chip forms and separates from the workpiece near the cutting edge and generates a plane surface. The chip formation is usually accompanied with large plastic deformations, high strain (1 – 4), strain rates ($10^4 - 10^6 \text{ s}^{-1}$) and high temperatures in the cutting zone (700 – 1000°C). The deformation in the process can be regarded as occurring in plane strain where the chip does not flow to either side and the width of the tool is greater than that of the workpiece [18].

Figure 1-2. Schematic view of orthogonal cutting.

In order to produce micro-features, the tool dimensions in the range of tens of micrometers to a few millimeter size, is often necessary [19]. Cutting such small

tools is different from conventional macro machining deviating from conventional metal cutting principles. For example in micro-cutting process, the cutting edge radius is comparable to the depth of cut [20] and depth of cut can be in the same order of magnitude as the average grain size of the workpiece material [21]. These and other factors cause size effects in micro-cutting processes [19].

In the literature, investigations in micro-cutting thick workpieces are widely reported while those in micro-cutting thin workpieces (i.e. where the depth of cut t_0 may be comparable to workpiece thickness t_w) are rare (Figure 1-3). The reduction in workpiece thickness can affect the mechanism of chip formation in the machining process and the machined workpiece properties. The deformation induced by machining process may be more significant in the thinner workpiece. An appropriate fixturing method is necessary to minimize the deformation induced and avoid thin workpiece detachment during machining. In addition, the cutting mechanism and plastic deformation of the thin workpiece is also affected by the interaction of the thin workpiece and the substrate underneath it. Challenges in micro-cutting thin workpieces are thus many: machining induced stress and warping, microstructural changes, fixturing challenges, substrate effects and burrs reduction. These are explored in detail in the following paragraphs.

Figure 1-3. Illustration of the cutting process on thick workpiece (left) and thin workpiece (right). In a thin workpiece, the machined workpiece thickness (t_w) is comparable to the depth of cut (t_0).

Machining induced stress and warping. The machining process involves thermal loading and mechanical loading, which can generate surface and subsurface damage or deformation altering mechanical and metallurgical properties of the machined workpiece and furthermore induce residual stresses [22-23]. The geometry of the

machined workpiece is influenced mainly by fixturing force and machining induced residual stress. By releasing the workpiece from the fixture, the residual stress in the surface and subsurface will redistribute to reach an equilibrium condition due to the unbalanced forces and moments caused by material removal leading to deformation [24-26]. Under similar machining conditions the residual stresses in the machined surface can vary between thick and thin parts.

In thick workpiece the ratio of depth of cut (t_0) to the machined workpiece thickness (t_w) is very small, and the stress penetration beneath the tool into the workpiece thickness is also usually insignificant. In the thin workpiece, the ratio of t_0 to t_w is larger; hence large stress may reach the bottom of the workpiece and interacts with the interface of the workpiece and fixture (Figure 1-3). The stress wave could either be deflected or may pass through the thickness of the thin workpiece and produce enhanced stresses and deformation; if the stresses are larger than the fixturing strength it can lead to detachment of the workpiece. In addition, the residual stresses are induced across the machined workpiece thickness leading to warping. In machining thick workpieces (thickness of about 75 mm) residual stress produced by the process can be detected to a depth of as much as 200 μm [27]. Thus it is important to consider the effects of plastic deformation, residual stress values and profiles, in the machining of thin workpieces (thickness less than 100 μm).

Fixturing of thin workpieces. One of the challenges in machining a thin workpiece relates to the fixturing strategy to minimize workpiece deformation and deflection caused by the removal of material [28] and prevent workpiece slip or lift off induced by the stresses created by the tools. Thin workpieces are very delicate and must be handled with care to avoid any deformation. Several fixturing strategies for machining thin plates have been proposed in the literature, such as magnetic chuck [29-30] (which can only be applied to magnetic materials), vacuum [31-32] (which needs the backside of the sample to be flat), use of multipin clamping devices supported by low melting temperature alloy [33] and electro-rheological gel (ERG) [34]. In addition, the use of adhesive in machining processes has been reported in literature for thick and complex shape workpieces [35-36] as well as for thin

workpiece [29]. The use of adhesive provides a thin, uniform bonding layer and can be removed easily after machining is completed. The shear strength and tensile strength of adhesive has to be high enough to withstand the shear load produced by the tool and to avoid workpiece slip or detachment. In the machining of thin workpieces stresses may reach the bottom of the workpiece leading to stress concentrations in the interface between dissimilar materials (adherent-adhesive). The thickness of the adhesive can also impact its ability to fixture the workpiece effectively. A study of the application of adhesive to hold thin workpiece has not been much reported in the literature.

Substrate effects. The cutting mechanism and plastic deformation of the thin workpiece is also affected by the interaction of the thin workpiece and the fixture (substrate) underneath it similar to that observed in the nano-indentation and nano-scratching of thin film (Figure 1-4). During nano-indentation of the thin film, the stress is transmitted elastically through the thin film and if the stress is high enough it can go through across the interface between the thin film and substrate and furthermore affect the thin film properties and can induce delamination. Similarly, in the case of machining thin workpiece, the stress produced by the tool is transmitted through the thin workpiece and if the stress is high enough it can go through the substrate or deflect back and affect the residual stress profile and/or cause slip-off. The plastic deformation behavior of the thin film and the delamination depend on the film thickness and elastic properties of the substrate [37] especially when the film thickness is thin or the depth and the magnitude of the load is high enough.

Figure 1-4. Substrate effects seen in nano-indentation of thin film (left), similar effects can occur in micro-cutting of thin workpieces (right).

In addition, delamination can occur when the thin film is pulled by high normal tensile stress and also slip on the substrate due to high shear stresses [38]. Hence, investigating the influence of substrate properties in the cutting mechanism and residual stress profile especially for thin workpiece conditions is needed.

Microstructural changes. Microstructural changes are reported in machining of only thick work materials but such changes are largely confined to the chip, machined surface or near-surface. Microstructural transformations in the form of decomposition of Zn rich phase on the machined surface of a Zn-Al alloy have been reported [39]; the transformations are confined only to the surface of the bulk material machined. Orientation changes in the form of lattice rotation during machining of thick single crystal materials are also reported [40]; changes are again confined to the surface only. Microstructural changes in the form of recrystallized structure in the sub-surface down to 76 μm has been suspected and reported in machining of thick samples made of Al7075 alloy [41] but no further investigations on the nature of change has been made. These surface and near surface microstructural changes are expected to be more severe in machining of thin work materials since the machining loads are now confined to a thin workpiece. Consequently, the mechanical and thermal loading induced by the advancing tool will affect not just the surface but the entire thickness of the work material. Also, one can expect through-thickness structural changes in the work material under such conditions.

Burrs challenges. In micro-milling, burr sizes can be comparable with the feature sizes therefore the removal of burrs in micro-parts is very challenging. The existence of burrs on the workpiece may lead to problems related with dimensional accuracy, surface finish, ease of part assembly, and furthermore increase the production cost and time for deburring [42]. Formation of burrs in the ductile materials can be reduced using sharp single crystal diamond cutting tools with very small edge radii; diamond micro-milling tools are commercially available in the market but are expensive and require good vibration control and precision on the machine tool for effective usage. Additional secondary process to remove the burrs

(deburring) in the micro-scale fabrication and ultra precision machining may also be too expensive or impractical to implement [21]. Hence, the challenge remains to reduce or eliminate burrs in simpler ways that further can be applied in the manufacturing of molds especially using conventional carbide cutting tools when used on conventional machining centers.

1.1.2 Need for the Research

There are thus substantial challenges in machining thin workpieces and hence these deserve a detailed investigation. There is also a gap of such investigation in the literature. The complex relation of the machining induced residual stress and warping in the thin workpiece, fixturing method, substrate effects, material states and properties of machined thin workpiece, and surface quality (burrs) are not well understood. Therefore, the intention of this work is to understand the fundamentals of micro-cutting process especially when the depth of cut is comparable with the machined workpiece thickness as the effect of reduction thickness.

This fundamental study on micro-cutting thin work materials can be applied as a new technique of fabricating polymer microfluidic devices using the hot roller embossing process in which a thin sheet hot embossing mold made by micro-cutting is used. The method is different in that the micro-milling process will be used to create the micro-features on the surface of thin sheet work materials. The challenge is to produce good quality and reliable thin sheet embossing molds for microfluidic devices using the micro-mechanical machining process. The thin sheet embossing mold can then be used in continuous roller embossing tool.

1.2 Objectives and Scope of Work

The objectives of the proposed research is to study challenges related with the machining of thin work materials including effect of the workpiece thickness reduction and substrate properties on the cutting mechanisms and machining induced stress, microstructural changes in the thin workpiece, and burrs reduction.

The scope of work covers the experimental and simulation work. The experimental work uses ductile homogenous materials such as Aluminium alloys as

the workpiece and sharp cutting tool such as single crystal diamond (SCD) for orthogonal and micro-milling experiments and also carbide micro-milling tool. Finite element analysis software such as ABAQUS is used in the simulation work.

1.3 Methodology

The methodology is divided into two: fundamental study and practical application to fabricate the thin mold. The overall approach of the research is shown in Figure 1-5. The main tasks of the thesis are described below:

1. The trends in measured cutting force and chip thickness as the workpiece thickness is reducing and the limits of thickness to which a workpiece material can be reduced by micro-cutting are studied using orthogonal micro-cutting experiments and a validated finite element simulation.
2. The residual stress and the contribution of the machining process to the curvature of the thin workpiece are studied. The residual stress is measured using curvature method and X-Ray Diffraction method in order to understand the contribution of machining in the warping of thin workpiece.
3. The effect of substrate properties on the micro-cutting of thin workpiece are studied using finite element simulation in order to observe the deformation trend of the machined workpiece.
4. Microstructural changes in the work material as thickness reduces by micro-cutting are studied using single point diamond turning (SPDT) method. The microstructural observation is conducted using optical microscope and electron backscattered diffraction (EBSD). Cutting temperature and strain in the primary deformation zone are calculated to understand the cause of the microstructural changes.
5. The reduction of the top burrs is proposed by strengthening the edge angle on the side walls of micro-milled slot using a tapered shape micro-milling tool. The method is also applied to produce micro-features on the thin mold and subsequently embossed the thin mold into polymer.
6. The application of the mechanical micro-machining is conducted by producing thin sheet mold. The quality and integrity of the thin sheet mold

produced by micro-milling are assessed by fabricating polymer microfluidic devices using hot roller embossing process.

Figure 1-5. The overall approach of the research.

1.4 Expected Contribution

The proposed research contributes to the knowledge of machining thin workpieces. The investigation of the effect of workpiece thickness and substrate properties on the machined thin workpiece is a new direction in the area of research in micro-cutting. The observations of the deformation profiles and materials properties can be useful for the understanding of phenomena that occur during micro-cutting of thin work material especially when depth of cut is comparable with the machined workpiece thickness. The application of the machining thin sheet workpiece in micro-milling process is also a new way to fabricate hot roller embossing molds. The thin sheet embossing molds produced by micro-milling will be advantageous for fabrication of polymer microfluidic devices with respect to cost and time. A novel method developed here to reduce burrs by strengthening edge angle using a tapered shape micro-milling tool can be used as an effective alternative solution in all micro-milling applications.

1.5 Thesis Outline

The report consists of nine chapters. The first chapter provides the background underlying the topic of the study, the objectives, the scope of the work to achieve the objectives and the expected contribution of the study. The second chapter discusses studies reported from the literature related to this research topic including, the discussion and critical review of the polymer microfluidic devices fabrication techniques and challenges when using micro-milling process, challenges in machining of thin materials, burrs formation, residual stress and plastic deformation in the machining process and also fixturing strategies for thin workpiece.

The research findings are reported over six chapters. The third chapter covers the experimental and finite element simulation of machining thin workpiece in order to understand the effect of the workpiece thickness in the mechanism of micro-cutting process. The fourth chapter reports the study of the effect of the residual stress in the warping of the thin workpiece. The numerical analysis of the effect of substrate in machining thin workpiece using finite element simulation is presented in the fifth chapter. The sixth chapter discusses the changes in microstructure of the thin workpiece as a result of micro-cutting. The seventh chapter describes the study of edge strengthening effect in burr reduction in the micro-features created by a tapered micro-milling tool. The eighth chapter discusses fabrication of thin mold for polymer microfluidic devices using the micro-milling process. The last chapter provides the conclusions from the current results followed by possible future research direction in this area.

Chapter 2.

LITERATURE REVIEW

This chapter reviews relevant literature reports and shows the knowledge gap that motivated this research work. One of the main motivations of this work is to fabricate the thin sheet molds for roller embossing using micro-machining. The microfluidic devices and their features, the embossing process and its molds manufacturing, and hot roller embossing process are thus first described. Subsequently, the micro-machining of thin workpieces is explored focusing on challenges observed in machined thin workpieces such as burr formation, residual stress induced warping and its measurement method, and fixturing strategies, with references to related work reported in the literature.

2.1 Microfluidic Devices

2.1.1 Microfluidic Devices Features

The design of microfluidic devices spread from the simple T-junction model for capillary electrophoresis (CE) to complex microfluidic circuits that contain thousands of connected channels (Figure 2-1).

Figure 2-1. Example of the simple CE chip [16] (left) and complex Nanochip™ Cartridge with microfluidic channels (courtesy of Nanogen Inc., San Diego, CA.) (right).

Most of the microfluidic devices consist of common features such as simple shapes of square cross section channels and the micro well circular shapes. The features in the microfluidic devices produced directly by conventional machining process can be as small as 20 μm with typical sizes ranging from 50 μm to 100 μm in height and 100 μm to 300 μm in width of the channels. Channels as small as 193 nm have been fabricated using laser micro-machining [4]. Free standing walls 8 μm in width and 62 μm in height have been obtained by micro-milling with mean roughness values (R_a) in the range of 65–90 nm [43].

Most of the microfluidic devices are disposable to avoid any contamination due to reuse and inadequate cleaning during sterilization; therefore they require materials and fabrication methods that are low cost and are of high precision. Polymer microfluidic devices can overcome the drawback of silicon based substrates because suitable micro-fabrication technologies are available for a large variety of geometries, they can be manufactured easily, they have wide range of applications, and, most importantly, their material cost is low [8]. There are several techniques to manufacture polymer microfluidic devices and hot embossing process is one of the suitable replication techniques [3].

2.1.2 Hot Embossing

Hot embossing process is a simple process with short cycle time and high repeatability suitable for a wide range of work materials when compared to thermoforming and injection molding methods [5]. Figure 2-2 (a) shows schematic drawing of the micro hot embossing process. Embossing process is well suited for small structures and low aspect ratios as well as high aspect ratios [8]. In the hot embossing process, the features on the mold are transferred into the polymer by applying constant pressure at a temperature above the glass transition temperature (T_g) of the polymer and by removing the pressure during de-embossing step when the temperature is reduced to below T_g (Figure 2-2 (b)) [6]. The heat from the embossing mold makes the polymer become viscous causing it to flow and conform exactly to the negative embossing features by filling the cavities [44]. The final quality of the embossing mold feature replication on to the polymer depends mainly on three factors: temperature cycle, time, and embossing force or pressure. Several

other factors also affect the success of the replication, such as temperature distribution across the mold structure, existence of trapped free air which can form a bubble, chemical compatibility between embossing mold and polymer, and good surface quality of the embossing mold in order to avoid sticking [5].

Figure 2-2. (a) The micro hot embossing [45], (b) Temperature and pressure profile of hot embossing process [6].

One of the essential aspects of replication techniques especially using hot embossing process is the embossing mold. Selection of the material and choice of method to fabricate the mold depends on the type of geometry, dimension, and life expectancy [15]. There are several techniques to manufacture embossing mold as described in the next section.

2.1.3 Embossing Mold Fabrication

The embossing mold not only must have lowest possible surface roughness but also chemical interface properties suitability with the substrate and be amenable to easy de-embossing. Moreover, the transfer process must replicate geometrical features on the embossing mold accurately on the polymer [5]. Embossing mold materials must have high mechanical strength, high hardness, good wear resistance, high thermal strength, high fatigue strength, and resist corrosion for high

repeatability [7, 46]. In this case, metallic alloys are the most preferable materials for the embossing mold [15]. Embossing molds made from brass [15, 47], aluminium [7], and hardened steel [46] have been reported by various researchers. Silicon molds also have the capability to be used as the embossing mold due to the excellent surface quality which is also helpful in the de-embossing process. Becker *et al.* [5] made the summary table of the most common embossing mold fabrication methods with their properties (Table 2-1) that shows every process has its advantages and disadvantages.

Table 2-1. Summary of the main embossing mold fabrication methods [5]

Microfabrication technology	Choice of geometry	Minimum feature size	Height	Total surface area	Aspect ratio	Lifetime	Cost	Commercial availability
Wet silicon etching	-	+	0	++	-	+	+	++
Dry silicon etching	+	++	+	++	+	-	0	+
Photoresist	+	++	+	++	++	-	+	0
Polymer casting (elastomer)	+	++	0	++	-	-	++	-
Optical lithography & electroforming	+	++	+	++	0	+	0	0
Laser ablation & electroforming	++	+	+	-	+	+	-	-
LIGA	+	++	++	-	++	+	-	-
(Ultra) precision micromachining	+	0	+	+	0	++	-	-
μEDM	-	0	+	+	+	++	-	-

The fabrication of embossing mold for polymer microfluidic devices using wet etching processes such as that used in the MEMS (Micro Electro Mechanical System) devices [5, 48] are more popular. Such processes produce low surface roughness which can reduce friction during de-embossing, but molds produced by such processes have limitations due to durability and strength [48]. Other processes such as *LiGA* (*Lithographie Galvanoformung Abformung*); the German acronym for lithography electroforming and replication; produces higher resolution and more durable mold than MEMS based processes. However this process is very expensive and has a long series of stages which require tight tolerance control [14]. Dry film resist has an excellent quality for creating structure with low and submicron scale using lithography. However, this process is more expensive compared to other thermoplastic materials especially due to the requirement of clean room facilities [49]. In addition, laser ablation technology can be used to fabricate the micro-

structural features for the mold. However this process can change the properties of surfaces [49].

Various researchers have looked for alternative processes such as mechanical micro-machining because of its advantages. Mechanical micro machining process using micro-milling tools are more favorable than MEMS processes to produce high aspect ratio structures with complex geometry [46]. The micro-milling process produces micro features in the embossing mold materials by creating the positive features. However, additional finishing processes might be needed to produce smoother surfaces. Hence the embossing mold can be used directly to produce polymer microfluidic devices by means of replication techniques. Consequently, high-precision mechanical micro-machining such as micro-milling requires less steps compared to *LiGA* [15], produces cheaper embossing mold than lithography based process [16] and is also simpler and consumes less time [15]. Furthermore, MEMS based processes are usually limited to silicon, while mechanical micro-machining can be applied to a wider range of materials [50]. Lithography can be applied to metals, but only those that can be easily electroplated [15]. Mechanical micro-machining is a flexible process which can be applied also to silicon based substrate materials [51]. Nevertheless, besides its advantages micro-milling is limited in its ability in creating sharp interior corners because of the finite radius of the milling tool [14].

Figure 2-3. SEM of brass embossing mold produced 200 μm diameter micro-milling (a,b) and the replicated embossed into PMMA [15] (c,d).

Guber *et al.* [47] produced brass embossing mold with channel width and depth of 50 μm each and sidewall roughness of about 200 nm using micro-milling. The hot embossing process is applied to produce microfluidic lab-on-a-chip made of PMMA (*Polymethyl methacrylate*). Hupert *et al.* [15] also developed embossing mold for hot embossing using micro-milling on a 6.3 mm thick brass plate, with tool diameter as small as 50 μm (Figure 2-3). The result proved that the mold is comparable to that developed with LiGA process. They argued that this process is suitable to produce embossing molds that do not require very fine surface roughness on the walls as produced by MEMS based process.

Mecomber *et al.* [7] also made low cost aluminium micro embossing molds, milled with a 51 μm diameter carbon tool using conventional CNC milling and successfully produced simple T-junction design microfluidic devices on PMMA and PC (*Polycarbonate*). Aluminium mold fabricated using CNC high precision milling machines has also been reported [1] and used to produce PDMS (*Polydimethylsiloxane*) microfluidic capillary gel electrophoresis. Moreover, Bissaco *et al.* [46] also applied milling tool of diameter 200 μm to produce microinjection molds made from hardened steel. It has been shown that the mechanical micro-machining such as micro-milling is capable to be used to produce embossing mold with thick workpiece conditions. Hence the micro-milling is also a potential method to produce thin embossing mold by overcoming several problems related with the process.

2.1.4 Hot Roller Embossing Process

In order to increase the productivity of the polymer microfluidic devices fabrication, continuous mass production of the devices is needed. The conventional hot embossing process is a batch process which has long thermal cycle of heating, holding and cooling hence it is inefficient for mass production. The polymer must be heated to above its glass transition temperature which is time consuming [44]. Another problem is the stresses build up during thermal cycle if the mold and substrate are made from materials with different thermal expansion coefficients, such as metal or silicon with polymer. Such problems furthermore can destroy the mold during de-embossing [52].

Roller embossing process offers such advantages compared with the conventional embossing. The roller embossing method has advantages such as better uniformity, less force and ability to repeat a mold continuously on a large substrate [53]. The roll embossing or roll-to-roll technology has been widely applied for structuring of thin polymer sheet on one side or two sides [10] and it is a promising method to fulfill the needs for continuous mass production of polymer-based chips [54]. Figure 2-4 shows the principle of roll-to-roll embossing process.

Figure 2-4. Principle of the roll-to-roll embossing process [9].

However besides its advantages, roller embossing process has certain limitations such as: limited to small and shallow structure [49] and inaccuracy to replicate micro/nano structures. The inaccuracy occurred due to the unwanted viscoelastic recovery of the film or polymer sheet when it leaves the roll at a temperature higher than the polymer softening temperature [55].

Hot roller embossing [12, 54] is one of the roller embossing or roll-to-roll methods besides ultraviolet (UV) curing roller embossing [44, 52, 55]. Hot roller embossing particularly is one of the processes to manufacture micro-features of Lab-on-a-Foil systems. Lab-on-a-Foil is the combination of Lab-on-Chip and foil technologies in order to get low material consumption, low cost materials and to have high-throughput production of micro-structured foils and disposable chips [49]. Foil is a semi-finished part of any material that is thinner than 500 μm and of flexible character [49]. Hot roller embossing uses thinner embossing mold, applies constant pressure and temperature. In contrast, the conventional hot embossing uses cyclic temperature and force [12]. Due to the continuous process, hot roller

embossing needs lower embossing force because only localized area contacts with embossing roll hence improves the de-embossing process [11]. The thin and flexible foil molds used for hot roller embossing process offers low thermal resistance for efficient thermo-cycling [49]. In the application of hot roller embossing, the foil materials, pattern geometry and direction, loading pressure, roller temperature, rolling speed (feed rate), and foil (polymer sheet) preheating are important parameters which influence the process uniformity and ability to replicate the features depth onto the polymer sheet [9, 12, 54-55].

The embossing mold can be placed directly on the substrate and the roller rotated on top of the mold (Figure 2-5 (a)). The method provides easiness in mold attachment and replacement and in addition can reduce the limitation of mold thickness and lateral dimension. In contrast to the previous method, the embossing mold can be bent into the cylinder shape and mounted around the roller (Figure 2-5 (b)). In this kind of method, the embossing mold should be flexible enough to wrap onto a roller and in addition should be durable for continuous imprinting and have sufficient modulus and strength to transfer the features to the substrate [52].

Figure 2-5. Side view scheme of hot roller embossing (a) the substrate is sandwiched between the mold and a support [11] (b) the embossing mold is wrapped around the cylinder [12].

The micro-features to be transferred into the polymer sheet from the thin embossing mold can be fabricated by several methods. There are many fabricating methods to produce the thin embossing mold reported in the literature such as using dry etching [9], lithography [10], electroplating [11-12], and *UV-LiGA* [13] with most of the mold materials made from nickel [11, 13] and also flexible silicon [9]. The thickness of the mold is varied from 50 μm [9, 13] up to about 113 μm [11] which consists of sub-features down to the depth about 30 μm [12] and width 230

μm [54]. Though Dreuth *et al.* [10] had mentioned about the use of micro-milling in the production of the thin mold, no detailed explanation has made regarding the result and the challenges when using micro-milling in the thin worksheet.

Figure 2-6. Microfeatures on 113 μm thick Ni electroplated for hot roller embossing mold [11].

Shan *et al.* [11] developed a large area patterning technique for ceramic green substrates using a modified roller laminator for integration of micro embossing and printing. Figure 2-6 shows the positive features on the mold generated using nickel electroplating on nickel film produced a mold with total thickness of 113 μm . Velten *et al.* [9] used flexible silicon substrates as the embossing master. The submicron embossing pattern is prepared on silicon wafer by lithography and dry etching techniques and subsequently, the wafers are thinned down to a thickness of 40 μm , which guarantees the mechanical flexibility of the embossing masters (Figure 2-7).

Figure 2-7. Metal foil assembled with patterned silicon dies (left) and with it mounted on the roller (right) [9].

In the case of larger structures used on rolls, milling process can be used to create structures into a brass ring followed by an electrochemical polishing process

[10]. However no detailed discussions on how the milling process is applied on the brass ring have been made. The electrochemical polishing process generally is conducted in order to remove the burr formed and to improve the surface finish. In addition, the productivity of the production of large area pattern can be increased by the conveyor roller mold technique [56]. Figure 2-8 illustrates the difference between roller embossing and conveyor roller embossing. The latter process offers more efficient thermal cycle of the mold and the total continuous mold length is no longer constrained to the circumference of the embossing roll [56].

Figure 2-8. Illustration of transition from roller embossing to conveyor roller embossing process [56].

The hot roller embossing is a potential method to be used to increase the productivity of polymer microfluidic devices fabrication through replication techniques. Production of the thin mold using simpler and cheaper process is needed such as using mechanical micro-machining. However several challenges of the micro-machining especially for thin workpieces have to be studied.

2.2 Micro-machining of Thin Workpiece

This section covers the critical study of the literature related with the challenges of micro-cutting generally observed in thin workpiece, such as: the study of the surface finish specifically the burr formation, residual stresses and thin plate deflection, residual stress measurements techniques, machining induced microstructural changes and also the fixturing techniques. The machining of thin parts especially of thin floors has been less studied than the thin wall especially for micro features. There are two types of thin sheet metal machining processes

reported in the literature; webs (thin floors) and ribs (thin walls) (Figure 2-9). In conventional machining, the machining of thin parts (webs and ribs) particularly using milling is performed especially in the aeronautic industry. As the webs or ribs become thinner, the rigidity of the part also decreases. The machining of thin mold with the thickness of about 0.1 mm and the size of 25 mm x 75 mm for hot roller embossing application can be categorized as membrane and also as web.

Figure 2-9. Schematic views of rib and web definition (left) and the thin embossing mold as a web type of machining (right).

2.2.1 Challenges in Micro-machining Process

The cutting phenomenon involved in the micro-machining process is different from that in conventional macro machining; hence conventional metal cutting principles cannot be directly applied. There is no general definition when machining would be classified as micro-machining. Liu *et al.* [20] defined micro-machining process as that occurring when the cutting edge radius becomes comparable to the depth of cut. According to Chae *et al.* [19] micro-machining is the machining process to create features that range from tens of micrometers to a few millimeters in size. Min *et al.* [21] described micro-machining as machining with a tool whose dimensions is of the order of the average grain size of the workpiece material and/or the specific feature being generated or machining with a tool whose dimension is small enough to lose isotropic homogeneity with respect to the workpiece material.

Figure 2-10. Up milling (left) and down milling (right) [57].

Most of the commercial tools are available in three dimensional shapes, such as those used in milling and drilling. In these processes, the oblique cutting model is applicable instead of orthogonal; the cutting edge is no longer perpendicular to the cutting velocity. The cutting action in the milling process is performed by the flutes of the milling cutter in rotational motion. This can take place in two ways, one by up milling which involves removal of material starting from zero to maximum uncut chip thickness, and, the other by down milling involving removal of the material from maximum down to zero (Figure 2-10). Another type of milling process is end-milling, in which the cutting tool axis is perpendicular to the finished surface. The major cutting edge is parallel to the cutter axis and secondary cutting edge perpendicular to the cutting axis with a nose radius connecting the two [18].

Figure 2-11. Micro gearwheel cavity produced by 100 µm diameter micro-milling in brass [58].

The micro-milling process can be used to generate micro features with high aspect ratios and complex geometries; in addition it can produce tools for mass

production of micro components like micro molds [59]. Uriarte *et al.* [60] categorized micro-milling as the process with feed per tooth less than 1 μm , depth of cut in the range of 2-15 μm , spindle rotation speeds higher than 50,000 rpm and tool diameter less than 0.3 mm. Figure 2-11 shows some micro-features produced by a 100 μm diameter micro-milling tool in brass MS 63 work material.

Size effects, ploughing force, multiphase microstructure of materials, dynamic mechanisms resulting from tool run out and tool deflection are conditions that must be considered during the micro-machining process [19-20, 60-61]. These aspects are related to each other and simultaneously influence the process performance and quality of the machined workpiece. Size effect occurs when the uncut chip thickness is in the same order as that of the cutting edge radius and occurs when cutting at the micro scale with small uncut chip thickness or cutting using a relatively blunt tool or large edge radius. The cutting edge radius is relatively comparable with the grain size in the micro cutting thus different grain orientations will influence the cutting mechanism and surface quality [19, 21].

In the milling process, as the tool diameter becomes smaller, the spindle speed has to be increased in order to compensate the material removal rate as shown in equation (2.1).

$$v = \frac{\pi \cdot D \cdot s}{1,000} \quad (2.1)$$

where v is cutting speed (m/min), π is circular constant (3.14), D is diameter of the milling tool (mm) and s is spindle speed (rpm). As a consequence of the small tool diameter and high spindle speed, the tool experiences more vibration, which in the end influences the surface finish and generates error in the accuracy of the geometrical feature produced by the milling process [60]. The accuracy of the machined workpiece produced by micro-milling is also influenced by the specification of the machine tool. The machine tool is required to have high motion accuracy, stiffness, thermal stability, precise spindle bearings, and high resolution of linear and rotary motions [61].

The challenges of micro-machining process described earlier are not only observed in the thin workpiece but also in the thick workpiece conditions. These

challenges have to be considered when applying micro-machining to produce thin embossing molds or to create micro-features.

2.2.2 Burr Formation

In order to achieve good surface finish on the polymer microfluidic features, the embossing mold must have a good surface finish. Hot embossing replicates the same result of geometrical features and surface finish from the embossing mold into the polymer substrate. In addition, low surface roughness is needed in the embossing mold for ease of de-embossing process. Moreover, the embossing mold features have to be transferable and wear resistant. The surface roughness is commonly indicated by parameters such as average roughness (Ra) or root mean square roughness (Rq). Geometry of tool, milling parameters (spindle speed, feed rate and depth of cut) and irregularities in cutting operation (tool wear and lubricant), material properties of tool and workpiece are several factors which influence the surface quality especially in the micro-milling process [62].

One aspect of machined surface quality commonly discussed in literature and seen in practice is burr formation. Burr is defined as the material plastic deformation produced at workpiece edges as a result of machining or shearing process [63]. In general, the real profile of the burr will be difficult to quantify due to the limitation of the conical shape of the tracer point, hence the burr measurement using stylus methods are suitable to measure burr heights only [64]. According to Gillespie [63] there are six physical processes which form burrs: lateral flow of material which occurs whenever a solid is compressed, bending of material, tearing of chip from workpiece, redeposition of material, incomplete cut-off and flow of material into cracks. Proper selection of machining parameters, quality and sharpness of cutting edge, cutting fluid and also material properties of the workpiece can be helpful in reducing burrs [65].

The ductility or brittleness as well as the strain hardening behavior of materials have important contribution to the burr size [66]. Larger and more burrs are likely to be formed with increasing ductility due to the high elastic-plastic deformation occurring in the machining. In contrast, burr formation is less if the material is restricted to deform due to workpiece geometry and machining

conditions [67]. In addition, tool wear affects the burr formation mostly in brittle or hard materials [68].

Burrs are usually formed in micro-milling when the cutting edge leaves the surface being cut. In micro-milling, as in any other machining processes, there is considerable plastic deformation around the cutting tool edge; this plastic deformation is normally resisted by the bulk material in front of the edge. When the advancing plastic deformation reaches a free surface there is little resistance to the deformation and hence the material gets pushed out resulting in a burr. Such burrs formed by the exiting cutting tool edge are called exit burrs (Figure 2-12). This can be clearly visualized in an orthogonal cutting process. In addition to the exit burrs there are also side burrs formed in orthogonal cutting. The side burrs are the burrs attached to the transition surface machined by the major edge while the top burrs are defined as burrs formed on top edge of the side walls in micro-milling (Figure 2-12). Here although the cutting tool edge does not exit a surface there is considerable burr formation as the chip flows and exits the surface - this is also called tear burr [69].

Figure 2-12. (a) Exit and side burr formations are easier in the simple case of orthogonal cutting (b) Exit and top burrs formed in micro-milling.

In the micro-milling of a slot there are differences in the top burrs formed on the two sides of the walls. The side wall where the cutting edge enters into the cut (up-milling) has smaller burrs than the other wall where the tool edge finishes the cut (down milling). In the up milling side, the burr is a Poisson burr formed by side bulging action only. On the down milling side, the top burr is formed by the action of the chip material tearing away as it flows as well as side bulging deformation;

hence the down milling burrs tend to be larger. The material tearing action due to flow has more influence than the side bulging action in the burr formation. In contrast, down milling exhibited better surface finish in the sidewall with no variation of surface profile with feed rate, but showing variation with the depth of cut [70].

Deburring is defined as the removal of minute amounts of material from edges after major part features have been produced [66]. Deburring process is difficult to apply on micro-features produced by micro-milling; the process must be carefully conducted to avoid damage to the small features. Incorrect selection of deburring techniques or parameters may also introduce dimensional errors, damage, poor surface finish and residual stresses. The additional deburring process and edge finishing in the micro-scale fabrication and ultra precision machining due to the small changes in edge and surface quality may also be too expensive or impractical to implement [21]. Nevertheless, several techniques have been reported for burr removal (deburring) including electrochemical polishing [65], diamond milling (Figure 2-13) [65], micro-EDM [71], powder blasting [72], and micro-peening [73].

Figure 2-13. SEM photo of micro-features before burr removal (upper right) and after burr removal (lower left) by diamond milling [65].

Changes in process parameters can be adopted to reduce burr formation. Lowering depths of cut [42, 69], increasing cutting speeds [68-69], use of larger tool rake angles [74] are examples of techniques suggested for burr reduction. In addition, coated tools can also reduce the burrs size when micro-milling hardened steel [75]. Lekkala *et al.* [76] argued that the speed has less significant effect on the burr thickness and height whereas tool diameter, depth of cut, number of flutes and

the interaction between feed rate and number of flutes have significant effect on the burr height in the micro-milling process.

Park and Dornfeld [74] developed finite element models to study the exit burr formation of various workpiece exit edge angles of 60, 80, 90, 100 and 120 degrees for the case of orthogonal cutting. However their finite element model was in 2D and used a predefined cutting line to simulate the chip formation. Hashimura *et al.* [77] observed the formation of exit burrs and side burrs on the oblique cutting experiment and finite element model for Al2024-O. The exit burr's thickness decreased and the side burrs increased as the inclination angle of the tool increased. Chen *et al.* [78] investigated the exit burr size of different exit angles in the feed direction of slot milling aluminium alloys. The exit burr size decreases with the increasing of the exit angle.

Burr formation is one of the problems faced in the production of micro-features using the micro-milling process. In order to economically manufacture the thin molds, the challenge remains to reduce or eliminate burrs using conventional carbide cutting tools.

2.2.3 Machining Induced Residual Stress and Warping

Residual stresses in the cutting process are the distribution of stresses on and beneath the cut surface of the workpiece after all fixturing and cutting forces have been released and the workpiece cools down to room temperature [79]. Besides relieving the residual stress, new stresses are also induced by the tool on the surface of the workpiece which influence the original residual stress distribution [25]. In the microscopic point of view, residual stress can be considered as the permanent change in the plastic region (for the case of elastic-plastic materials) of the microstructures in the form of stretching and distortion after the load is removed [80].

At high cutting speed, thermal load will be more dominant and causing tensile residual stresses in the machined surface, whereas mechanical load will have greater effect in the low cutting speed and furthermore induces compressive residual stress [81-82]. Tensile residual stress is detrimental for the machined workpiece because it can generate fatigue and stress corrosion cracking [83].

Compressive residual stress in contrast is favorable to avoid such problems. It is observed that the high tensile residual stress produced by rough machining is decreased by the next fine machining and change to become compressive near the finished surface. After few passes, the residual stresses become tensile in the surface and compressive far from the surface [84]. Sasahara *et al.* [84] argued that the repetition of fine cutting produces much more shallow depth of affected regions by residual stress.

Not only is the nature of residual stress important, but also its magnitude and depth into the workpiece sub-surface. The residual stresses profile caused by manufacturing processes usually show very steep profile to depth gradients [80]. Residual stress as deep as 200 μm was observed when cutting AISI 4340 with depth of cut 200 μm [27]. El-Khabeery and Fattough [85] found that the absolute value of the residual stress is initially high in the surface and decreases continuously with an increase in the depth of cut. They observed the residual stress until about 300 μm depth beneath the machined surface. Guo *et al.* [86] observed the residual stress is tensile at a depth of 20 μm and changes to be compressive at 100 μm in the high speed milling of aluminium alloys. In addition, the depth of residual stress is dominantly affected by the mechanical loading [87].

Figure 2-14. Possible residual stress profile resulting from machining process [27].

Jacobus *et al.* [27] proposed a detailed analysis about the phenomena that occurs in machining (Figure 2-14):

Case 1: when the thermal strain is less than plastic deformation causing compressive residual stress in the surface and sub surface.

Case 2: when the thermal strains is more than plastic deformation causing the surface and near surface to become tensile and the subsurface compressive.

Case 3: when the plastic deformation in the subsurface is less than zero causing the stress in the surface and subsurface to become tensile.

Simulation has also been used to study residual stress effects in machining. The metal cutting simulation using finite element method showed that the increase in the tool-chip interfacial friction coefficient resulted the residual stress shifted from tensile to compressive [88]. The FE analysis of residual stress performed by Ulutan *et al.* [89] showed the results are very close to the residual stress measured using XRD.

Residual stresses can be reduced or completely relaxed by the application of mechanical and/or thermal energy. Relaxation of residual stresses occurs by complex interaction of a large number of factors. It depends not only on the residual stress state itself but also on the material state, loading condition, geometry and environment of the component under consideration. One of the simple and well-known residual stress relaxation methods is the annealing process [90].

The machining induced residual stress influences the internal stress equilibrium state and in the end re-distribute the in-plane and out-of-plane stresses especially in the case of thin workpiece because the ratio of the depth of deformation to the workpiece thickness become larger [26, 91]. The distribution of out-of-plane stress contributes significantly to the final state of the workpiece in comparison to the in-plane stress. Out-of-plane residual stresses (through the cross section) of component is usually most relevant in the case of distortion of component rather than the location or magnitude of the maximum tensile residual stress [80] and may lead to fracture. The in-plane residual stresses are not visually detectable but can promote slow crack growth as in the stress-corrosion cracking of metals, or fast fracture as in the brittle fracture of ceramics and glasses [92]. In the machining of webs or plates, the curvature (deflection) and dimensional instability (distortion) occurred as the compensation of the component self equilibrates (relaxation) for the unbalancing of forces and moments upon removal of the material from the fixture [25-26].

It is noted that the influence of the machining strategy, machining parameters, workpiece conditions, tool conditions and workpiece fixture are significant to the workpiece deflection and depth and distribution of damage [93]. The deflection or deformation of the workpiece is also referred to warping. Warp is the distance between the peak and valley of a free, unclamped workpiece with reference to the least squares reference plane of the medium surface [94].

Figure 2-15. (a) 8 μm micro-milled thin walled structure [17] and (b) Test part configuration for micro-machining strategy [95].

Horia *et al.* [96] have tried to measure the residual stress of the 500 μm Al-Mg alloy by eliminating the influence of specimen thickness in order to investigate the effect of diamond tool cutting edge radius to the residual stress. The curvature method is used to measure the residual stress profile existing down to about 15 μm, while the XRD method is measured on the surface down to about 10 – 25 μm. The residual stress value measured using XRD is lower than that using curvature method. Robinson *et al.* [26] have also attempted to characterize the effect of residual stress redistribution to distortion, however the effects of residual stresses do not account for any machining induced stresses due to the effect of machining procedure and cutter end radius and no fixture effect was applied. Furthermore, Jacobus [24] argued that residual stresses in the machined thin parts after removed from the fixture are balanced by appreciable stresses beneath the surface and by changes in the machining induced residual stresses brought by warping. The 1 mm

thick layer of newly machined surface sliced using wire electric discharge machining (EDM) is used as the sample in order to avoid further stress; similar to releasing the 1 mm thick part from its fixture. This method is proposed in order to avoid the difficulties faced when creating a thin, stress free part and to avoid the fixturing problem of thin part during machining.

Wang *et al.* [17] obtained micro-milled sample of 3J21 alloy as thin as 8 μm and subsequently measured the residual stress using the load-deflection method by nano-indentor (Figure 2-15(a)). However there is no discussion of the effects of the fixturing systems to obtain such thin part and no features produced on that thickness. Popov *et al.* [97] discussed a strategy to minimize deformation for micro-milling thin webs and ribs as thin as 1 mm on brass. In order to minimize the force component normal to the web, the tool path is chosen so that the area being machined is supported by as much un-machined workpiece as possible. They adapted the same part configuration as that of Smith and Dvorak [95] (Figure 2-15(b)). In order to minimize bending, deflection and vibrations effects when milling low rigidity parts, Herranz *et al.* [98] proposes a methodology for efficient process planning. In the case of thin floor, the solutions are proposed using a two level step strategy, reduce the tool corner radius and using vacuum fixture [98].

Figure 2-16. The Finite Element results for prediction of the plate deflection, (a) After surface cutting, (b) After pocket cutting, (c) Final geometry after removing the fixture [99].

Sheng Ping and Padmanaban [99] developed a finite element (FE) model to predict the deflection of the machined workpiece due to the pocket milling. However the simplification of the material removal process cannot represent the real machining process which is performed by removing elements using deactivation (Figure 2-16) and the final dimensions of the workpiece was not

mentioned. Nevertheless the results showed the capability of their FE model to predict the effect of the deflection of the final shape of the machined workpiece.

The micro-machining induced residual stress can affect the quality of the machined workpiece. In the case of the machining of thin workpiece, the depth of the residual stress can be significant compared to the thickness of the machined workpiece. There is not much studies that discussed the effect of the machining to the warping of the thin workpiece. Hence, there is a gap in understanding the warping of the thin workpiece due to the contribution of the machining induced stress especially in the micro-scale. Therefore, the residual stress has to be measured using suitable methods.

2.2.4 Residual Stress and Deformation Measurement Methods

Residual stresses can be used to evaluate the machining process because residual stresses are a sensitive indicator for variations of machining parameters and tool properties [100]. Residual stress is also used to describe the amount of thermal or mechanical influence on the workpiece deformation [29]. The residual stress basically is determined indirectly by measuring the elastic strain. In general, the measurement of residual stress is divided into two methods, i.e. destructive and non-destructive. The non-destructive method has an advantage in specimen preservation and the measurement can be repeated many times. However, these methods commonly require detailed calibrations on representative specimen material to give required computational data and the process is time consuming [91, 101]. The non-destructive methods include X-Ray Diffraction (XRD) [27], Moiré interferometer [92], optical interferometer [32], and neutron diffraction [26].

Destructive methods rely fundamentally on stress-relaxation procedures obtained by relaxing the residual stress in some finite-volume element of the component, normally by removing some stressed material, and measuring the resulting strain change [80]. The material removal or cutting process changes the geometry and boundary conditions of the specimen material, and thus changes the elastic response of the material to the (unchanged) inherent strains. The destructive method is suitable for measuring the residual stress profile. In addition the non-destructive method such as XRD can also measure the residual stress profile by

coupling with layer removal process, which makes the method destructive. However, the cutting or removal layer of materials must not introduce new stresses induced by the process which can disturb the original residual stress in the specimen. Electrolytic polishing method is a suitable layer removal process for such measurement [80]. Any areas affected by the surface roughness generated by polishing should be avoided as it may disturb the diffraction pattern.

It is important to have simple metrological methods to measure residual stress with high accuracy and resolution especially in the thin plate in which the residual stress distribution most likely varies in the thickness direction. Two relevant and applicable methods for the thin specimens will be discussed below:

2.2.4.1 Curvature Method

The material removal of the plate can be used to predict the residual stress by measuring the curvature [29] or the strain change [25]. Treuting and Read [23] proposed the residual stress determination method by uniformly removing thin layer of material on one side of the sheet or plate and measuring the workpiece curvature using the equation below [23]:

$$\sigma_x(z_1) = \frac{-E}{6(1-\nu^2)} \left\{ (z_0 + z_1)^2 \left[\frac{d\kappa_x(z_1)}{dz_1} + \nu \frac{d\kappa_y(z_1)}{dz_1} \right] + 4(z_0 + z_1) [\kappa_x(z_1) + \nu \kappa_y(z_1)] - 2 \int_{z_1}^{z_0} [\kappa_x(z) + \nu \kappa_y(z)] dz \right\} \quad (2.2)$$

where $\sigma_x(z_1)$ is the residual stress in the x direction, E is the Young's Modulus, ν is the Poisson's ratio, z_0 is the half thickness of the workpiece before material removal, z_1 is the left thickness above the original middle plane of the workpiece after specified thickness of workpiece layer is removed, $\kappa = \frac{1}{\rho}$ is the bending curvature with $\rho = \frac{L^2 + 4\phi^2}{8\phi}$. The definition of the z_0 , z_1 , L and ϕ are shown in Figure 2-17 with the z-axis is assumed to be in the thickness direction. This method assumed the stresses were constant over the plane of the sheet or plate and varied only through the thickness.

Figure 2-17. (a) Element of workpiece showing the coordinate system and principal components of residual stress, (b) Element showing layer to be removed and (c) Determination of the curvature of a deformed bar [23, 102].

A similar method was adopted by Horia *et al.* [96] when they measured a 500 μm thick round shape workpiece, except that the removal process was conducted by chemical etching and then subsequently measuring the curvature to determine the residual stress. Rathbun *et al.* [25] used a strain change method to calculate out-of plane residual stress caused by different quenching processes. The principle of the work is similar with Rosenthal and Norton [103]. The residual stress distribution is calculated by recording the strain change at the back of the workpiece, while the material removal is conducted incrementally layer by layer at the face of the workpiece. Osterle *et al.* [104] also used the plate deflection measurement method to examine the distribution of the residual stress as a function of depth from the machined surface of the ground nickel plate. In both techniques proposed by Treuting and Read [23] and Rosenthal and Norton [103], biaxial stress varying through thickness can be determined and the specimen assumed to behave in linear elastic manner following Hooke's law.

In this method, the thin plate is assumed to follow certain criteria such as [105]: the material is isotropic (linear in pure bending over the range of curvatures resulting from layer removal), the deflection of the mid-surface is small in comparison with the thickness of the plate (the slope of the deflected surface is much less than unity), straight lines initially normal to the mid-surface remain

straight and normal to that surface subsequent to bending, meaning $\gamma_{xz} = \gamma_{yz} = \varepsilon_z = 0$. Since the thickness is very small compared to the other dimensions, $\sigma_z = 0$. No mid-surface straining or in-plane straining, stretching, or contracting occurs as a result of bending.

2.2.4.2 XRD Method

The residual stress measurement can be conducted using X-ray Diffraction (XRD). The residual stress measurement using x-ray method is known to give a higher value than the destructive method [91]. In general, the XRD method can be used to measure the residual stress on the surface; the x-rays penetrate up to about 10 – 25 μm deep into the surface depending on the x-ray source and specimen materials. The selection of the stress constant, focusing geometry, location of the diffracted peak, texture, grain size, microstructure, surface conditions and cold-working crystallography have to be considered in order to minimize the error when using x-ray diffraction to measure residual stress [106].

Figure 2-18. Principles of x-ray diffraction stress measurement; (a) $\psi=0$, (b) $\psi=\psi$ (sample rotated through some known angle ψ); D is x-ray detector; S is x-ray source; N is normal to the surface [106].

The principle of the x-ray diffraction residual stress measurement is to measure the strain in crystal lattice and subsequently calculate the residual stress by assuming linear elastic distortion of the crystal lattice [106]. The strain is determined by measuring the different plane spacing (d), at different incident angles of x-ray (ψ) as illustrated in Figure 2-18. In the stressed sample, the spacing

d_{hkl} varies with crystal orientation and changes with ψ . Different ψ angle produces different intensity and peak location which produce different ' d ' values. The stresses can be determined by plotting the ' d ' to $\sin^2 \psi$ (Figure 2-19). Residual stress can be determined from the slope of the plot based on the equations [107]:

$$d = \frac{d_\psi - d_0}{d_0} = \frac{1+\nu}{E} \sigma_\phi \sin^2 \psi - \frac{\nu}{E} (\sigma_{11} + \sigma_{22}) \quad (2.3)$$

where d_ψ is the spacing of the planes under stress, d_0 is the spacing of the plane in the absence of stress, ν is the Poisson's ratio, E is the Young's Modulus, σ_ϕ is the residual stress, σ_{11} and σ_{22} are the principle stresses. Equation (2.3) can be applied with the assumption that the stress at the direction parallel to the surface normal (σ_3) at the surface is always zero and that only two normal stress components exist at the surface (σ_1 and σ_2).

Figure 2-19. d vs. $\sin^2 \psi$ plot.

The curvature and XRD methods are established methods and suitable to measure residual stress especially for thin workpiece. In addition, the observations of microstructural changes can indicate the presence of the severe deformation in the thin machined workpiece due to the high ratio of depth of cut to the machined workpiece thickness.

2.2.5 Machining Induced Microstructural Changes

The deformation produced by machining process can also be characterized by its metallurgical changes such as the change in the microstructures [39] or crystal orientations [40] in addition to the residual stress parameters. These methods

can also give faster and less expensive analysis to characterize the effect of machining on the surface integrity of machined workpiece. Microstructural transformations on the machined surface of a Zn-Al alloy have been reported [39]; the transformations are confined only to the surface of the bulk material machined. Optical microscopy, back-scattered electron microscopy (BSEM), electron back-scattered diffraction (EBSD) and x-ray diffraction techniques (XRD) can be used to analyze the changes in microstructure of surface and sub-surface of the machined results [39].

Structural changes during machining of thick single crystal materials are reported [40]; changes are confined mainly on the surface. Microstructural changes in the near-surface has been merely observed and reported in machining of thick samples made of Al7075 alloy [41] but no further investigations on the nature of change has been made. The recrystallization in the surface and subsurface indicates the existence of high strain rate [108]. Plastic strain increases with increasing depth of cut or reducing the rake angle. The grains recrystallization not only occurs in the chips but also at the surface and vicinity of the machined surface of the workpiece. Analysis of both chips and workpiece microstructures indicates that recrystallization occurs as a result of high strains and temperature gradient via dynamic recrystallization [109].

2.2.6 Fixturing Strategies for Machining Thin Work Materials

The main purpose of fixturing in the machining process is to hold the workpiece firmly and to avoid the slip and lift-off. The challenge in machining of thin sheet metal, also related with the workpiece fixturing strategy, is to minimize workpiece deformation and deflection caused by removal of materials [28]. The problems of using side clamping or other traditional methods of fixturing in the machining of thin workpiece is the generation of deflection and distortion in addition to workpiece lift off or slip due to the forces produced by the tools.

Barkman [110] argued that the forces to secure the part must be higher than the cutting forces but not exceed the required tolerance limits to avoid distortion during the machining process. If the workpiece is held in a distorted condition during machining, the thin workpiece might warp after the fixturing forces are

released and the part relaxes into an unstressed condition. The clamping force preloads, fixture rigidity, contact interaction and dynamic stiffness between the workpiece and fixture have a considerable influence on the machined surface. It is found that workpiece deflection caused by clamping preloads and cutting forces varies with the depth of cut. The sources contributing to surface error is as follows: 14% from clamping preloads, 80% due to machining forces and 6% from forced vibration [111].

Fixturing method and thickness of the workpiece are reported to be the major contributors to the flatness error. Flatness accuracy becomes poor and vibration effect becomes prominent if the thickness of the plate workpiece is becoming thinner. These problems can be avoided by using a correct fixturing method, or using initial thick workpiece to stiffen the part [112]. Uniform fixturing force is appropriate to hold the thin workpiece during the machining process because it can assure the uniformity of the workpiece thickness, flatness and minimize subsurface damage [31]. Several fixturing strategies for machining thin plates have been proposed in the literature such as magnetic chuck [30], vacuum chucks [31-32], and porous sintered *fluororesin* [113]. Flat electro-magnetic chuck is commonly used to fix the rolled plates in face milling or surface grinding Figure 2-20 [30].

Figure 2-20. Illustration of the effect of the electro-magnetic chuck in the face-milling of the thin workpiece [30].

Aoyama and Kakinamu [33] developed special fixturing devices using low melting temperature alloy to support compliant workpiece as thin as 1 mm in order to minimize deformation due to the machining forces (Figure 2-21). Following this work, Kakinamu *et al.* [34] proposed a new fixturing strategy using electro-rheological gel (ERG) for micro-milling a 20 μm deep groove in a 0.2 mm thick aluminium substrate and 0.8 mm thick borosilicate glass substrate.

Figure 2-21. Schematic view of fixturing system for thin workpiece using low melting temperature alloys [33].

In addition, the use of adhesive as the fixturing method for thin workpiece in machining process has also been reported in the literature. The use of adhesive types of fixture such as: wax, epoxy and also cements can give thin, uniform bonding layer and can be removed easily after the machining process finishes [9]. Adhesive bonding also gives good damping to vibrations and shock absorption [114]. It is noted the wax clamping gives more uniform support and generates homogenous deflection compared to magnetic clamping while grinding 1.27 mm thick tool steel [29]. By increasing the fixturing forces, the radius of the workpiece warping increases. Treuting and Read [23] applied Cenco sealstix, a thermoplastic cement, to fix 0.371 mm thick phosphor bronze for the grinding and subsequently removed the adhesive using hot plate in order to measure the curvature for residual stress measurement.

There are several criteria that have to be considered when using adhesive to hold the workpiece. Thin adhesive layer offers the highest shear strength when the bonded area is forced out [114]. Whereas thicker adhesive conditions may cause greater internal stresses during cure, concentration of stress under load, and void formation. The formation of voids typically originates as small trapped air bubbles. As the adhesive polymerizes, the voids grow in size. In turn, the voids act as stress risers, and generally decrease the strength and ductility of the adhesive [114]. As the thickness and volume of the adhesive increases, this problem becomes exacerbated. In general, thermoset polymers are used as the primary element for adhesive due to their excellent tensile strength, high modulus of elasticity, high service temperature, and good environmental resistance [114]. Unfortunately pure thermosets tend to be very brittle and have low toughness. To overcome this

problem, the adhesive also contains an elastomeric resin to improve its ductility, toughness, and fatigue resistance of the adhesive. Hence, the fixturing method using adhesive can give uniform and strong force, and also simpler method to hold the thin workpiece. The application of the adhesive with correct properties and thickness are challenges and need to be studied.

2.2.7 Substrate Effects in Thin-Film Indentation Studies

Based on the general rule known as Bückle's rule, the mechanical properties of the film will be affected by the substrate when the indentation depth exceeds 10% of the film thickness in nano-indentation of thin films [115]. Ohmura has reported that h_{cr}/t (ratio of critical penetration depth of indentation at which substrate begin to affect the film/film thickness) is in the range of 0.167 – 0.2 [116]. The observation of the delamination of aluminium thin film due to the micro-grooving has been reported [38]. Bourne *et al.* [38] found that the region of the maximum tensile and shear stress are behind the cutting edge. Therefore, the role of the substrate properties is important in the case of micro-cutting of thin workpiece based on the findings in the nano-indentation process. The substrate properties can affect the cutting mechanisms and residual stress in the machining of thin workpiece.

2.3 Summary of Literature Review

It can be noted from the literature review that many studies have been conducted in the area of machining of low-rigidity structures such as webs (thin floors) and ribs (thin free standing walls), with most of the research efforts focusing on the strategies to reduce the deflection and to fix the thin workpiece. However, there is not much work reported on micro-cutting of thin sheet workpiece in the form of webs that are held on one side of their surface and related challenges such as the influence of workpiece thickness and fixturing methods on the mechanism of cutting process, machining induced deformation and changes of material properties, effect of the substrate properties, and also surface quality (burrs). Therefore, several challenges related with micro-cutting of thin workpiece have to be studied and solved for its effective application for making thin molds.

In general, the depth of the residual stress produced in machining process can be up to 200 μm . There is thus a gap in understanding of the workpiece thickness reduction to the deformation mechanism and to the material properties of the machined thin sheet workpiece when the workpiece thickness is less than 100 μm based on the micro-cutting process of thin sheet metallic alloys. The uses of adhesive as the fixturing method for holding the thin workpiece can give thin layer, uniform and high forces. Due to its flexibility and strength, an adhesive is the suitable candidate to be applied in the machining of thin workpiece materials. As the workpiece become thinner the properties of the adhesive can significantly affect the cutting process. The effect of the adhesive (substrate) properties in the machining of thin workpiece is also worthy of study.

There is limited study on the effect of workpiece thickness to the curvature induced by machining in a thin sheet workpiece. The complex relation of the machining induced residual stress and the warpage in the thin workpiece has not studied whether part distortion in the thin workpiece purely occurs due to the redistribution of the stress to reach equilibrium state induced by material removal or by machining process induced stress. In addition, no quantification methods have been proposed in order to study this problem. A suitable residual stress measurement method is necessary to be conducted in order to quantify the residual stress in the thin worksheet and to understand the contribution of the residual stress in the warping. The curvature method and XRD analysis is preferred since they are simpler and faster methods.

As noted from the literature review, burr formation is still a problem that needs to be resolved in the micro-milling process especially in ductile materials. Ductile materials can be used as thin embossing molds for hot roller embossing due to their flexibility and strength. The existence of burr is prominent in the micro-milling process and during the embossing mold fabrication because the burr shape will be transferred on to the embossed polymer. Works have been conducted to solve the burr problem with additional secondary processes which make the fabrication more complex and increase the production time. It is important to find a simpler, faster and cheaper method to solve the burr problem in the ductile materials.

From literature review it can be concluded that there is a strong demand for producing polymeric microfluidic devices by hot embossing. The hot roller embossing process has potential to increase the productivity of the polymer microfluidic devices manufacturing. Also, the micro-milling process has the capability of producing the necessary micro-features in the embossing mold, with a possibility of producing thin embossing mold for roller hot embossing process using the micro-milling process. The micro-milling process is such a complex process in which the quality of micro-milled workpiece depends on the effects of machining parameters, tool geometry and workpiece materials.

It is thus important to investigate these aspects in order to produce flexible continuous roller embossing mold. Producing thin features at the micro size is not only important in the embossing mold applications but can also be applied to other micro engineering applications such as housings for mechanical micro-devices and surgical instruments [97].

Chapter 3.

EFFECT OF WORKPIECE THICKNESS REDUCTION IN THE MICRO-CUTTING PROCESS

This chapter reports experimental and simulation work of the orthogonal micro-cutting of thin work materials. The intention is to understand the micro-cutting process effects on thin workpieces by continuously cutting to reduce the workpiece to a thickness less than 100 μm . The thin workpieces fixtured using adhesive are continuously orthogonally cut from thick to thin state with a single crystal diamond tool. Study of the trends in measured cutting forces, the minimum thickness the workpiece can be machined down to, and in what form the adhesive fails are reported. Subsequently, a validated finite element machining model is used to understand the stresses in the workpiece, interface, and adhesive when the workpiece is thick and when machined to thin condition.

3.1 Experimental Method

3.1.1 Workpiece and Tool Materials

The workpiece is made of Al6061-T6 alloy, is 3.37 mm wide and 900 μm thick with a length of about 25 mm. The entrance section of the workpiece is made in such a way that it has a small taper angle. The purpose of taper shape is to gradually increase the width of cut from zero to 3.37 mm minimizing the effect of cutting force during the initial chip formation. The workpieces are ground using #400 grit sandpaper and have a surface roughness (R_a) of about 0.36 μm . The single crystal diamond (SCD) insert tool used for the orthogonal micro-cutting process has a width of 5 mm. The single crystal diamond tool is selected in order to get a sharp edge, i.e. edge radius of 0.1 μm (measured visually using SEM), as compare to

other tool materials. The small edge radius helps in minimizing the size effects and tool engagement stresses.

3.1.2 Experimental Setup

The orthogonal micro-cutting method is used as the experimental method to study micro-cutting of five workpiece samples. The machine used is a 3-axis CNC machine tool (Mikrotools DT-110; resolution and accuracy of the machine are 0.1 μm and 1 $\mu\text{m}/100\text{mm}$ respectively). The experimental setup and sketch are shown in Figure 3-1. In this setup, the thin workpiece is adhered to the substrate (workpiece holder) using an adhesive. The workpiece holder is also made out of Al6061-T6 alloy. The top surface of the workpiece holder is machined flat with a surface roughness (R_a) of 0.05 μm . The diamond insert is held using a tool holder leading to a 1° rake angle and 4.5° clearance angle.

Figure 3-1. Experimental setup and sketch of orthogonal micro-cutting of thin workpieces.

UV light curing adhesive Dymax® 6-621 is selected as the adhesive. Dymax® 6-621 is a multi-cure adhesive that polymerizes (cures) mainly by photo activation (UV light exposure). In addition, it can also cure using chemical activation or thermal activation [35]. In order to bond two substrates using UV light, at least one of the substrates must be capable of transmitting the UV light. However, both of the adherents in this setup are not capable of transmitting curing light. Therefore, chemical activator is applied to polymerize the adhesive (activator data sheet is shown in Appendix B). The adhesive is applied at the bottom surface of the workpiece and activator on the surface of the workpiece holder. This method

has demonstrated that it can give the same results, both joint strength and ductility, as that of photo-cured joints [35].

Initially, the adhesive was applied manually using a small paintbrush. However this method is undesirable because the adhesive thickness is uncontrolled resulting in non-uniform thickness especially along the width of the workpiece after machining at certain workpiece thickness conditions ($< 100 \mu\text{m}$). In addition, by using this method the thickness of adhesive is unrepeatable. As mentioned in the previous section, the other factors such as workpiece thickness was controlled accurately; the base workpiece holder surface was also machined flat. Therefore, in order to control the adhesive thickness a dispensing controller (Cysco) is used by controlling the volume of the adhesive to be applied. Three different adhesive thicknesses of $30 \mu\text{m}$, $45 \mu\text{m}$ and $55 \mu\text{m}$ are achieved using this method. Adhesive thicknesses larger than $55 \mu\text{m}$ are difficult to achieve due to the viscosity of the uncured liquid adhesive. On the other hand, obtaining thinner adhesive is limited by uniformity of spread of the adhesive. Hence the adhesive thickness in the range of 30 to $55 \mu\text{m}$ is the optimum amount that can be applied in this setup. According to manufacturer specifications, the joint strength of the bonding using chemical activator is equivalent to that obtained by photo activation when cured for 12–24 h.

In order to examine the adhesive curing (crosslink), Differential Scanning Calorimetry (DSC) or Fourier Transform Infra-Red (FTIR) methods are commonly applied [117]. However, it is difficult to prepare the adhesive sample for the DSC and FTIR analysis in this experimental setup. In the DSC method, the sample has to be placed in the small chamber with specific weight of sample that is more than the applications of adhesive in this thesis. In addition, the adhesive does not mix with the activator if adhesive and activator are not applied on two different surfaces and the mixing does not harden if the activator is applied on one surface and the adhesive drops on top of activator. While in FTIR, the probe is bigger than the thickness of the adhesive mixture if the adhesive is applied on one surface and activator on other surface. In addition, based on the Dymax catalogue when cured with the activator (Appendix B) with curing (crosslink) period of 30 minutes the strength can reach up to about 94% of the tensile lap shear specification of the adhesive (tested based on ASTM D1002 - Standard Test Method for Apparent

Shear Strength of Single-Lap Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal),. Therefore with the curing (crosslink) period up to 20 hours applied in the thesis, the strength is expected higher than 94% of the specification. Hence, cross-linking is expected to be sufficient. The adhesive can be relatively easily removed by dipping it into an *acetone* solution.

The adhesive properties are shown in Table 3-1. The adhesive can be relatively easily removed by dipping it into an *acetone* solution. The reported values of the material properties listed in Table 3-1 are based on a specific joint type used in the test with the adhesive thicknesses of about 200 μm [114]. Some important test parameters such as strain rate, joint thickness, adherent surface roughness, and method of adherent surface preparation were also not reported [35]. Hence these values are used only as a reference since the strength values may be different with experimental conditions used here. De Meter [35] argued that the maximum Von Mises stress experienced by the adhesive joint in tensile or axial loading is more sensitive to the Poisson's ratio value rather than the elastic modulus of the adhesive. De Meter [35] found the true value of Poisson's ratio for the adhesive lies between 0.25 and 0.35.

Table 3-1. Adhesive material properties (Dymax® 6-621).

Density (kg/m^3)	1,066
Specific heat (J/kg K)	0.263
Coefficient of thermal expansion ($^{\circ}\text{C}^{-1}$)	9×10^{-6}
Young's modulus (GPa)	2.206
Poisson's ratio	0.25 – 0.35
Tensile Lap Shear strength (steel-steel) (MPa)	24.82
Tensile at Break (MPa)	35.9
Elongation at Break (%)	35

Five workpieces (all made of Al6061-T6 and of the same initial dimensions) were machined down to thickness less than 100 μm and the results are as shown in Table 3-2. The final workpieces are numbered as #1 to #5 after machining based on the final workpiece thickness (t_w) that they were machined down to. Forces data from the initially thick workpiece #2 are randomly chosen as the baseline for comparison. Initially, the un-machined workpiece thickness is measured using a micrometer. Afterwards, the workpiece is attached onto the holder using the adhesive and the adhesive is cured for 16 hours. Measurement of adhesive thickness

is conducted using a dial gauge with a resolution of 2 μm before and after machining. The measurements were conducted at three locations: front, middle and backside of the workpiece and three times for each position. The initial adhesive thickness (t_a) is the difference between the dial gauge reading on the top of the attached thin workpiece and the base of the holder; the workpiece thickness is deducted from this difference. Whereas the final adhesive thickness (if peel-off occurs) is the difference between the dial gauge reading on the top of the adhesive (after the workpiece is removed) and the base of the holder.

The cutting starts continuously from an initial thickness of 900 μm . The initial thick workpiece condition is used in order to make the workpiece more rigid and to avoid difficulty in holding and handling the thin workpiece. The sequential cut of the fine machining is not expected to cause significant change in residual stress [84]. The cutting process is conducted with a constant depth of cut (t_0) of 5 μm and a cutting speed of 0.1 m/min. The low depth of cut and cutting speed are selected in order to minimize chances of workpiece detachment from the adhesive and the workpiece holder. In addition, low cutting speed is used in order to reduce the temperature effect and prevent producing excessive heat during the cutting [84, 118]. In order to record and visually observe the continuous cutting process, a video camera with a speed of 30 frames per second is used.

The consistency of the depth of cut is examined by measuring the workpiece thickness using a dial gauge after every pass when the thickness goes below 200 μm . The depth of cut is observed to be consistent for every pass for all samples. The forces involved in the cutting process are measured using a multi-component dynamometer (Kistler MiniDyn 9256C1) attached to the bottom of the workpiece holder. The dynamometer was connected to micro-channel charge amplifier (Kistler 5070). The force data (cutting force (F_x) and thrust force (F_z)) are collected using a DEWESoft 6.5 software. The final workpiece thickness is measured using a micrometer.

3.2 Experimental Results and Discussion

The adhesive thickness is observed to be in the range of 27 to 54 μm , which is in the range of the targeted adhesive thickness using dispensing controller. The

targeted adhesive thickness for workpiece #1, #2, and #5 is 30 μm , for workpiece #3 is 45 μm and for workpiece #4 is 55 μm . Hence the application of adhesive thickness using dispensing controller is controllable and repeatable. The adhesive thicknesses are also measured when the thin workpieces got detached and in general the values are consistent with the initial adhesive thickness.

1. *Forces*

The forces measurement was conducted at every pass during the cutting process from an initial workpiece thickness of 900 μm down to the values of final workpiece thickness (t_w) shown in Table 3-2. The final thin workpiece thicknesses are comparable to the adhesive thickness (t_a). As the workpiece thickness reduces continuously, at one point there is seen to peel-off during the process. The final workpiece thicknesses reported are thickness values when the workpiece get detached (peeled). The final workpiece thicknesses are in the range of 28 to 51 μm .

Table 3-2. Thin machining results

	t_w (μm)	t_a (μm)
Workpiece #1	51	31
Workpiece #2	32	32
Workpiece #3	47	45
Workpiece #4	28	54
Workpiece #5	45	27

Figure 3-2. Forces profile for one pass of workpiece #1 at the thickness of about 141 μm .

Figure 3-2 shows one sample of the forces profile for one pass cutting process of workpiece #1 at the thickness of about 141 μm . The cutting force and thrust force signal for one pass show relatively constant values during the cutting process. The cutting and thrust forces between thick and thin conditions for

workpiece #2 are showed in Figure 3-3 to represent the forces profile. The cutting force is in the range of about 12 to 19.5 Newton and the thrust force is in the range of 1.5 to 5 Newton. This resulted in a range of specific cutting energy of 771 to 1128 MPa calculated as cutting force divided by the product of depth of cut and workpiece width. It can be seen that the forces for the thicker workpieces have smaller range of variation when compared to thin workpieces. In addition the thrust force is slightly lower for thinner workpieces.

Figure 3-3. Cutting force profile (top) and thrust force profile (bottom) of workpiece #2 for thin (A) and thick (B).

Similar variations are also seen for the other workpieces as shown in Figure 3-4 and Figure 3-5. Figure 3-4 and Figure 3-5 show the cutting force and thrust force profiles for workpiece #1, #3, #4 and #5 starting from a thickness of 160 μm to thinner conditions prior to peel-off. In summary, average cutting and thrust forces do not change as the workpiece thickness is reduced. Force variations are seen to be larger as the thickness is reduced.

Figure 3-4. Cutting force profile of workpiece #1, #3, #4 and #5 for thin conditions down to the final thickness.

Figure 3-5. Thrust force profile of workpiece #1, #3, #4 and #5 for thin conditions down to the final thickness.

2. Chips

Figure 3-6. Chip thickness profile of workpiece #1.

The chips were seen to be formed continuously during the cutting process. The chips length is measured in order to know the ratio of the depth of cut (t_0) and chip thickness (t_c). There was no significant variation of the chip thickness with the workpiece thickness (Figure 3-6). The chips length is in the range of 10 to 11.5 mm and the chip thickness of 10.9 to 12.5 μm giving a cutting ratio (t_0/t_c) range of 0.4 to 0.46. In summary, no significant variation in chip thickness was seen as the workpiece thickness was reduced to a few tens of micrometers.

It can be concluded that no significant changes in cutting force, thrust force and chip thickness as the workpiece becomes thinner. Changes may occur in the machined sub-surface; these are examined in the subsequent chapters. The one factor that prevented achieving very thin machined work thickness was peel-off. This is examined closely next.

3. Peel-off

The detachment of the thin workpiece from the holder was captured using high speed camera (30 frames per second). The peeling of the thin workpieces was seen to occur at the tool entrance region (when the tool starts to engage into the workpiece); the thin workpiece was pushed by the tool and rolled as the tool moved forward. Figure 3-7 shows (from left to right) the comparison between the chip

formation for the thick workpiece (thickness = 370 μm) and the peel process of the thin workpiece (thickness = 51 μm) for adhesive thickness of 31 μm . Peeling process occurred at the incipient chip formation stage. Instead of forming the chip, the tool pushes the thin workpiece.

Figure 3-7. The formation of chip in the thick workpiece (top) and the peel mechanism of the thin workpiece (bottom) captured by high speed camera for adhesive thickness of 31 μm .

A comparison of the peeled thin workpiece with the un-peeled thin workpiece, released from the holder using *acetone*, is made in order to observe the final shape of the thin workpieces (Figure 3-8). It is seen that the peeled thin workpiece has a fully rolled shape due to the pushing action by the tool toward the end of the workpiece. And the peeled sample has more curl to it even after it is straightened out compared to the non-peeled sample. The non-peeled sample relatively is not severely deformed. It can thus be inferred that the thin workpiece experiences less intense accumulation of stress from previous passes. The curled shape might be formed due to the plastic deformation induced during peeling of the thin workpiece.

Figure 3-8. The comparison of the (a) un-peeled sample with (b) rolled peeled sample just after cutting finished and (c) after the peeled sample straightened.

The bottom section of the peeled thin workpiece was visually observed using SEM (Scanning Electron Microscope). It can be seen that there is no evidence of the remnant adhesive layer at the bottom side of the thin workpieces (Figure 3-9) suggesting that the thin workpieces mainly are peeled from the setup with the adhesive failure mode rather than cohesive failure i.e. failure within the adhesive layers. In general, the failure mode is consistent with the assumption that the tendency of the failure of the joint between thick and thin adherents will be peeled of the thin part. In addition, peel detachment failure occurs when load at one end of adhesive joint acts to pry the adherent with one of the adherents less rigid than the other [114]. This type of failure was also seen in the adhesive peel test with a thin adherent. Duke and Stanbridge [119] observed the cohesive failure of the adhesive occurs adjacent to the yielding thin adherent. Crocombe and Adams [120] also showed that failure is near the adhesive-flexible adherent interface but leaving a visible layer of adhesive on the adherent in the peel test. In such peel tests, the thin workpiece is assumed to experience plastic deformation and the process is under steady state conditions [121].

Figure 3-9. SEM Pictures of the bottom side of workpiece #2 (left) and #3 (right) after the thin workpieces peeled from the setup. No obvious remnant adhesive is observed.

The steady state peeling force values when the thin workpieces got peeled are plotted in Figure 3-10. It is shown that the peeling forces are independent of the final workpiece thickness and adhesive thickness in the range of this experiment. In addition the peeling forces are significantly lower than the cutting and thrust forces during the cutting process. In contrast, in the peel test by Thouless and Yang [121] and wedge test by Williams [122] there is a trend that the forces decrease as the workpiece thickness decreases. The wedge test based on ISO Standard 11343-2003 is often used to characterize the total load needed to peel and the energy dissipated during the adhesive peeling when the wedge is moved steady state through the bond between the adherent and the adhesive [122-123].

Figure 3-10. Plot of the forces on the last pass when the thin workpieces peeled-off.

The effect of the substrate (adhesive) in the thin machining workpiece is similar to the effect of the substrate in the nano-scratching test. In the nano-scratching test, it is shown that the plastic deformation behavior of the thin film depends on the elastic-plastic deformation of the substrate [124]. At a certain deformation of the substrate the thin film undergoes cohesive-adhesive failure that leads to detachment. The failure will always occur when critical deformation is reached, independent of substrate hardness. In the micro-cutting of thin workpiece, similar phenomenon may occur when the thin workpiece gets detached from the adhesive. The thin workpiece adjusts initially to the elastic-plastic deformation of the adhesive. If the deformation force exceeds the strength of the adhesive it will

undergo adhesive failure. This leads to the thin workpiece detachment. The failure will always occur when critical deformation is reached.

The stresses induced in the workpiece and its effect on the fixturing may also be the cause of the peeling observed. The peeling of the thinner workpiece is mostly related to the stresses acting in the cutting process which has a larger effect on thin rather than thick workpieces. During the engagement of the tool on the thin workpiece, the stress is concentrated only at one point of the joint which is in the area of the entrance. This localized stress concentration will reduce the adhesive strength especially at the interface [114]. The stress created by the tool is more significant when the thickness of the thin sheet metal reach down to the point where the stress reaches the thin workpiece-adhesive interface and affects the strength of the bond at the interface. As the workpiece becomes thinner, the stress is deeper and at certain thickness, the stress is higher than the strength of the adhesive joint especially at the interface between the thin workpiece and the adhesive. However, it is difficult to measure the stress acting at the interface. Therefore a finite element analysis is conducted in order to study the mechanism of the thin workpiece machining and to study the stress created by the tool across the thickness of the thick and thin workpiece and along the bottom of the workpiece; the simulation model and results are explained in the rest of the chapter.

3.3 Finite Element Model to Study Peel-off

A finite element model to simulate the machining of incipient chip formation is developed in ABAQUS 6.10. The finite element is used to study the detachment mechanism of the thin workpiece. As revealed in the experimental work, the peeling of the thin workpiece mainly occurred in the entrance tool region (incipient chip formation) and failed at the interface between the workpiece and the adhesive layer. A three dimension (3D) incipient chip formation using a Lagrangian method resembling an indentation process is developed in order to simulate the transient beginning of orthogonal cutting process. Simulations are conducted until the region of the workpiece in front of the cutting edge experiencing highest deformation, where beyond this point chip starts to form. The highest deformation is expected to occur because no chip separation criterion is applied on the

workpiece. Hence the process is assumed to be the initiation of chip formation similar to that observes in the peeling process. The tensile and shear stresses, obtained from the simulations along the interface of the workpiece–adhesive and across the thickness of the adhesive at initial chip formation are extracted and analyzed. The stress variation along the interface especially at the adhesive side can be used to understand stresses that the adhesive has to withstand during entry and to explain the detachment and peel off. In addition, the stress variation across the thickness of the adhesive may explain why the failure is likely to occur at the interface and not within the adhesive layer. The effects of the workpiece thickness and adhesive thickness on the variation of the stress are also studied in the simulation.

3.3.1 Model Setup

Eight-node brick trilinear coupled displacement and temperature with reduced integration, hourglass control element type is used in this model. The coupled thermal-stress element (C3D8RT) utilizes temperature degree of freedom, in addition to displacement degree of freedom, at each node. The fully coupled temperature-displacement analysis is suitable to be applied because the heat generated by plastic deformation at primary deformation is significant [125-126]. The size of the element is $0.625\ \mu\text{m} \times 1.25\ \mu\text{m}$ in the $15\ \mu\text{m}$ of the top side of the workpiece. Whereas the element size of the adhesive is $1\ \mu\text{m} \times 2\ \mu\text{m}$. The workpiece and the adhesive are one element wide with the width of $1\ \mu\text{m}$ in order to reduce the simulation time for the 3D model. The process is assumed to be one of plane strain deformation since the tool is wider than the workpiece width. The workpiece is set to be fixed while the cutting tool moves horizontally towards the workpiece with a depth of cut of $5\ \mu\text{m}$. The left and right sides are constrained in the direction perpendicular to the cutting speed, while the back side of the workpiece is fixed in all directions.

The cutting parameters used in the simulations are summarized in Table 3-3. Three workpieces with thickness of $45\ \mu\text{m}$, $65\ \mu\text{m}$ and $150\ \mu\text{m}$ are used in order to observe differences between thin and thick workpiece machining conditions. Two adhesive thicknesses are selected as $30\ \mu\text{m}$ and $45\ \mu\text{m}$ to represent experimental

conditions. The combination of the 45 μm workpiece with 30 μm adhesive and 45 μm workpiece with 45 μm adhesive are selected to represent workpiece #5 and workpiece #3 respectively; peel-off occurred for these workpieces. The interface between the metal and adhesive is modeled using tie-constraint.

Table 3-3. Simulation parameters

Workpiece	Al6061-T6
Tool	Single Crystal Diamond
Adhesive Dymax® 6-621 thickness (μm)	30 and 45
Tool rake angle and clearance angle	1° and 4.5°
Cutting speed (m/min)	0.1
Depth of cut (μm)	5
Machined workpiece thickness (μm)	45, 65, 150

3.3.2 Materials Properties

The workpiece, tool and adhesive properties are presented in Table 3-4, Table 3-5 and Table 3-1 respectively. The tool is modeled as Single Crystal Diamond (SCD) and the workpiece as Aluminium Al6061-T6, similar with the materials used in the experimental work. The Johnson-Cook (J-C) constitutive model is used as the workpiece material model. The Johnson-Cook material model covers strain up to about 7 [127] and strain rate from 10^{-4} to 10^4 s^{-1} [128].

Although this chapter is only simulating incipient chip formation similar to the indentation process, the material model used in here will also be used in the simulation of steady state machining process discussed in Chapter 5. The J-C uses Von Mises plasticity model and is a suitable material model for simulating the cutting process because it considers the mechanical behavior of materials as multiplicative effects of stress, strain, strain rate and temperature [127]. The J-C material model is given as:

$$\bar{\sigma} = [A + B(\bar{\epsilon}^{pl})^n] \left[1 + C \ln \left(\frac{\dot{\bar{\epsilon}}^{pl}}{\dot{\epsilon}_0} \right) \right] \left[1 - \left(\frac{T - T_0}{T_{melt} - T_0} \right)^m \right] \quad (3.1)$$

where $\bar{\sigma}$ is the flow stress, $\bar{\epsilon}^{pl}$ is the equivalent plastic strain, $\frac{\dot{\bar{\epsilon}}^{pl}}{\dot{\epsilon}_0}$ is the dimensionless plastic strain rate for $\dot{\epsilon}_0$ (reference plastic strain rate) = 1.0 s^{-1} , $\dot{\bar{\epsilon}}^{pl}$ is equivalent plastic strain rate, T is the current temperature, T_{melt} is the melting temperature and T_0 is the reference temperature (room temperature). While A , B , n , C and m are the Johnson-Cook constants.

The tool is modeled as an elastic deformable body. Its material and mechanical properties are significantly higher than workpiece and it does not experience the high strain, strain rate and stress compared to the workpiece. Therefore, only conductivity, density, elastic modulus constant, coefficient of expansion and specific heat of the tool are specified in the model. The adhesive is assumed to be isotropic [35].

Table 3-4. Workpiece material properties (Al6061-T6) [128-130]

Density (kg/m ³)	2700
Specific heat (J/kg K)	896.0
Thermal conductivity (W/m K)	167.0
Coefficient of thermal expansion (°C ⁻¹)	25.2 x 10 ⁻⁶
Young's modulus (GPa)	68.9
Poisson's ratio	0.33
Melting temperature (°C)	582
Johnson-Cook strength model	A=324.0 MPa, B=114.0 MPa, n=0.42, C=0.002, m=1.34

Table 3-5. Tool material properties (SCD) [130]

Density (kg/m ³)	3500
Specific heat (J/kg K)	0.4715
Thermal conductivity (W/m K)	2000
Coefficient of thermal expansion (°C ⁻¹)	1.18 x 10 ⁻⁶
Young's modulus (GPa)	850
Poisson's ratio	0.1

General contact model between the tool and the workpiece is applied in the simulation [125]. Zorev friction model [131] is applied between the tool and the workpiece assuming two regions of contact: sticking and sliding with the friction coefficient value of 0.1 [132] assuming the area of tool-chip contact in the incipient chip formation is relatively small and no chip is formed during the simulation.

3.4 Simulation Results and Discussion

Figure 3-11 shows the result of the incipient chip formation (indentation process) and the area where the analysis will be conducted. The study of the finite element analysis is mainly focused on the stress induced in the interface and the entrance side.

Figure 3-11. Incipient chip formation during the tool engagement and the area of the interest (left) and axis directions guide (right).

3.4.1 Stress at the Interface

Figure 3-12 and Figure 3-13 plot the tensile stress perpendicular with the cutting direction (S22) and shear stress parallel with the cutting direction (S12) at the adhesive side in the interface between the bottom of the workpiece and the top of the adhesive when the chip starts to be formed in the entrance region. The left end of the horizontal axis marks the entry region of the workpiece. Stress at this entry point is critical for detachment and peel off to occur.

Figure 3-12. Tensile stress at the adhesive side on the interface during incipient chip formation.

The stresses value is highest at the entry region and reduces gradually as the distance further away. The tensile stress value is about 5 times higher than the shear in the interface. This result implies that the tensile stress plays a dominant role in the interface i.e., peeling mainly occurred due to the high tensile stress rather than shear stress. In general, the adhesive joint is the weakest when subjected to cleavage stresses [119] especially when the thin adherent peels from the thick substrate and occurs at the interface of the thin adherent–adhesive. In the thin adherent peeling process during typical peel test, cleavage is the preferred failure mode rather than shear. Crocombe and Adams [120] employed an elastic, large-displacement, finite element analysis approach and have reported that initial failure is caused by the principal tensile stresses in the adhesive driving a crack towards the interface between the adhesive and flexible substrate. Therefore, similar stresses induced by the advancing cutting tool have a role in the detachment of the thin workpiece in the transient beginning of the tool engagement.

Figure 3-13. Shear stress at the adhesive side on the interface during incipient chip formation.

The tensile stress of the 45 μm thick workpiece and 30 μm adhesive in the entry region (36.3 MPa) exceeded the reference tensile at break of the adhesive which is 35.9 MPa (refer to Table 3-1). This result confirms the experimental result where at about 27 μm adhesive thickness, the workpiece peeled-off upon reaching a

thickness of about 45 μm (workpiece #5). In contrast, for the case of 45 μm workpiece with 45 μm adhesive, the stress value at the entry region (34.1 MPa) is just below the value of the tensile at break of the adhesive, however peel-off is still seen in the experimental result (workpiece #3) at this condition.

It is noted that there is a variation or range in the tensile at break value of the adhesive. The failure limit value, i.e. tensile at break, is taken from the tensile test result based on ASTM D-638 [133]. The ASTM D-638 test results for some plastics have range of values within laboratory standard deviation (S_r) and between laboratory standard deviation (S_R). The S_r and S_R values for acrylic (Dymax® 6-621 is urethane acrylic type) can reach up to about 5% and 8.26% respectively [133]. Hence the value of the failure limits maybe in the range of the 34.11 - 37.7 MPa (S_r) and 32.93 - 38.87 MPa (S_R). Hence, the prediction for peeling-off is still valid and within the range of failure limit.

In addition, the variation may also be due to the different conditions between the reported values of the adhesive properties that have different parameters with the conditions used in this experiment of the micro-cutting thin workpiece. The difference might be attributed due to the differences in adhesive thicknesses [114], strain rate, adherent surface roughness, and method of adherent surface preparation [35]. The air entrapment can occur in the rougher surface of the adherent, however rough surface also can help because it gives ‘teeth’ to the substrate and increase the total effective area over which the forces of adhesion can develop and provide as a crack propagation barrier [114]. These results imply that the adhesive can only withstand the strength of the bond of the thin workpiece down to these ranges of workpiece thicknesses. Below these thicknesses, the stress created by the tool will exceed the critical deformation stress the adhesive can withstand.

3.4.2 Stress across the Adhesive

The stress profile across the thickness of the adhesive can also be used to understand why peeling mainly occurred at the interface (adhesive failure mode) rather than cohesive failure mode. Figure 3-14 shows the tensile stress perpendicular with the cutting direction (S_{22}) across the thickness of the adhesive for different workpiece thickness and adhesive thickness. The left end of the

horizontal axis marks the top region of the adhesive (interface workpiece-adhesive). It can be seen in Figure 3-14 that the peak stress occurred at the interface rather than in the middle of the adhesive thickness. Deeper or further away from the interface, the stress becomes lower. Therefore, peeling is likely to occur at the interface due to the higher stress experienced by the adhesive at the interface.

Figure 3-14. Tensile stress across the thickness of the adhesive during incipient chip formation.

3.4.3 Effect of Workpiece Thickness

Figure 3-12, Figure 3-13 and Figure 3-14 can be used to study the effect of workpiece thickness especially for the adhesive thickness of 30 μm . It is seen that the tensile stress and shear stress increase as the workpiece becomes thinner especially near the entry region for the case of 30 μm adhesive (Figure 3-12 and Figure 3-13). Tensile stress variation across the adhesive thickness shows similar trend viz. as the workpiece become thinner, the stress become higher (Figure 3-14). The 150 μm workpiece has lower stress profile along the entire bottom of the workpiece compared to the 65 μm and 45 μm workpiece. There are minimal stress variations along interface and across the adhesive when the workpiece is thicker. These results indicate that the tensile stress may not be significant in the interface of workpiece-adhesive and across the adhesive in the thick workpiece. Therefore, a thinner workpiece is more susceptible to peel-off and detachment than the thicker workpiece by the cleavage failure mode.

In this context, it is relevant to note that Rosa *et al.* [134] reported that the material in the vicinity of the flank surface of the tool is pulled under tensile stresses, whereas material adjacent to the rake surface is under compression at the transient beginning of the chip formation in the cutting process. A larger or thicker uncut chip thickness will have more resistance to peel from the rake surface than a thinner uncut chip thickness. Similarly, the thicker workpiece has more resistance to peel than the thinner workpiece.

3.4.4 Effect of Adhesive Thickness

The study of the effect of adhesive thickness is conducted by comparing two different adhesive thicknesses, namely 30 μm and 45 μm but with the same workpiece thickness (45 μm). The tensile stress variation of 45 μm workpiece for the case of 30 μm and 45 μm adhesives shows similar trend along the interface and across the adhesive thickness (Figure 3-12 and Figure 3-14). Furthermore, the simulation results show that the 30 μm adhesive case has slightly higher stress compared to 45 μm adhesive case at the entrance side and consequently more susceptible to fail in the peeled mode. In addition, the shear stress also shows similar trend such that the 30 μm adhesive has slightly higher stress near the entrance, though at distances farther away from the tool the stress becomes higher for the 45 μm adhesive case. However the difference considers to be small (± 1 MPa) and may not be so significantly affect the process. The higher shear stress of the 45 μm adhesive thickness compared to 30 μm adhesive thickness may be occurred due to the compliance effect of the thicker adhesive.

3.5 Summary

The cutting mechanism of thin workpieces and limitations to achieve thin workpiece conditions are explored in this chapter. There are no significant differences in forces and chip thickness during the cutting experiments for thick and thin workpieces. The thinnest Al6061-T6 workpiece machined using orthogonal micro-cutting process and fixture using a 54 μm thick UV-curing adhesive is about 28 μm . The limitation to achieve even thinner workpieces is seen to be detachment of the thin workpiece by peel-off that occurs in the initial chip formation when the

tool engages with the workpiece. The detachment is induced by adhesive fracture mode that occurred in the interface between the thin workpiece and the adhesive.

Simulation results show that the tensile stress induced by the tool at the top of the adhesive is higher for a thinner workpiece (45 μm) than a thicker workpiece (150 μm) and higher at the entrance. Hence the thinner workpiece is more susceptible to peel off. Through-thickness stress profiles of the adhesive extracted from simulation indicate that higher tensile stresses are experienced when the workpiece is thinner and is highest at the interface of the thin workpiece-adhesive rather than in the middle section of the adhesive suggesting that the peel-off is adhesive failure mode. Finite element study of the chip formation initiation shows differences in stress across the workpiece thickness as the tool indents into it. Therefore it is suspected there is a residual stress variation across the thickness of the machined workpiece. The results also show there are different stress effects in the substrate (adhesive) when cutting thick and thin workpieces. These topics are explored in subsequent chapter.

Chapter 4.

WARPING AND RESIDUAL STRESS MEASUREMENTS ON THE MACHINED THIN WORKPIECE

This chapter discusses the experimental work related to machining induced warping as the workpiece becomes thinner. The curvature and surface residual stresses of workpieces machined to various thicknesses using orthogonal micro-cutting are measured and trends are reported.

4.1 Introduction

Machining induced deformation severely affects thin workpieces leading to deflection and warping when released from the fixture. Under usual conditions of machining thick workpieces, the stresses that remain behind in the workpiece, the so-called residual stress is influenced by two factors: the loading imposed by the machining process itself, and the elastic recovery effect caused by unloading during fixture releases. The former is a strong function of process conditions while the latter depends on work geometry and is often inherently accounted for.

In the case of machining thin workpiece, there is an additional factor that influences the residual stress: the material removal effect. The material removal effect occurs when machining is performed on thin workpiece because the geometry of the thin workpiece changes substantially enough to influence the stresses within it. This material removal effect influences warping of the workpiece and a measure of this warping is often used as a way to measure residual stress that was in the removed layer as long as the method of material removal does not cause its own induced stress (e.g. etching). The etching method, which does not induce its own stress in the process, is very difficult to implement on thin workpieces and hence cannot be adopted here. The method proposed in [24] is also not applicable here because fixture effects and machining induced stress effects in thin workpieces are

not captured using this method of slicing a thin layer from the thick machined workpiece using EDM method.

How then do we assess the machining induced stresses in the machining thin workpieces? In such situations we can perhaps represent the total residual stress as shown by the equation below:

$$\sigma_{total} = \sigma_{machining\ induced\ stress} + \sigma_{material\ removal}$$

If we can measure the total stress using an experimental method (e.g. XRD method) while estimating the material removal effects using measured curvature and theoretical considerations (such as that popularly used in the etching method), it may be possible to estimate the machining induced stresses in thin workpieces. This procedure is only approximated at best because the stress estimation using material removal method depends on measured curvature which in itself is influenced by both machining induced stresses and material removal effects. This chapter will nevertheless adopt this proposed method to study trends in machining induced stresses in thin workpieces.

Micro-cutting experiments will be conducted to reduce several thick workpieces by machining, at the fixed cutting parameters and several passes, to various thicknesses. The curvature of the workpieces is then measured. The surface stress of the workpieces is measured using the thin-film XRD experimental method. The stress due to material removal is assessed using the curvature method (details in Section 2.2.4.1). The measured XRD stress and the theoretically assessed stress due to material removal are then compared.

4.2 Experimental Method

The experimental setup, materials, tools, cutting parameters and material preparations are the same as described in Chapter 3. The orthogonal cutting setup on a 3-axis CNC machine tool (Mikrotools DT-110) is used. The workpiece is made of annealed Al6061-T6 alloy, is 3.37 mm wide and 900 μm thick with a length of about 15 mm. The workpiece was annealed in order to remove any residual stress due to previous manufacturing processes (such as plate rolling). The workpiece is attached onto the holder using UV light curing adhesive Dymax® 6-621. The adhesive thickness is 30 μm and cured using chemical activation. The single crystal

diamond (SCD) insert tool used for the orthogonal micro-cutting process had a width of 5 mm. Seven workpieces were machined down to various thicknesses. Cutting is initiated continuously from an initial thickness of 900 μm . The cutting process is conducted with a constant depth of cut (t_0) of 5 μm and a cutting speed of 0.1 m/min. It was shown that the sequential cut of the fine machining does not cause significant change of the residual stress [84]. Hence it is assumed that the residual stress will not accumulate to the next machining pass due to the low depth of cut and continuous cutting used in this experiment.

4.3 Curvature Developed in the Thin Workpieces

Figure 4-1. Seven machined workpieces conditions after being released from the adhesive.

Seven workpieces were machined down to various thicknesses (Table 4-1). The thin workpieces are released from the workpiece holder by dipping into the *acetone*. Figure 4-1 shows the top view of the thin machined workpieces after their release from the adhesive. Visually, the deformation is not severe especially for workpiece #1 to #4; however the curvature is seen to develop for workpieces #5 to #7. Experiments are conducted to produce one sample for every workpiece thickness due to the difficulty in determining the residual stress using thin film XRD method. The software to determine the residual stress using thin film XRD method is not available in the XRD machine. Hence only few samples are proceeded to be calculated with the help of the XRD machine supplier. However,

one thickness is repeated for the target thickness of about 150 μm which are workpiece #1 and workpiece #2.

Table 4-1. Final thickness of the machined samples

Workpiece	Final thickness (t_w) (μm)	t_0/t_w
workpiece #1	149	0.034
workpiece #2	147	0.034
workpiece #3	127	0.039
workpiece #4	97	0.052
workpiece #5	85	0.059
workpiece #6	73	0.069
workpiece #7	43	0.116

In general, the free thin workpiece condition is very delicate and needs to be handled carefully in order to avoid changes in curvature and shape. Hence the curvature is measured using a non-contact method such as a laser probe available in surface profiler (Taylor Hobson Talyscan 150). Subsequently, the residual stress measurement using XRD is conducted and finally the final thickness is measured using a micrometer at three different locations.

The profile measurement along the length of the workpiece is conducted three times at three different locations. The curvature used in the calculation is the average from the three measurements. Figure 4-2 shows an example of a measured profile for workpiece #5. The measured profiles for other samples are presented in Appendix C.

Figure 4-2. Profile of workpiece #5 measured using laser probe Taylor Hobson Talyscan 150.

The curvature ($\kappa = \frac{1}{\rho}$) is measured using surface profiler (Taylor Hobson Talyscan 150) with laser probe method and is calculated using the height (ϕ) and the length (L) of the measured workpiece as $\rho = \frac{L^2 + 4\phi^2}{8\phi}$ [102]. Measurements conducted three times along the length of the workpiece, on the two sides and on the middle section. Subsequently, the curvature is plotted against the thickness and a polynomial regression model is fitted to the plotted points.

Figure 4-3. Curvature vs thickness. As the workpiece became thinner, the curvature become higher.

Figure 4-3 shows the plot of the curvature against the workpiece thickness. The curvature is fitted to a 2nd order polynomial equation, which shows a good fit an R^2 value of 0.84. The measured curvature is larger as the workpiece becomes thinner with the shape of the workpiece becoming more concave. Large scatter in the curvature data is observed in some samples due to the non-uniform curvature shape along the length of the thin machined samples after removed from the adhesive. The curvatures are not uniform between the two sides and middle section. However, the results show that the curvature method is applicable because the deflection of the midsurface is small in comparison to the thickness of the plate [105].

4.4 Residual Stress Measured Using Curvature Method and XRD Method

The determination of the residual stress of the machined surface is conducted in two ways: curvature method and X-Ray Diffractions (XRD) method. Detail explanation of both methods is provided in section 2.2.4.

4.4.1 Curvature Method

The residual stress is measured using the curvature method proposed by Treuting and Read [23] (equation (2.2)). However, the curvature perpendicular to the cutting direction is assumed to be negligible ($\kappa_y = 0$) where the strain perpendicular to the cutting direction is negligibly small because the width of the workpiece is much smaller than the length. Hence, only the curvature parallel in the cutting direction is measured resulting in a modification of equation (2.2) as:

$$\sigma_x(z_1) = \frac{-E}{6(1-\nu^2)} \left\{ (z_0 + z_1)^2 \frac{d\kappa_x(z_1)}{dz_1} + 4(z_0 + z_1)\kappa_x(z_1) - 2 \int_{z_1}^{z_0} \kappa_x(z) dz \right\} \quad (4.1)$$

where, $\frac{d\kappa_x(z_1)}{dz_1}$ is the differentiation of the fitted equations and $\int_{z_1}^{z_0} \kappa_x(z) dz$ is the integration of the fitted equations at intervals of $z_1 = 43 \mu\text{m}$ and $z_0 = 149 \mu\text{m}$, not necessarily experimental points [23]. From the fitted curve (Figure 4-3), $\frac{d\kappa_x(z_1)}{dz_1}$ and

$\int_{z_1}^{z_0} \kappa_x(z) dz$ are calculated as:

$$\frac{d\kappa_x(z_1)}{dz_1} = 7.12 \text{ E}^{-07} (z_1) - 0.00013 = -0.00013,$$

$$\int_{z_1}^{z_0} \kappa_x(z) dz = 1.19 \text{ E}^{-07} (z_1)^3 - 6.6 \text{ E}^{-05} (z_1)^2 + 0.014 z_1 = 7.79 \text{ E}^{-05}.$$

These two values are constant values to be applied in equation (4.1). The Young's modulus of Al6061-T6 is taken as 68.9 GPa and the poisson ratio as 0.33 are applied. The residual stress is plotted against the thickness ratio and shown in Figure 4-7.

4.4.2 XRD Method

The surface residual stress of the thin workpieces is also measured using a x-ray diffractometer system (PANalytical Empyrean). The normal XRD stress measurement method can be used to measure the residual stress on the surface and the x-rays penetrate to about 10 – 25 μm deep into the surface depending on the x-

ray source and specimen materials. In the case of the thin workpiece, with the thickness down to 50 μm , this method is not suitable. Therefore, thin film residual stress method is used in which the depth of the x-ray penetration is shallower compared to the conventional method. Unlike the normal residual stress method using XRD, in the thin film residual stress measurement method, not only one peak is selected as the base for the residual stress calculation, but at least 6 peaks have to be selected. Hence, the phase measurement has to be conducted to determine the peak prior to the residual stress measurement. The 2theta angle is defined from 30 to 130 degree for the phase analysis. In general, the lattice planes exist in the samples are the allowed FCC reflection for aluminium. The plot of the Intensity vs. 2theta angle for bulk (un-machined) sample and workpiece #1 are shown in Figure 4-4 and Figure 4-5 respectively. The plots for other workpieces are shown in Appendix D.

Figure 4-4. Plot of Intensity vs 2theta angle for bulk (un-machined) sample.

The XRD measurement results for bulk (un-machined) sample revealed the presence of (111), (200), (220), (220), (311), (222), (400), (331), (420) and (422) with the highest intensity at the (200) plane. Workpiece #1, #2 and #7 have the

same lattice plane consisting of (111), (200), (220), (311), (222), (331), (420) and (422) with the highest intensity at (111). In these three samples, (400) plane was not observed. Workpiece #3, #4, #5 and #6 have similar lattice planes with the bulk (un-machined) sample with the highest intensity at the (200) plane. However, the intensity of the (111) plane of the bulk (un-machined) sample is significantly higher compared to workpiece #3, #4, #5 and #6.

In general, none of the thin machined samples have the same intensity and lattice planes with the un-machined sample from the phase analysis using XRD thin film method. In addition, there is no presence of preferred orientation of the lattice planes in all the samples.

Figure 4-5. Plot of Intensity vs 2Theta angle for workpiece #1.

The modification of crystal lattice and intensity in the thin machined samples occurs mainly due to the deformation induced by the cutting process [40, 135]. The deformation introduces strains into the grains located in the surface and subsurface of the workpiece during chip formation. The strain experienced by each grain is varied due to the different crystallographic orientation in the polycrystalline materials [136]. In each grain, the dislocation glide takes place during deformation. The dislocations move on the slip systems, interact and cause uneven elastic and

plastic deformation within each crystal grain and produce different orientation of the grains [136].

Figure 4-6. Epsilon vs $\sin^2\psi$ for workpiece #1 to determine residual stress using XRD method.

The calculation to determine the residual stress is conducted directly in the software. The plots of epsilon vs. $\sin^2\psi$ for determining residual stress using XRD method for workpiece #1 is shown in Figure 4-6 and for other workpieces are attached in Appendix E. During the data calculation using XRD method, the sample points do not fit to a linear curve, instead the points fit to a psi splitting curve. The fitting of splitting curve indicates the presence of shear stress in addition to the normal stress. With this adjustment and treatment, the surface residual stresses determined by XRD are more compressive than the values determined by indirect method (curvature method) as shown in Figure 4-7. The compressive stress indicates that the mechanical deformation is more dominant than the thermal deformation, since the process is conducted at a low cutting speed. At a low cutting speed, the cutting temperature is low and furthermore reduces the heat transferred into the machined workpiece. In contrast, the rise of the temperature tends to induce surface tensile residual stresses at higher cutting speed [27, 91, 137].

Figure 4-7. Residual stress vs. t_0/t_w measured using XRD method and curvature method, the stress values are compressive with the XRD method showing higher values.

The residual stress measured using curvature method shows low values in the range from -19.64 MPa to 1 MPa with the standard deviation in between of 2.19 to 12.19 MPa. The residual stresses measured using XRD show that the values are in between -19.30 MPa to -59.40 MPa with the standard deviation in the range from 5.1 to 8.4 MPa. At t_0/t_w of 0.069, the stress is seen to be the highest. No clear trends of residual stress are seen from the XRD measurements. One may expect to see large compressive stress at small t_w based on the measured curvature. This is because the compressive stress at the top surface and the concave shape of the free un-hold thin workpiece are similar with that of a beam being released from a high bending load [138]. In the beam theory, the radii of the concave shape increases as the workpiece become thinner. The concave shape indicates a compressive stress at the top surface and tensile stress at the bottom.

It is argued that the residual stress values obtained using XRD method are about 30% systematically higher than the indirect method (curvature method) [91]. In reference to this argument, the stress value determined in this work using curvature method is seen to be far less compressive than XRD method (>30%). This implies that there is a significant contribution of the machining to the warping especially when the workpiece become thinner. Hence, there are two mechanisms

that occur here, redistribution of the stresses caused by machining and relaxation due to the material removal effect.

The two methods proposed in this work have several drawbacks that also need to be considered. The residual stress measured using curvature method is sensitive to the equation used to fit for the points to determine the curvature against thickness. While the XRD method depends on several assumptions and input parameters, such as misalignment and fitting of the peak curve. Therefore the modification of the assumption or parameters will contribute to the measured residual stress values significantly.

4.5 Discussion

The measured curvatures show that the curvature increases as the workpiece becomes thinner. The formation of high curvature in the free specimen, upon releasing from the fixture, occurs due to the large bending effect or release of bending moment experienced by the thinner workpiece. In this condition, the internal stresses reach self-equilibrium, firstly because of the reduced cross section and secondly because of the stress profile across the thickness due to the machining induced stress [96]. The reduction of cross section of the workpiece increases the bending moment which is also seen in any non-stress inducing removal method. However, in this case the curvature is not increased in linear pattern but rather quadratic due to the increased effect of the machining induced stress.

In the thinner workpiece conditions, the machining induced stress may reach down to the interface between the workpiece and fixture. Hence, there are substrate effects to consider. The compliant substrate used in this experiment where the Young's Modulus is relatively lower than that of the workpiece ($E_{\text{workpiece}}/E_{\text{substrate}} = 31$), will elastically deform to its original shape after the tool leaves the workpiece. Different elastic properties of the fixture can give different stress variations across the workpiece which in the end can affect the shape of the workpiece when the workpiece is released from the fixture. Moreover, it is difficult to measure the residual stress profile of the free thin workpiece with a thickness of about 50 μm because the thin workpiece is very delicate.

4.6 Summary

In this chapter it has been shown that the machining process exacerbates the warping of the thin workpiece due to the induced stress that disturbs the balance of the stress in the thin workpieces. As the workpiece become thinner, the curvature increases. The residual stress measured using the two methods (curvature and XRD) show significantly different values implying that the residual stress in the warping of thin workpiece occurred due to the machining induced stresses and elastic relaxation. The measurement of the residual stress in a free thin work material is still a challenge. Hence, finite element analysis is necessary to be conducted in order to study residual stress profiles in the thin workpiece produced by machining and also the contribution of the substrate properties on the residual stress. This will be discussed in the next chapter.

Chapter 5.

EFFECT OF THE SUBSTRATE ELASTIC PROPERTIES ON THE RESIDUAL STRESS

This chapter reports machining simulation of the finite element model developed in ABAQUS. The finite element model is used to predict the residual stress profile in the surface and subsurface of the machined workpiece at various workpiece thicknesses and various substrate (adhesive) elastic properties. The developed finite element model can be used to predict the workpiece deformation especially for the thin workpiece materials.

5.1 Contribution of Substrate Effect in Micro-cutting Thin Workpiece

Nano-indentation tests show that the critical penetration depth is more sensitive to differences in elastic properties such as elastic modulus (stiffer or weaker) of thin film-substrate combination [37]. Such observation leads to the following questions: ‘Can the substrate properties affect the micro-cutting process and warping of the thin workpiece?’ and ‘At what level of thickness do such effects appear in micro-cutting?’ Thus, the investigation of the influence of substrate properties in the cutting mechanism and residual stress profile especially for thin workpiece conditions is essentially to be conducted as similar phenomena observed in the nano-indentation process.

The finite element model developed in ABAQUS 6.9-2 is utilized to simulate the machining of thin workpiece to study the effects of workpiece thickness and substrate properties on the residual stress profiles in the workpiece. Stress values parallel to the cutting direction (S11) are dominant and contributed to the warping [80]. Hence this stress is extracted from the simulation across the thickness of the workpiece at each nodal point down to the bottom of the workpiece during steady state cutting condition and after the tool leaves the workpiece with the boundary conditions remained intact.

5.2 Finite Element Model

Three dimension (3D) orthogonal cutting using a Lagrangian method is used to develop the finite element model. The three dimension model can accommodate arbitrary element failure at the element surfaces by using shear failure model instead of using predefined separation criterion during chip formation. This option is not available in a 2D ABAQUS modeling where it would be necessary to define separation line. The severe distortion and a priori separation criterion can be avoided in 3D simulation by using appropriate failure parameter criterion and friction conditions [125].

Figure 5-1. Element mesh and boundary conditions for 20 μm workpiece thickness.

The model setup and element type (C3D8RT) used are similar to that described in section 3.4.1. Figure 5-1 shows the model setup and boundary conditions for 20 μm workpiece thickness. Smaller element sizes are used for 10 μm thick; starting from the top of the workpiece with a size of 0.625 μm x 1.25 μm . In order to reduce the simulation time, the width of the workpiece is considered to be 0.5 μm consisting of one element thick. The process is assumed to be plane strain because the width of the orthogonal process workpiece is more than 5 times of the thickness. The workpiece is held fixed while cutting tool moves horizontally towards the workpiece with a fixed depth of cut (t_0) 5 μm . Four final workpieces

thickness (t_w) values of 5, 10 μm , 50 μm , and 80 μm are used in order to observe differences between thin and thick workpiece machining conditions. The thickness range is selected from the thinnest condition where the machined thickness is the same as the depth of cut ($t_0/t_w = 1$) up to condition similar to those observed in experimental results in Chapter 4 (workpiece #5 and workpiece #7). The substrate is modeled below the workpiece with the fixed thickness of 30 μm . The interface between the metal and substrate is modeled using tie-constraint so that the two materials are assumed to be perfectly bonded. This assumption is made because we have seen the detachment of the thin workpiece at the ratio of t_0/t_w about 0.1 in the incipient chip formation where sudden increase in the load occurs [134]. However in this case the process is assumed to be in steady state condition, where the detachment is assumed not to occur.

Table 5-1. Simulation Parameters

Workpiece	Al6061-T6
Tool	Single Crystal Diamond
Tool rake angle and clearance angle	1° and 4.5°
Cutting speed (m/sec)	30
Depth of cut (t_0) (μm)	5
Substrate thickness (μm)	30
Substrate Elastic Modulus (GPa)	275.6; 6.89; 2.206; 0.689
E_w/E_s (Elastic Modulus ratio)	0.25, 10, 31, 100
Machined workpiece thickness (t_w) (μm)	5, 10, 50, 80
t_0/t_w	0.0625, 0.1, 0.5, 1

In this simulation, higher cutting speed is applied similar to the experimental data (from literature) used in the validation of the material separation criterion for Al-6061-T6 [139] in contrast to the slow cutting speed earlier used in the experiments. It is expected that similar trends can be observed at higher cutting speeds. A complete set of cutting parameters used is shown in the Table 5-1.

5.2.1 Materials Properties

In this simulation, material models similar to that described in section 3.4.2 (Numerical Simulation of The Peeling) is applied. The workpiece, tool and substrate (adhesive) properties used are as shown in Table 3-4, Table 3-5 and Table 3-1 respectively. The tool used is Single Crystal Diamond (SCD) and the workpiece used is Aluminium Al6061-T6, and the substrate is Dymax® 6-621. However, the

effect of the substrate properties will be studied by varying the ratio of elastic modulus between metal (Al6061-T6) and substrate; the process could prove to be sensitive to this parameter similar to the critical penetration depth to film thickness ratio in the case of thin film-substrate combination reported in nano-indentation test [37]. Here, the elastic modulus of the metal is fixed (the elastic modulus of Al6061-T6), while the elastic modulus of the substrate is varied in order to get different combination of the ratio of elastic modulus of workpiece (E_w) and elastic modulus of substrate (E_s) as shown in Table 5-1. Therefore the other substrate properties remain the same as in Table 3-1. The E_w/E_s ratios are defined to cover the stiff substrate (high substrate elastic modulus) for the case of $E_w/E_s = 0.25$ and flexible substrate (low substrate elastic modulus) for the case of $E_w/E_s = 10, 31$ and 100 respectively. The ratio of $E_w/E_s = 31$ is selected as one of the elastic modulus ratio in order to represent conditions similar to the experiment described in experimental work in Chapter 4.

The Johnson-Cook (J-C) constitutive model is used as the workpiece material model. The microstructural effects are not considered in this simulation because the workpieces used in Chapter 4 are annealed to get several grains across the workpiece thickness so that continuum assumptions are still valid. In addition, continuum plasticity breaks down only at length scales smaller than $1\ \mu\text{m}$ [140].

5.2.2 Material Separation Criterion and Failure Model

Dynamic failure parameters available in ABAQUS provide a more realistic mechanism of the cutting process and can overcome disadvantages of separation criteria and predefined fracture line. Johnson-Cook (J-C) shear failure model is suitable for high-strain rate dynamic process such as metal cutting. Therefore, this shear model is used here to model chip formation. The elements fracture when the damage parameter (ω) reaches a value of 1. The damage parameter (ω) is the accumulation equivalent plastic strain ($\bar{\epsilon}_0^{pl}$) of the elements divided by equivalent plastic strain at failure ($\bar{\epsilon}_f^{pl}$). The damage of the element is based on the basic form of the damage model [125]:

$$\omega = \frac{\bar{\epsilon}_0^{pl} + \sum \Delta \bar{\epsilon}^{pl}}{\bar{\epsilon}_f^{pl}} \quad (5.1)$$

where $\bar{\epsilon}_0^{pl}$ is any initial value of the equivalent plastic strain, $\Delta \bar{\epsilon}^{pl}$ is an increment of equivalent plastic strain and $\bar{\epsilon}_f^{pl}$ is the strain at failure. In Johnson-Cook shear failure model, the equivalent plastic strain is calculated using the following equation [141]:

$$\bar{\epsilon}_f^{pl} = [d_1 + d_2 \exp(d_3 \eta)] \left[1 + d_4 \ln \left(\frac{\dot{\bar{\epsilon}}^{pl}}{\dot{\bar{\epsilon}}_0} \right) \right] \left[1 + d_5 \left(\frac{T - T_0}{T_{melt} - T_0} \right) \right] \quad (5.2)$$

where $\eta = \frac{\sigma_m}{\bar{\sigma}}$, σ_m is the mean stress, $\bar{\sigma}$ is the equivalent stress, and d_1 to d_5 are material constants. The Johnson-Cook failure parameters (d_1 to d_5) for Al6061-T6 are given in Table 5-2 [129].

Table 5-2. Johnson-Cook damage parameters for Al6061-T6

Johnson-Cook failure parameters from [129]	$d_1=0.071$, $d_2=1.248$, $d_3=-1.142$, $d_4=0.147$, $d_5=0.0$
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The J-C parameters are taken from literature [129] obtained through experimental work of impact test using projectile on to the plate with thickness of about 1 mm. The velocity of the projectile is low hence adiabatic temperature rise was not considered to be significant. The maximum temperature rise was found to be 279 and 247 °C in the case of blunt and hemispherical projectiles, respectively. The temperature rise is too low to cause significant softening of the material. Therefore parameter d_5 was considered to be vanishingly small [129].

5.2.3 Chip-Tool Interaction

The friction condition proposed by Zorev [131] is used in this model. The model is defined such that there are two regions at the tool-chip contact during metal cutting, sticking and sliding region. In the sticking region, the shear stress (τ_f) is constant and equal to the average shear flow stress; this region starts from the cutting edge area until a certain transition point (l_p). Sliding region occurs from this position onwards for the rest of the contact, until the chip leaves the tool. In this region, the shear stress reduces monotonically. Thus, the shear stress is determined as follows:

$$\begin{aligned} \text{Sticking region: } \tau_f(x) &= \tau_p \text{ when } \mu\sigma_a(x) \geq \tau_p & 0 < x \leq l_p \\ \text{Sliding region: } \tau_f(x) &= \mu\sigma_a(x) \text{ when } \mu\sigma_a(x) < \tau_p & l_p < x \leq l_c \end{aligned} \quad (5.3)$$

where $\tau_f(x)$ is friction shearing stress function, τ_p is the average shear flow stress at tool-chip interface, $\sigma_a(x)$ is the normal stress function, l_c is the transition zone, l_p is the tool-chip interaction and μ is the coefficient of friction. The parameters for the friction conditions are determined to be $\tau_p=300$ MPa and $\mu=0.25$ [38].

5.2.4 Heat Transfer

The heat generated in the metal cutting process originated from severe plastic deformation in the primary deformation zone and the friction in the secondary deformation zone [142]. The thermal properties values of the Al6061-T6 and SCD tool are listed in the Table 3-4 and Table 3-5. It is assumed that 90% of energy dissipated by plastic deformation is converted into heat [143]. This assumption is made because the Johnson-Cook plasticity model is motivated by high-strain-rate transient dynamic applications in which temperature change is generally computed by assuming adiabatic conditions (no heat transfer between elements). Hence, heat is mainly generated in an element by plastic work [125].

5.2.5 Model Validation

The model validation is conducted to determine the Johnson-Cook values to be used in the simulation of machining thin workpiece. The experimentally measured cutting force and thrust force values from the literature [139] of high speed cutting for Al6061-T61 are used for the validation of the J-C failure parameters values. The cutting conditions are shown in Table 5-3.

Table 5-3. Cutting conditions for model validation [139]

Tool materials	Rake angle	Width of cut	Depth of cut	Cutting speed
D2 tool steel	5.5°	10.1 mm	0.25 mm	30 m/s

The results of the validation using the J-C failure parameters from [129] reveal that the forces simulated match with the experimental results within an error, in cutting force of about 14.03% and thrust force of about 8.9% (Table 5-4). The force profiles extracted from the simulation, using Johnson-Cook damage

parameters from reference [129], are shown in Figure 5-2. However, failure is seen to occur at damage parameter (ω) value of 0.6 (and not 1.0). Based on this comparison the model is well validated and the failure parameters are reasonable to be used in the simulations.

Table 5-4. Johnson Cook damage model validation results

Cutting force experiment [139]	Cutting force simulation	Thrust force experiment [139]	Thrust force simulation
214.85 N/mm	184.70 N/mm	58.61 N/mm	53.39 N/mm
Deviation	14.03%	Deviation	8.90%

Figure 5-2. Cutting force profile (left) and Thrust force profile (right) vs. time using damage parameters from reference [129].

5.3 Simulation Results and Discussion

Figure 5-3. ABAQUS simulation for the chip formation process.

The application of shear failure parameters in this simulation is seen to produce a more reasonable chip formation with chip separation occurring in front of the tool without any separation line. The element in front of the tool fails after the element meets the shear failure criterion leading to chip formation. Figure 5-3 shows a steady state situation in one of the 3D orthogonal cutting condition simulated.

Once steady state in the cutting process is achieved, the maximum deformation is seen to occur in the shear zone extending from the edge of the cutting tool to the junction between the undeformed workpiece and the deformed chip, known as the primary deformation region. As the tool move towards the workpiece during the cutting process, stresses in front of the tool and perpendicular with the cutting direction are also generated. As the tool leaves the machined area, it leaves behind a deformed zone at the surface and subsurface.

Figure 5-4. Cutting force (left) and thrust force (right) for various ratio of E_w/E_s .

Force values are extracted from the simulation when the steady state cutting process is achieved (Figure 5-4). In general, the cutting force ranges between 4.07 to 4.79 N/mm and the thrust force between 0.94 to 1.11 N/mm. Both the cutting force and the thrust force values are widely diverged as the t_0/t_w increased especially for the $t_0/t_w = 0.5$ and 1. These force variations may occur due to the significant effect of the elastic modulus of the substrate especially when the workpiece becomes thinner. The cutting force and thrust force values are the lowest for the case of $E_w/E_s = 100$ when the t_0/t_w are 0.5 and 1. The lower substrate elastic modulus ($E_w/E_s = 100$) causing higher displacement due to the more compliant

properties of the substrate which affect the cutting process producing low value of forces.

The finite element model was validated using data in the literature [139] at larger depths of cut (0.25 mm). When the model was executed at smaller depths of cut (similar to experimental conditions described in Chapter 4), the specific cutting energy are diverged from 814 to 958 MPa (compared to a value of 856 MPa). The higher specific cutting energy for some conditions can be expected since the size effects are being capture in the model effectively; size effect refers to increase in specific cutting energy at lower depths of cut as observed and reported widely in the literature [144]. Hence, the fact the specific cutting energy is higher and different from that at validated conditions only enforces the strength and validity of the model adopted. The simulation results are expected to give good prediction of the stress trend and cutting mechanisms with the experimental conditions described in Chapter 3 and 4.

5.3.1 Loading from the Tool during Steady State Machining

Figure 5-5. Illustration of the location where the stress is extracted from the workpiece. The stress is extracted across the thickness of the workpiece from below the tool tip down to the bottom of the workpiece.

The stress parallel to the cutting direction (S_{11}) is extracted from below the tool tip down to the bottom of the workpiece (Figure 5-5). The stress distributions across the workpiece thickness at steady state condition for different ratio of depth of cut (t_0) to the machined workpiece thickness (t_w) are shown in Figure 5-6. The y axis representing the loading stress from the cutting tool on the workpiece is plotted using the same axis scale for the four graphs for ease of observations. The stress

induced by the tool on the workpiece in steady state cutting process is resembled to that observed during indentation loading in nano-indentation of thin film process. The x axis represents the distance from the machined surface (tool tip) until the bottom of the workpiece (interface with the substrate).

Figure 5-6. Stress profile parallel with the cutting direction across the workpiece thickness below the tool tip at steady state condition plotted for different E_w/E_s ratio at various t_0/t_w .

In general, the stress profiles are tensile near the tool tip for all the elastic modulus ratios and have the maximum value at the depth about 1 – 5 μm from the tool tip for all values of t_0/t_w . The stress profile across the thickness of the workpiece is likely to have a S-shape curve that varies from tensile near the tool tip and turn gradually to be compressive into the bottom workpiece with the turning point near the middle section when $t_0/t_w = 1$ especially for $E_w/E_s > 1$ (compliant substrate) (Figure 5-6 (a)). The $E_w/E_s = 100$ has the highest tensile stress at the depth of about 1.5 μm and has the most compressive stress at the bottom of the workpiece. The $E_w/E_s = 0.25$ has lower stress value and less stress profile variation across the thickness compared to other E_w/E_s especially when $t_0/t_w = 0.5$ and $t_0/t_w = 1$ (Figure 5-6 (a) and (b)). The significant different of the stress profile for $E_w/E_s =$

0.25 especially in $t_0/t_w = 0.5$ and $t_0/t_w = 1$ can occur due to the effect of the stiff substrate, in which the stress is not penetrated deeper into the substrate and eventually is dissipated. The $E_w/E_s = 31$ and 100 have the highest tensile stress near the tool tip but the $E_w/E_s = 31$ is the most compressive compared to other E_w/E_s especially on the bottom of workpiece (more compressive) when $t_0/t_w = 0.5$ (Figure 5-6 (b)). In the case of $t_0/t_w = 0.1$ and 0.0625, the stress values are relatively the same just below the tool tip and increased to be more tensile in the vicinity of the tool tip and turn gradually to be smaller toward the bottom of the workpiece (Figure 5-6 (c) and (d)). For $t_0/t_w = 0.1$ and 0.0625, the high tensile stress occurs down to the depth about 3 – 5 μm resulting in the ratio of the depth of deformation to the workpiece thickness are about 0.1, and 0.0625 for t_0/t_w of 0.1, and 0.0625 respectively.

5.3.2 Substrate Effects during Steady State Cutting Conditions

Figure 5-7. Displacement profile across the substrate at steady state cutting condition plotted for different E_w/E_s ratio at various t_0/t_w .

The observation of the substrate displacement during steady state cutting conditions just below the tool tip is important in order to understand the contribution of substrate elastic properties to the cutting mechanisms (Figure 5-7). Similar with Figure 5-6 the four graphs shown in Figure 5-7 are applied using the same y-axis scale for the displacement while the x-axis represented the distance from the interface.

In general, the displacement increases as the t_0/t_w and E_w/E_s increased. For the case of $t_0/t_w = 1$ and 0.5, the displacement increases as the E_w/E_s increased, and it is the largest at the interface and as going deeper it reduces to zero (Figure 5-7 (a) and (b)). In contrast, when $t_0/t_w = 0.1$ and 0.0625 the displacements are very small compared to $t_0/t_w = 1$ and 0.5 (Figure 5-7 (c) and (d)). In addition, it can be observed that for $E_w/E_s = 0.25$ displacement is very low compared to others especially when $t_0/t_w = 1$ and 0.5 due to the effect of the stiff substrate. The compliant substrate is seen to produce more displacement and furthermore influences the forces especially for thinner workpiece conditions ($t_0/t_w = 1$ and 0.5). This can be observed especially for the case of $E_w/E_s = 100$ where the forces are lower than for other elastic modulus ratios (Figure 5-4). While $E_w/E_s = 0.25$ (stiffer substrate) has much less displacement which shows no significant changes of the forces at different t_0/t_w ratios. The observations are similar to those observe in the nano-indentation of thin film where the film will sink-in if the substrate is compliant, whereas stiffer substrates enhance the plastic flow of the film [145]. The substrate properties are seen to have less significant effect on the cutting mechanism in the case of thicker workpiece conditions ($t_0/t_w = 0.1$ and 0.0625) shown by the low displacement, low stress values near the interface of the workpiece and substrate (Figure 5-6) and less varied forces values (Figure 5-4). In contrast, the high displacement, more variation of stress across the thickness and more variation of the forces indicate the substrate properties are affected significantly to the cutting mechanism in thinner workpiece conditions ($t_0/t_w = 1$ and 0.5).

5.3.3 Residual Stress Profile after the Tool Leaves the Workpiece

The analysis of the stress profiles after the tool leaves the workpiece is also conducted. Figure 5-8 shows the stress profiles across the workpiece thickness for

various E_W/E_S at different t_0/t_w after the tool leaves the workpiece. In general, the compressive stress presents in the machined surface implies that the mechanical or plastic deformation is more dominant in the process [146]. The residual stress profiles across the thickness of the workpiece shown in this condition represent the equilibrium conditions of the workpiece due to the effect of the substrates where the change of the shapes is accommodated by the substrate.

Figure 5-8, Stress profile parallel with the cutting direction across the workpiece thickness after the tool leaves the workpiece plotted for different E_W/E_S ratio at various t_0/t_w .

For the compliant substrate ($E_W/E_S > 1$) when $t_0/t_w = 1$, the stress profile is appeared to be an S-shape curve with the turning point around the middle section and the stress values are still in the compressive state across the thickness with the $E_W/E_S = 100$ having the largest stress range from the top to bottom surfaces (Figure 5-8 (a)). In contrast, the $E_W/E_S = 0.25$ has lowest compressive stress at the machined surface, turned to become more compressive toward the bottom of the workpiece. The stress values in the machined surface for all the E_W/E_S combination when $t_0/t_w = 0.5$ are higher compared to other combination of t_0/t_w . The stress gradually becomes tensile to the depth of about 2 μm and turn to be compressive

again toward the bottom of the workpiece for $E_W/E_S = 100$ when $t_0/t_w = 0.5$. For $E_W/E_S = 0.25$ the stress become more compressive as deeper into the subsurface and has less stress variation values. The small variation of the stress for stiff substrate will not significantly affect the final shape not only for the thick but also for thin workpieces after the workpiece released from the substrate.

Figure 5-9. Displacement profile across the substrate thickness after the tool leaves the workpiece plotted for different E_W/E_S ratio at various t_0/t_w .

The existence of the high compressive stress only occurs down to the depth of about 3 μm for $t_0/t_w = 0.1$ and 0.0625 for all E_W/E_S , and gradually decreases to become constant which is not significant compared to the thickness (Figure 5-8 (c) and (d)). Though the stress remains constant, the values do not reach zero for the case of $t_0/t_w = 0.1$ because there may be minor effect from the substrate. This profile is similar with the typical stress profile observed in the result of machining thick workpiece when plastic deformation is more dominant than thermal strain [27] and also the ratio of the depth of deformation to the thickness is not significant. However, the workpiece still possible to experience shape changes in the form of warping after it is released from the substrate especially for the compliant substrate.

This is due to the pre-stretch conditions of the compliant substrate when it is held by the substrate.

5.3.4 Substrate Effects after the Tool Leaves the Workpiece

In general, the displacements trends and values of the substrate after the tool leaves the workpiece are similar with those in steady state cutting conditions for all variation of t_0/t_w . Figure 5-9 shows the displacement profile across the substrate thickness after the tool leaves the workpiece for various t_0/t_w .

5.3.5 Discussion

Machining induced stress can influence the workpiece across the thickness and may reach the interface of the workpiece and the substrate in the thin workpiece. The high t_0/t_w and high E_w/E_s conditions have greatest effect on the machined workpiece especially in the combination when the $t_0/t_w = 1$ and the compliant substrate with the stress profile generally having wider range of stress values from the machined surface down to the bottom. Hence, these conditions, due to the large variation of the stress across the thickness, may produce larger deflection of the workpiece shape. In the case of lower thickness ratio, the less variation of the stress mainly due to the dissipation of the stress to other parts of the thicker workpiece condition. These effects are observed in both the stress at steady state cutting condition and the residual stress after the tool leaves the workpiece. Moreover, it can be seen from the simulation results that the stress is tensile in the machined surface under steady state cutting condition but turned to be compressive after the tool leaves the workpiece regardless the ratio of t_0/t_w and E_w/E_s . In the thicker workpiece, the depth of the loading from the tool is highly affected only down to about 3-5 μm below the machined surface. This is also seen in the residual stress where the high stress value only occurs down to the same depth which is insignificant to the thickness.

Upon releasing of the workpiece, the compliant substrate will elastically deform to its original shape and furthermore exacerbate the warping of thin workpiece in the form of residual convex shape due to the relaxation process of the substrate. Hence when the workpiece is released, the higher curvature will be

developed as the workpiece becoming thinner due to the higher residual strain of the substrate. Meanwhile, the stiffer substrate ($E_s > E_w$) produces less variation of the stress values across the thickness due to the stress dissipation by the stiff substrate. In general, the effect of the different elastic modulus is more obvious when the thickness ratios are 0.5 and 1. In contrast, the effect becomes less significant when the workpiece becomes thicker ($t_0/t_w \geq 0.1$). Although the residual stress profiles seen in the simulation show the high stress is observed only down to about 5 μm (less than half of the machined thickness) and the displacement is very small (Figure 5-9), these conditions still impacted on the warping of the workpiece which is seen in the experimental results described in Chapter 4 especially for the case of $t_0/t_w \approx 0.1$ and 0.06 (workpiece #5 and workpiece #7). Hence there are two mechanisms involved in the development of the warping: firstly, the depth of the residual stress and its profile, and secondly, the effect of the substrate. The small displacement experienced by compliant substrate can still induce warping even at thicker workpiece conditions.

In the application of the hot roller embossing, the thin embossing mold produced by machining can be attached to the cylinder roller by using suitable substrate. The workpiece conditions after the tool leaves the workpiece without releasing the boundary conditions seen in the simulation is similar to the attachment of the thin embossing mold onto the substrate (fixture) for the application of hot roller embossing where the mold is elastically bend onto the cylinder mold. The low stress value in the machined surface and narrow stress variations across the thickness seen in the thick machined conditions (low t_0/t_w) combined with low E_w/E_s is suitable workpiece condition to be applied for fabrication of thin mold because at this condition the workpiece is more rigid similar to that of conventional machining thick mold used for hot embossing mold.

5.4 Summary

In this chapter, a cutting model was developed with the application of proper damage parameters, i.e.: shear failure in the 3D setup model produces more realistic chip formation. The use of a predefined separation line and re-meshing method was thus avoided. The cutting force and thrust force values extracted from the

simulation are relatively comparable for the thick and thin workpiece and for different variation of elastic modulus, although as the t_0/t_w becoming larger the forces range is broader for different elastic modulus ratio due to the higher displacement experienced by the substrate. The stress profile is broader when $t_0/t_w = 0.5$ and 1 in steady state cutting conditions and after the tool leaves the workpiece implying that as the machined workpiece become thinner, the stress is more significant not only on the machined surface but also it reaches the bottom of the workpiece. The stiffer substrate produces less variation of the stress across the workpiece thickness while more compliant substrate produces broader stress variation. The small residual displacement in the compliant substrate and shallow residual stress can still induce warping. The results show a significant effect of the workpiece thickness and the influence of the substrate properties on the stress profile in the micro-cutting process and the warping of the thin workpiece.

In the view of the fabrication of thin mold, the narrow stress variations across the thickness seen in the thick machined conditions (low t_0/t_w) combined with low E_w/E_s are suitable conditions to be applied because at these conditions the workpiece is more rigid similar to the thick machined mold used for hot embossing mold. In addition, the low value and compressive state residual stress in the machined surface of the thin workpiece are favorable in thin embossing mold in order to avoid fatigue and stress corrosion cracking [83].

Chapter 6.

MICROSTRUCTURAL CHANGES IN THE MICRO-CUTTING OF THIN WORKPIECE

This chapter reports investigations in studying microstructural changes in the machined thin workpieces. The deformation induced by machining process can influence the microstructure not only in the surface of the machined workpiece, but through its thickness as well.

6.1 Introduction

Figure 6-1. Schematic view of the diamond face turning.

In this chapter, experimental trials using oblique cutting face turning (Figure 6-1) are conducted to study the microstructural changes of the workpieces with thickness less than 100 μm . In the previous chapters, it has been described that the orthogonal cutting setup has a limitation when using high depth of cut where the workpiece is easily to be peeled earlier at higher thickness. Therefore, the oblique face turning method is conducted in this experiment because it can avoid such a problem by minimizing the forces due to the movement of the tool and it can also achieve a higher depth of cut so that the final thickness and depth of cut is comparable and the effect of plastic deformation can to be significant. Even though

the diamond turning process introduces very little damage to the machined surface in the range from 1 to 17 μm for very sharp single point diamond tool, the final quality of the machined surface depends on the depth of cut [135].

6.2 Experimental Setup

Figure 6-2. Experimental setup of the face turning process.

The Single Point Diamond Turning (SPDT) machine, Precitech Nanoform 200 is used to study the machining of thin workpieces. The machine tool is equipped with an air bearing spindle with single rear mounted thrust plate. Rear mounting the thrust plate creates a higher radial stiffness at the spindle nose. The laser holographic linear encoder position feedback mounted to the axis slides provides 8.6 nm resolutions. The machine has a natural granite base to absorb vibration and produce high rigidity. The machine provides two axis of motion, the z and y axis. The tool moves in the z direction while the workpiece holder moves in y direction.

The machine has a vacuum chuck mounted on the spindle that has several coaxial circular grooves. The width of the each groove being 4.46 mm is used to hold the workpiece. The vacuum chuck can supply up to 0.935 Barr of vacuum pressure. The tool insert is secured to the tool holder and then fixed on a multi-component dynamometer (Kistler 9250) for force measurement (Figure 6-2).

6.2.1 Workpiece and Tool Materials

The workpiece is made of Al2024-T6 aluminium alloys and has an annular ring like shape. The workpieces were produced initially from a cylindrical aluminium rod which was parted to form a disc shape with a thickness of about 1 mm. The discs were subsequently machined by single point diamond turning on both sides and also reduced in thickness to about 800 μm . The disc was subsequently milled into 3 mm wide annular ring shape with outer diameter of 33.20 mm and inner diameter of 27.20 mm. Figure 6-3 shows the schematic view of the fabrication for the ring shape workpiece. The single crystal diamond (SCD) tool has a cutting edge radius about 1 μm , -2.89° back rake angle, 0° side rake angle, 29.65° side cutting edge angle and 15.5° clearance angle.

Figure 6-3. Schematic view of the workpiece fabrication.

6.2.2 Machining Parameters

In the case of face turning, the tool moves across the face of the workpiece. Hence, three forces exist in the process. The cutting force involved in SCD diamond face turning is relatively low. Thus, higher depth of cut can be used in order to get the significant effects of cutting process in the thin workpiece. The axial depth of cut in this case can be stated as high when compared to the final workpiece thickness of about 100 μm .

Table 6-1. Face turning parameters

Spindle speed (rpm)	1,000
Feed rate (mm/min)	20
Axial depth of cut (μm)	100

Initial experiments are conducted in order to get optimum feed and spindle speed which can produce good surface finish. In the face turning process the surface roughness is determined mainly from the feed and the tool radius. Preliminary trials

showed that the spindle speed of 1,000 rpm resulting in an average cutting speed of 1.58 m/s, produced good surface finish. In addition, a depth of cut (feed rate) of about 20 μm is used so that the final thickness of the work sample and depth of cut are comparable. The cutting process is conducted with a constant depth of cut, from an initial workpiece thickness of 800 μm to a thickness below 100 μm . The machining parameters are shown in Table 6-1.

6.2.3 Fixturing Methods

Figure 6-4. Illustration of the top view of the fixturing method for face turning process.

In this setup, the vacuum force is applied indirectly to hold the workpiece. A 40 mm diameter workpiece holder with the thickness of 9 mm was used to mount the workpiece onto the circular vacuum chuck. The workpiece is attached to the workpiece holder by applying a thin layer of Dymax® 6-621 UV curing adhesive. Figure 6-4 shows the illustration of the fixturing method for the face turning. The adhesive provides strong bonding and uniform forces to hold the thin workpiece. The adhesive can be removed relatively easy by dipping into an *acetone* solution.

6.3 Characterization Techniques

In order to compare the result of machining thin sheet, the characterization analysis is also conducted on a thick sample. The thickness measurement was conducted using a digital micrometer at eight different places for each workpiece of single point diamond turning. These samples were chosen with the intention of examining the effect of the workpiece thickness on the machining process.

6.3.1 Force Measurement

The forces involved in the SPDT are measured using multi-component dynamometer (Kistler 9250) attached to the tool insert. The dynamometer is

connected to micro-channel charge amplifier (Kistler 5070). The force data is collected using the DEWESoft 6.5 software. Three forces exist during face turning experiments namely feed force (F_x), cutting force (F_y) and thrust force (F_z).

6.3.2 Qualitative and Quantitative Analysis

Visual observation using Zeiss Axioskop2 Mat optical microscope is conducted in order to study the microstructure of the bulk workpiece, machined thick and thin workpieces. The cross section of the workpiece is observed under optical microscope. The specimen is cut, mounted, ground, polished and subsequently etched using *Keller's* reagent in order to reveal the microstructures. The Electron Backscattered Diffraction (EBSD) is conducted on the thick and thin machined samples. EBSD analysis mainly is conducted for phase and crystal mapping, crystal lattice orientation and strain measurement from the backscattered patterns [147]. In addition, EBSD is also used to obtain grain size data with their orientation which is not available using x-ray measurements. In this work, EBSD is used to enhance the microstructure seen in the optical microscope, to map the crystallographic orientation and to calculate the grain distribution and size in the range of the measured across the thickness.

The specimen analyzed in the EBSD is positioned inside the chamber so that it creates a small angle, typically about 20° between the incident electron beam and the specimen surface. This angle is needed in order to obtain sufficient intensity to be captured. When the beam in an electron microscope is directed onto a material, the electrons will be scattered due to the different lattice planes orientation in the specimen. Part of the backscattered electrons produce diffraction pattern which can be used for imaging purposes, for chemical composition determination, and for crystallographic analysis of the sampled volume [147]. The same samples used for microstructural analysis are also used for EBSD. In order to get better result, an oxide layer on polished surface samples is removed prior EBSD analysis using focused ion beam (FIB) mounted inside the SEM. The size of the EBSD scanned area is 13 μm wide x 70 μm high for the thin machined sample C and 10 μm wide x 70 μm high for the thin machined samples D and E. The thick machined sample is scanned over a larger area of 30 μm wide x 70 μm high, with the vertical direction

parallel with the machined workpiece thickness. Hence, the EBSD scanned area covers almost across the thickness of the thin machined samples. While for the thick machined samples the scanned area is nearer to the machined surface.

6.4 Results

Three thin samples with different final thicknesses, one thick sample produced by the face turning of thin workpiece and as-received bulk sample are selected for microstructural and EBSD analysis. The bulk sample is identified as sample A. The thick sample is machined under same conditions as the thin samples and identified as sample B. The three thin samples are identified as sample C, sample D and sample E with the average thickness of 102 μm , 97 μm and 72 μm respectively (Table 6-2).

Table 6-2. Final thickness and thickness ratio of the thin machined samples produced by single point diamond turning

Sample Name	Depth of cut (t_0) (μm)	Final thickness (t_w) (μm)	Ratio (t_0/t_w)
Sample B	100	295	0.34
Sample C	100	102	0.98
Sample D	100	97	1.03
sample E	100	72	1.39

The un-machined and the machined thin workpiece sample are shown in Figure 6-5. The thin annular ring machined is seen to have uneven shape due to the high deformation after released from the fixture.

Figure 6-5. The un-machined (left) and the machined (right) of the thin workpiece sample.

6.4.1 Force Measurements

The forces are constant as the thickness reduces from thick to thin as shown in Figure 6-6. The force that is used in the data is taken when the signal has reached steady state. The cutting force is about 3.21 Newton, the thrust force is about 0.56 Newton and the feed force is about 2.71 Newton. The force measurements prove that the Dymax® 6-621 UV curing adhesive has good potential to hold the thin workpiece in the diamond face turning process.

Figure 6-6. Forces at different thickness for the face turning at a fixed depth of cut of 100 μm.

6.4.2 Qualitative Microstructure Analysis

The qualitative analysis of the microstructure and lattice planes are conducted using optical microscope (Figure 6-7 - Figure 6-10) and electron backscattered diffraction (EBSD) (Figure 6-11).

Figure 6-7. Micrograph of the cross section view of (a) sample A (bulk rod un-machined) and (b) sample B (thick machined sample) at 200x.

The observation of the as-received (un-machined) Al2024-T6 (sample A) revealed a rich set of elongated grains structure parallel with the rod axis due to the drawing process in the manufacturing of the rod (Figure 6-7(a)) with the average length of the grains is longer than 350 μm . Some black discs like structures which are typical of Al_2CuMg precipitate are also observed in the microstructures similar to that appearing in the common microstructures of Al2024-TXX alloys [148].

Figure 6-8. Micrograph of the cross section of the sample C (average thickness is 102 μm) at 200x.

The same microstructures are also observed in the thick machined workpiece (sample B). There are no changes of microstructure on the surface and in the vicinity of the machined surface (Figure 6-7(b)). The micrograph revealed the same elongated grains structure parallel with the rod axis and perpendicular to the machined surface with some black discs like structures. The lattice planes are dominated mainly by (111) and (101) planes with no significant sign of (001) plane (Figure 6-11).

Figure 6-9. Micrograph of the cross section of the sample D (average thickness is 97 μm) at 200x.

The visual observations of the micrograph across the thickness of the machined thin samples show a significant change of the microstructures compared to that of the machined thick sample (sample B) as well as the bulk rod (sample A) (Figure 6-8 - Figure 6-10). In general, the microstructures of the thin samples become more random, denser, and finer with the shape of the grains less elongated as compared to the bulk and thick machined sample with some black discs like structures are also remain randomly distributed. In addition, the grains in the thin machined samples are seen to have different grain orientation with the thick sample indicating the presence of grains misorientation (Figure 6-11).

Figure 6-10. Micrograph of the cross section of the sample E (average thickness is 72 μm) at 200x.

Sample C has slightly different microstructure compared to sample D and E with the presence of partially refined grains and dominant amount of large grains but not elongated such as sample B. The mixture between finer and larger grains generally observed in the materials experiencing partial dynamic recrystallization due to the large strains and high temperature [109]. The grains are observed dominantly having (001) and (111) lattice planes.

Sample D consists of skewed grains with respect to the rod axis and thickness. The grains are observed to be finer, less elongated and also more uniform compare to sample C and the lattice planes are also seen to be more random. The grains in sample E are finer and less elongated compared to the thick sample and other thin samples with the presence of (001), (111) and (101) lattice planes. Most of the smaller grains are seen to be having lattice plane close to (001).

Figure 6-11. EBSD images across the thickness of the samples represent the grains size distribution with the orientations.

6.4.3 Quantitative Analysis of Grain Size

The analysis of the grain distribution is conducted using Electron Backscattered Diffraction (EBSD). The grains distribution is observed to be more visible as compared to the optical microscope results and the grains lattice plane can be indicated from the grains color. It can be observed from Table 6-3 and Figure 6-12 that the average diameter of thick machined sample (sample B) is the biggest compare to thin samples with grain sizes as large as 32 μm . In contrast, the thin machined samples have significantly narrow range of grain diameter with the biggest diameters only up to about 17 μm , half of largest grain diameter of the thick machined sample. For a given area of observation, samples D and E have more number of grains as compared to sample B (thick sample) and sample C. These two samples also have a smaller average diameter of the grains with the size about 3.49 and 3.81 μm respectively. While sample C ($t_0/t_w = 0.98$) has less number of grains

compared to sample B but the average diameter is smaller with a size about 5.55 μm .

Figure 6-12. Grain diameter distributions of the thick and thin machined samples.

Table 6-3. Grain size range in machined thick and thin samples

Sample	t_0/t_w	Range of grain diameter (μm)
sample B	0.34	0.65 – 32.17
sample C	0.98	2.28 – 17.58
sample D	1.03	0.61 – 12.37
sample E	1.39	1.18 – 15.62

6.4.4 Shear Strain and Cutting Temperature in the Shear Plane

The microstructural observations show the existence of the refined grains in the thin workpieces across the thickness indicating that the effect of deformation more severe than that seen in a thick machined workpiece. The finer grain size especially in the vicinity of the machined surface can be induced by mechanical deformation due to the high strain and possible large heat generated mainly in the primary deformation zone. However, it is difficult to directly measure the

temperature rise in the cutting process especially in the shear zone though several researchers have attempted to do it with most focusing on the temperature in the secondary deformation zone.

The mean temperature in the shear plane in the workpiece side ($\overline{\theta}_s$) can be calculated using metal cutting concepts explained in [18], such as:

$$\overline{\theta}_s = \frac{(1 - R_1)u_s}{C_1\rho_1} + \theta_0 \quad (6.1)$$

where θ_0 is the ambient workpiece temperature, R_1 is the fraction of the heat which leaves the shear zone with the chip, u_s is the shear energy per unit volume of metal cutting, C_1 is specific heat of the workpiece and ρ_1 is the density of the workpiece. The detail development of equation (6.1) is explained in Appendix F. The calculated oblique cutting tool geometry and cutting parameters are shown in Table 6-4. The chip thickness is about 0.023 mm measured using SEM.

The cutting temperature and the heat fraction are calculated iteratively to account for the temperature dependent thermal properties of the Al2024-T6. From the calculations it is found that R_1 is 0.26; the large fraction of heat going into the workpiece is mainly because of the low Peclet Number (N_{Pe}) of about 0.42 [149]. This results in a temperature raise in the vicinity of the shear plane on the side of the workpiece ($\overline{\theta}_s$) of 523 °C using thermal properties obtained from [150] for this alloy (Table 6-5).

Table 6-4. The calculated cutting tool geometry, cutting parameters and measured machining forces

Normal rake angle (α_n)	-1.43°
Normal shear angle (ϕ_n)	40.39°
Shear flow angle (η_s)	-0.24°
Shear strain (γ)	2.07
Feed force (F_x)	2.71 Newton
Thrust force (F_z)	0.56 Newton
cutting force (F_y)	3.21 Newton

Table 6-5. Thermal properties of Al 2024and Peclet Number [150]

Conductivity (k_1)	193 W/m K
Specific heat (C_1)	0.95 J/g °C
Density (ρ_1)	2.75 g/cc
Thermal diffusivity (K_1)	73.88 mm ² /s
Peclet Number ($N_{Pe} = \frac{vt}{K_1}$) [149]	0.42

The temperature raise in the shear zone calculated using this method is rather high ($>0.5T_m$). However, the temperature calculated using this method is reported to be overestimated by about 35% [151]; hence the shear plane temperature is likely to be closer to about 387 °C – this is lower than typical annealing temperatures for this alloy [152]. Besides this, Komanduri and Hou [149] argued that the cutting temperature during ultra precision machining of aluminium using single crystal diamond tool, with Peclet Number (N_{pe}) of about 0.5 (close to 0.42 for our cutting conditions), at a cutting speed of 8.63 m/s is only about 120 °C, while Stephenson [151] measured the cutting temperature of Al2024 at the shear zone is around 150 °C for cutting speeds in the range of 0.88 to 3.91 m/s (1.58 m/s is our cutting speed in comparison). Thus, both analytical calculations and experimental measurements from literature indicate that temperatures are likely to be low. In addition, the fact that the refined grains are observed only in the thin machined samples and not observed in similarly machined thick samples point to the conclusion that thermal effects cannot be a dominant factor in the grain refinement observed.

The other factor that can cause grain refinement is severe mechanical deformation. The shear strain in primary deformation zone (γ) is calculated to be about 2.07, a fairly severe one. But, can such strains occur close to the machined work surface? It has indeed been shown that the plastic strain levels in the near machined surface are quite large and approaching those of the levels in the chip [153]. Shankar *et al.* [154] observed the formation of dislocation activity extended far from the primary deformation zone as an indication of substantial sub-surface damage on the machined workpiece. The large strain in the machined surface can reach down to about 100 μm deep and gradually decreases with depth into the subsurface. Mechanical grain refinement has been reported in other contexts. Prangnell *et al.* [155] argued that for a strain of less than 2 submicron grains can be generated from coarse grain by the formation of new high angle grain boundary in the Equal Channel Angular Extrusion (ECAE) of aluminium alloys. The rate of grain refinement is much increased in the aluminium alloys at strains close and above 2 with transverse high angle grain boundaries [156]. In addition, Kabyshev *et al.* [157] observed formation of subgrain structure with a strain about 2 in severe

plastic deformation of aluminium alloys at temperature 250 °C. The negative rake angle and larger depth of cut cutting conditions used in this study produce thicker deformed layer in the machined surface and greater levels of strains in the chips [153] which furthermore can create refined grains in the form of equiaxed grains in the chips [109]. The strain experienced by each grain is varied due to the different crystallographic orientation in the polycrystalline materials and produced different orientation of the grains [158].

6.5 Discussions

In machining thick samples, the heat and high strains could be distributed and dissipated deeper into other region of the machined workpiece while the high strains in the shallow and confined (reduced cross section) deformation zone in thin machined may promote shear localization and this can act as an grain refinement mechanism similar to the ECAE process [155]. The machining process induces severe plastic deformation through the thickness of the machined thin workpiece due to the higher ratio of the depth of cut to workpiece thickness. Hence, we argue here that the mechanical deformation is more dominant and is the cause of the change of microstructure across the thickness of the thin workpiece. Thermal effects are expected to have only a minor influence, because the magnitude and duration of the heat in the shear zone is not sufficient enough to cause refinement. Apparently, with the same cutting conditions, grain refinement did not occur in thick machined sample.

6.6 Summary

In summary, the machining of thin work materials using diamond face turning method generates microstructural changes in the form of grain refinement through the workpiece thickness and modifies the grain orientation. The microstructures of machined thin workpieces become more random, denser, and finer with the shape of the grains less elongated as compare to the bulk and thick machined sample. These changes are induced by significant plastic deformation in the form of localized large strains experienced by the thin workpiece. The magnitude and duration of the heat due to the temperature rise in the shear zone is

shown to have a smaller effect in the grain refinement of the machined thin workpiece. From this study, there is a possibility that under controlled conditions the severe plastic deformation in machining can not only be produced in the chips [108] but also in the machined workpiece with a ratio of the depth of cut to the machined thickness about 1 ($t_0/t_w \approx 1$). Hence, fine grains may also be produced in machined work material similar to that produced in the chips using the reported Large Strain Extrusion Machining (LSEM) process [109] where the chip thickness is controlled in order to get certain grains size and grains properties.

Chapter 7.

BURRS REDUCTION IN MICRO-MILLING ALUMINIUM ALLOYS

This chapter describes efforts in reducing the burrs, an unexpected by product during micro-milling of ductile materials such as aluminium alloys. A novel way of reducing burrs is explored here with the use of tapered micro-milling tools. The results from investigations using this method are described below.

7.1 Introduction

Increasing the rake angle is one of the techniques of burr reduction [74]. Larger rake angles reduce the deformation in the chip and work surface ahead and below the tool and can significantly affect the burrs formed. It has been shown using finite element models that an increase in rake angle causes the burrs to be initiated later, when the tool gets closer to the edge, and the pivot point, that causes bending of the chip, occurs closer to the workpiece surface [74].

Figure 7-1. (a) Exit angle reduced the formation of exit burrs (b) Can similar edge strengthening can be used to reduce the top burr formation in micro-milling a slot?

Another way to minimize burrs is by changes in part design features that prevent burrs from forming during micro-milling. One such way to reduce the burr

formation is by providing better resistance to the plastic deformation closer to the edges; this can be accomplished by strengthening the edge of the surface where the cutting edge will exit or where the material (in the form of a chip) is expected to tear away. This strengthening in-turn can be achieved by increasing the edge angle, normally 90° , to a higher angle; the edge angle is the angle between the machined surface and the intersecting free surface at which the tool exits (Figure 7-1).

Increasing the edge angle, also called exit angle, has been reported [63, 74] to minimize the exit burrs in orthogonal cutting. It is reported that no burrs are formed at exit angles close to 150° . Using finite element simulations involving five different exit angles it has been shown by Park and Dornfeld [74] that higher exit angles reduce burr formation by initiating burr pivoting as the cutting tool edge reaches closer to the edge closer to the machined surface. In addition, high exit angles favor tool chipping reduction by reducing the impact loading that the tool experiences upon exit. It is also obvious that at exit angles greater than 90° the edge is now, in some sense, stronger and more resistant to deformation.

Figure 7-2. (a) Stages of burr formation for lead angle of 16° , 66° , 81° (top to bottom respectively) [159] and (b) Burr dimensions vs. tool lead angle in turning of Al6061-T6 [159].

The effect of the edge angle has also been studied in the turning process [159]. Increasing the initial edge angle (created by the combination of the workpiece angle and tool angle) while turning Al6061-T6 work material using tungsten carbide tool produces smaller size burrs. The increase in workpiece angle will increase rigidity of the workpiece leading to a significant decrease of burr

height for every lead angle, and at a certain value the burr is seen to disappear (Figure 7-2 (a)). They argued that the increasing of the workpiece angle reduces bending but increases *poisson* effect (lateral flow of material under normal pressure). In addition, the workpiece angle variation also changes the direction and the depth of the plastic deformation. An increasing of the tool rake angle and tool lead angle (Figure 7-2 (b)) can also reduce the burr thickness and height. The tool rake angle and tool lead angle of the turning tool are shown in Figure 7-3.

Figure 7-3. Illustration of the tool lead angle (left) and tool rake angle (right) of the turning tool

The focus of burr reduction has been more on exit burr formation rather than other burrs such as top burrs formed in micro-milling. Exit burrs are formed mainly by the tool exiting action and do not have the side bulging action of a *poisson* burr nor the chip flow action leading to tearing. The top burrs formed in slot micro-milling, while do not have the tool exiting action, have components of both the *poisson* burr and the material tearing action by the flowing chip. In addition, the effect of reducing chip thickness in the up milling side also effects the top burrs formation due to additional ploughing action caused by the minimum chip thickness effect. Hence, the fundamental way in which the top burrs are formed is different from the way in which the exit burrs are formed. The effect that edge angles have on this type of burr formation needs to be investigated. There are some studies of the effect of rake angle in the burr reduction in the simulations of orthogonal cutting [74] and experiments of turning [159]. However there are no studies reporting efforts in reducing the top burr formation via edge strengthening or rake angle increase in the milling process especially micro-milling. This is the main motivation of this chapter.

In this chapter, a fundamental study of the effect of edge strengthening by increasing the edge angle on the side walls of a micro-milled slot is conducted. The edge strengthening is provided in two ways: one by changing the workpiece surface geometry and two by introducing a taper in the micro-milling tool; various side edge angles are studied. Micro-milling experiments are conducted to create a slot and the resulting burr formation studied qualitatively in a scanning electron microscope and the burr height measured quantitatively using surface profiler. Trends in the top burr formation are analyzed and effort is made to explain the observations by comparing literature explanations and also by an analysis of the geometry of the tool.

7.2 Experimental Method

Micro-milling experiments are conducted to produce slots using a 3-axis machining centre (Mikrotools multiprocessing machine DT110). The channels were manufactured by slot micro-milling process using tapered end-mill (with a bottom diameter of 0.5 mm) of carbide milling tool. The work material used is aluminium alloy Al6061-T6. The cutting tools are two flute end mills made of super micro grain carbide (NS Tool Co. Ltd., Japan) (Figure 7-4).

Figure 7-4. Milling tool, from left to right: 15°, 30°, 40° and 50° tapered tools.

Table 7-1. Experimental conditions

Workpiece	Al6061-T6
Milling tools	Super micro grain carbide tool 0.5 mm bottom diameter tapered tool with 15°, 30°, 40° and 50° angle taper
Slot micro-milling	
Feed rate	25 $\mu\text{m}/\text{rev}$
Depth of cut	25 μm
Spindle speed	10,000 rpm
Cutting condition	Dry cutting

The experimental conditions are shown in Table 7-1. Micro-milling of slots under dry conditions is undertaken at a spindle speed of 10,000 rpm and a feed rate 25 $\mu\text{m}/\text{rev}$ resulting in a cutting speed of 261 mm/s. The choice of these cutting conditions is similar to that reported in the literature. Mecomber *et al.*[7] used a lower cutting speed of about 106 mm/s to successfully remove the material left at the intersection of the micro-features channel using a 102 μm diameter end mill with a spindle speed of 20,000 rpm when creating embossing molds made out of aluminium alloys. A spindle speed of 10,000 rpm has also been used by Vázquez *et al.* [160] when investigating the influence of milling process parameters on the dimensions, geometrical feature and surface finish quality on the micro-milling process of aluminium alloy. Furthermore, they used smaller tool diameter of about 0.2 mm. In addition, it is expected that such cutting conditions can be applied, to reduce the burrs, when micro-milling using conventional CNC machines that operate at reduced spindle speeds of less than 10,000 rpm.

Figure 7-5. Work, tool and edge angles.

Table 7-2. Taper angle, workpiece angle and side edge angles

No.	θ_T	θ_w	θ_{Edge}
1	15	200	125
2	15	165	90
3	15	130	55
4	30	185	125
5	30	150	90
6	30	115	55
7	40	175	125
8	40	140	90
9	40	105	55
10	50	165	125
11	50	130	90
12	50	95	55

Slots are produced at three different side edge angles, θ_{Edge} , between the side wall and the top surface (Figure 7-5) namely, 55° , 90° and 125° ; note that this range represents acute, right and obtuse angles. These various edge angles were produced through a combination of workpiece geometry variations and taper angles in the micro-milling tool. The tool taper angle, θ_T , is varied from 15° through 50° with the bottom diameter of 0.5 mm, while the workpiece side angle, θ_w , was varied from 95° through 200° . Different combinations of workpiece side angle and taper angle will provide different side wall edge angles as shown in Table 7-2. The total depth of cut of the slots is about 100 μm .

The micro-milled slots and micro-channels are observed under an SEM (JEOL 5600L) to qualitatively study the nature of the burrs formed and the burrs height are measured quantitatively using Taylor Hobson Precision Talyscan 150 surface profiler using a mechanical stylus probe. A line scan of the cross section of the wall and the floor of the slot micro-milled is taken using the mechanical stylus probe providing a 2D plot including the side wall and the slot floor surface. The burr height is then measured as the excess material at the edge of the side wall protruding above the original surface.

7.3 Results

7.3.1 Effect of Side Edge Angle

The SEM micrographs for 55° , 90° and 125° representing acute, right and obtuse angles for each of the taper angle is shown in Figure 7-6. The effect of the side edge angle is clearly seen in Figure 7-6. Each SEM micrograph shows a top view of the milled slot with the two lines in the centre depicting the slot edges. The top burrs can be seen on these edges. It is clear from these micrographs that the down milling side of the slot edge (the top edge) has greater burrs than the up milling side (bottom edge). It can be seen that the micro-slots created by 15° taper tool regardless of the side edge angle exhibit severe burrs size. There is no significant change of the burr size as the machined edge angle become larger. The same trend is seen in the 40° taper tool. The size of the burrs at the side edge angle is relatively comparable between the three edge angles. However, for the case of 30° taper tool angle, the burrs are visually seen for the 55° and 90° while there are

practically no burrs observed with a side edge angle of 125° . Similar trend is also observed for the case of 50° taper tool.

Figure 7-6. Summary of qualitative observation of burrs using an SEM.

7.3.2 Effect of Tool Taper Angle

Figure 7-7. Effect of increasing taper angle at a constant side edge angle 90° .

The effect of the varying the taper angle when the edge angle is a constant value of 90° can be seen from Figure 7-7 (the micrographs are different from Figure 7-6). This side edge angle is chosen for comparison since this is typically seen in most micro-milling situations where tapered micro-milling tool is not used. At a taper angle of 15° , the burrs are very large. As the taper angles increases the top burr sizes are seen to notably reduce with the 50° taper angle tool producing the smallest burr. In addition, observation of the effect of the taper angle variation when the acute and obtuse edge angles are also showed similar trend as the 90° edge angle (Figure 7-8), as the taper tool angles increases, the top burrs size become smaller.

Figure 7-8. Effect of increasing taper angle at a constant side edge angle 55° (left) and 125° (right).

Researchers have reported in the literature that increasing the rake angle of the tool reduces burr size in orthogonal cutting [74]. Milling is a complex oblique cutting process and in order to understand rake angle effects, we discuss here the effect of taper angle on the various rake angles in a complex cutting tool. In an oblique cutting process, there are three rake angles that can be considered: velocity rake angle (α_v), normal rake angle (α_n), and effective rake angle (α_e) as shown in Figure 7-9.

The velocity rake angle or true rake angle (angle COF) is the angle measured from a normal to the finished surface in a plane containing the cutting velocity vector (plane OCED). The normal rake angle (angle COG) is the angle measured from normal to the finished surface in a plane perpendicular to the cutting

edge (plane OABC), while the effective rake angle (angle COH) is the angle measured in the cutting velocity vector and chip-flow direction [18].

Figure 7-9. Oblique view (left) and top view (right) of the oblique cutting model.

There is considerable difference of opinion as to which rake angle is the key to understanding the oblique cutting process. According to some researchers [18] the effective rake angle (α_e) plays the same role in oblique cutting as the rake angle in orthogonal cutting. Some researchers [161] have argued that the normal rake angle is the critical angle that affects the mechanics of oblique cutting process especially the force component parallel to the cutting direction and the specific cutting energy. Alternatively some others [162] have argued that the velocity rake is the angle which determines cutting performance and is a compound angle of side rake, back rake and side cutting edge angle in turning process or a compound of axial rake, radial rake and corner angle in the milling process. Here we calculate all these rake angles and study their trends to understand the effect of tool geometry on the burr formation.

The velocity rake angle is calculated as follows [162]:

$$\tan \alpha_v = \tan b \cdot \sin c + \tan s \cdot \cos c \quad (7.1)$$

where b is back rake, s is side rake and c is the corner angle. The normal rake angle can then be expressed as follows [18]:

$$\tan \alpha_n = \tan \alpha_v \cdot \cos i \quad (7.2)$$

where i is the inclination angle. In the plane milling process, the inclination angle generally is the same as the helix angle of the face milling tool [18]. However in this case, the milling tool is tapered, and also the milling tool diameters (0.5 mm) are significantly larger than the axial depth of cut (0.1 mm). Hence, this is different from the plane milling process where the diameter is smaller compared to the axial depth of cut. Hence, the chip formation at the bottom cutting edge of the tool is significant. Hence, the inclination angle is calculated as [162]:

$$\tan i = \tan b \cdot \cos c - \tan s \cdot \sin c \quad (7.3)$$

For a tapered milling tool b can be replaced with the axial rake (this is same as the instantaneous helix angle, β), s can be replaced with radial rake (r) and c can be replaced with the taper angle (γ). Assuming Stabler's rule that the chip flow angle is same as the inclination angle, the effective rake angle can then be calculated as [18]:

$$\sin \alpha_e = \sin^2 i + \cos^2 i \cdot \sin \alpha_n \quad (7.4)$$

Figure 7-10. Side view (left) and bottom view (right) of the tapered milling tool geometry.

The instantaneous helix angle (β) and the radial rake angle (r) are measured on the tapered tool using an SEM image and an image manipulation program. The instantaneous helix angle (β) is the angle between the tool axis rotation and the projection of the cutting edge at the bottom end of the tool and perpendicular to the machined surface measured on the side view of the tool. The radial rake angle is the angle between the rake face and the centre line connecting two edges measured from the bottom view of the tool. The three angles are schematically shown in Figure 7-10.

Table 7-3. Measured instantaneous helix angle and radial rake, and calculated rake angle

Taper angle (γ)	Instantaneous helix angle (β)	Radial rake angle (r)	Inclination angle (i)	Velocity rake angle (α_v)	Normal rake angle (α_n)	Effective rake angle (α_e)
15	20	0	19.37	5.38	5.08	10.88
30	27	8.1	20.31	20.71	19.52	24.48
40	28.5	2.4	21.26	20.86	19.55	24.97
50	26	11.63	8.86	26.84	26.56	27.40

In this analysis all the three rake angles are determined to study how they vary with increasing taper angle. The measured instantaneous helix and radial rake angle along with the calculated inclination, velocity, normal and effective rake angles for the milling tool used in the experiments are shown in Table 7-3. As evident from the table, the calculated velocity, normal and effective rake angles all increase with an increase in the taper angle. Thus, we can see that the increased velocity normal and effective rake angle play an important role in reducing the burrs for a given side edge angle.

7.3.3 Burr Height Quantification

Figure 7-11. Illustrating burr height calculation from surface profile trace.

A sample profile trace and burr height determination is shown in Figure 7-11 for the case of edge angle of 125° . The sloping surface on the right is the top surface of the workpiece. The flat line on the left side is the bottom of the milled slot. The burr appears as a hump on the edge; the shape of the hump is an artifact of the mechanical probe shape. Nevertheless, the height of the burr is still accurately captured by such a trace.

The burr height values obtained are plotted in Figure 7-12. The burr height measurement result shows similar trend as the SEM observations. As noted in

Figure 7-12, burr height decreases as the side edge angle increases and as the taper tool angle increases, especially for the case of 55° and 90° side edge angles. The 15° taper tool has significantly larger burr as compared to other taper angle tools for all side edge angles. In contrast, the burr height is lower for the case of 30° , 40° and 50° taper tool when the side edge angle is 125° which is also comparable with the 40° and 50° taper tool when the side edge angle is 90° . Thus both side edge angle and taper angle are seen to affect the top burrs formed.

Figure 7-12. Burr height vs. taper tool angle at different side edge angle.

7.4 Discussion

As discussed previously there are three important factors to consider for the top burr formation, particularly at the down milling edge: (a) the material tearing effect as the chip flows out, (b) *poisson* burr effect – this refers to bulging of the material, and (c) the minimum chip thickness in conjunction with the edge radius of the tool – down milling causes the chip thickness to reduce to zero as the edge finishes the cut. The effects of each of these vis-a-vis the side edge angle needs to be analyzed to explain the results observed. The material tearing effect and its relation to the side edge angle can be understood in context of literature studies on the effect of exit angles on burr formation [74]. There is an important difference however: the tool does not exit the edge in our case. Nevertheless, the ductile fracture growth as the chip separates from the bulk material, and its interaction with

the side edge can be considered similar to the case of the exit angle study. The side edge angle strengthens the edge and hence causes the pivot point of the bending of the burr as the chip flows out to come closer to the surface and hence the reduction in burr as the chip breaks out. The *poisson* burr effect and associated bulging of the material can be considered in the context of conical indentation and the strains and pileup associated with this process. It is noted here that machining has been considered by many researchers as a wedge indentation process [163]. In a study done with varying conical indenter angle [164], it was reported that experimental and finite element simulations indicated strains to be much higher when the conical angle of the indenter was low and it was also highly localized close to the indenter surface. When the conical angle was increased the strain magnitudes dropped but the strain distribution was deeper into the surface. Such increase in strain causes more plastic deformation at the lower side edge angle leading to higher deformation at the edge where the burr is formed.

The effect of the chip thickness reaching down to zero in the down milling cut has to be analyzed from a context of ploughing caused by a finite edge radius and the associated minimum chip thickness. In the experimental conditions considered for this work, the edge radius and associated ploughing effect is considered negligible but the minimum chip thickness effect will be present. It is well known [20] that for each material and cutting conditions, there is a certain value of chip thickness below which the cutting does not occur, and the tool merely pushes the material. Such ploughing of the material close to the finish of cut will cause an effect similar to the indentation and *poisson* burr discussed previously. Hence, a larger side edge angle will tend to diminish these effects, and hence results in a smaller burr. In addition, the formation of the top burrs in the micro-milling process might be induced by the compressed material around the edge between the floor and the sidewall of the slot [38]. In this recent simulation-based work, the authors argued that the compressed material plays a large role in top / side burr formation in micro-grooving of an aluminium alloy. Their finite element study shows that material on the sidewall begin to get pushed sideways below the burr, which causes it to be squeezed upward and increase the height of the burr. The compression is attributed to the high stress concentration induced by the edges

formed where the chip separates from the workpiece and where the sharp side edge of the tool meets the workpiece. Similarly, the high stress is also likely to occur around the edge between the floor and the sidewall of the slot in the micro-milling process due to the multiple cutting actions from the micro-milling tool. The stress concentrated around the edge is influenced by the angle of the edge. The various edge angles in the slot are produced by various taper micro-milling tools; higher angle will have less stress as compared to the smaller angle and furthermore reduce the amount of compressed materials. Hence, smaller edge angle tend to produce larger burrs.

7.5 Summary

A study of the reduction of the top burrs in the micro-milling process is presented in this chapter. Both side edge angle and taper angle were seen to affect the top burr formation; a combination of largest taper and largest side edge angle produced the smallest burr. As the side edge angle increases, the top burrs reduced at all taper angles; this effect was seen to be more prominent at larger taper angles. Hence it is concluded that the side edge angle strengthening affects top burr formation. Analogies with exit angle burr studies, conical indenter studies, and recent related finite element simulation studies in literature help come to a conclusion that higher side edge angle can effectively help in reducing the burrs. As taper angle increases, the top burrs are seen to reduce significantly; the taper angle is seen to affect the velocity, normal and effective rake angle of the tool, with higher taper angle tools having a higher effective rake. This can explain the formation of smaller burrs at higher taper angles. The use of a tapered tool is thus a possible technique to avoid top/side burrs in micro-milling. Even though this was tested only in thick workpieces, similar burr reduction efforts are expected even in thin workpieces. Confirmation trials to check this are reported in Chapter 8.

Chapter 8.

FABRICATION AND TESTING OF THIN EMBOSSING MOLD MADE USING MICRO-MILLING

This chapter reports attempts in fabricating a thin embossing mold for microfluidic devices using the micro-milling process. The molds of two different thicknesses are manufactured and subsequently embossed onto a polymer sheet (PMMA). In addition, application of the taper micro-milling tool is also studied in order to create micro-features at three different workpiece thicknesses. The study draws upon the lesson learnt from the fundamental investigations reported in the earlier chapters, specifically the thickness of the adhesive and mold thicknesses chosen.

8.1 Introduction

In the first part, thick and thin embossing molds are produced using micro-milling process and subsequently used to produce PMMA microfluidic devices. The thick mold will be used on a conventional hot embossing process while the thin mold will be used on hot roller embossing process. Aluminium alloys is used as the embossing mold material due to its strength, availability and cost. As in the previous discussions, the adhesive will be used to hold the thin workpiece in the fabrication of thin mold and the mold subsequently will be used for hot roller embossing applications. Hence, the objective of this work is to understand the thin mold fabrication using micro-milling, hot roller embossing and measurement methods related to the fabrication of embossing molds. The observations in this study will be focusing on the mold quality and the surface finish of the milled parts and feature edges.

In this chapter, the application of the tapered micro-milling tools is not applied directly to produce the complete molds nevertheless in the second part; the use of a tapered end-mill is conducted to reduce burr formation in the specific

micro-features for different workpiece thicknesses. This work is needed to be conducted especially for ductile materials using carbide tools, to confirm that use of tapered tool can solve the burr problems during fabrication of thin embossing mold using micro-milling. Micro-channels that represent common features in microfluidic devices are used as the experimental feature to be produced by slot end-milling. Such use of a tapered milling tool necessitates a design change in the device since the walls of the microfluidic channels are no longer perpendicular to the channel top surface (or the channel floor). Microfluidic channels with angled walls are reported in the literature [48], where the embossing molds were made in Silicon by wet-etching. The etched plane preference causes sloped walls in the Silicon channels. It is reported that such sloped walls result in better mold release and hence lead to better embossed features; also the edges are now stronger resulting in less edge breakage.

8.2 Experimental Method

Fabrications of the embossing molds consisting of micro-features that are conducted using a 3-axis machining centre (Mikrotools multiprocessing machine DT110).

8.2.1 Fabrication of Thick and Thin Embossing Molds

Figure 8-1. Micro end mill carbide tool diameter 1mm (left) and single crystal diamond tool diameter 500 µm (right).

Workpiece and tool materials. The mold material is aluminium Al6061-T6, two types of cutting tools were used: a two-flute end mill made of tungsten super micro grain carbide tool (0° taper angle) and a diamond end-mill tool (Figure 8-1). Most

of the material was removed by pocketing methods using micro-milling carbide tools except for the generation of the channel and the circular feature which was created by diamond end-mill tool. The pocketing method is the preferred method used in machining thin workpiece [97]. In addition, this strategy is used in order to reduce the burr formations created at the edge of the micro-features that was observed during preliminary tests when using straight carbide milling tool (Figure 8-2).

Figure 8-2. The micro-features created by the micro-end mill carbide with tool diameter of 0.5 mm.

The burrs occurring in the micro-features are detrimental and can be comparable with the size of the features itself. One of the solutions to avoid and reduce the burrs is by using the sharp tool, i.e. diamond tool. The diamond tool has sharp and small edge radii compared to carbide milling tool.

Mold design.

Figure 8-3. Embossing mold design.

The micro-features to be created in the mold were selected in order to represent common shapes found in the microfluidic devices and also to challenge the capability of the micro-milling process. Figure 8-3 shows the mold design used in this experiment, where the lines representing the micro-features consist of channel and circular region. The channel height (t_0) is 100 μm and width is 100 μm .

The overall embossing mold size is 50 mm x 50 mm. The molds are produced with two thicknesses of 500 μm and 260 μm . The 260 μm thick workpiece is produced by reducing the thickness of a 500 μm thick workpiece using single point diamond turning (SPDT) process. The 260 μm thick workpiece is selected to give higher ratio of feature height (t_0) to the machined thickness (t_w). In addition, this thickness is considered not to be too thin to avoid damage and to get stronger molds but also not to be too thick which is difficult to bend onto the cylinder roller.

Figure 8-4. Illustration of the mold thickness (t_I), channel height or depth of cut (t_0) and machined thickness (t_w)

Table 8-1. Milling parameters

Workpiece	Al6061-T6
Pocketing parameters	
Tool	Tungsten super micro grain carbide tool diameter 1 mm
Feed rate	100 mm/min
Axial depth per cut	0.025 mm
Spindle speed	40,000 rpm
Total depth of cut	0.10 mm
Milling direction	down milling
Cutting condition	dry cutting
Finish profiling parameters	
Tools	Diamond end-mill diameter 0.5 mm
Feed rate	50 mm/min
Axial depth per cut	0.025 mm
Spindle speed	20,000 rpm
Total depth of cut	0.1 mm
Cutting condition	dry cutting

Cutting Parameters. Cutting parameters used in the experiment are shown in Table 8-1. The cutting is conducted in four passes with each pass having an axial depth of cut of 25 μm to give total axial depth of cut (t_0) of 100 μm . These resulted in t_0/t_w of about 0.625 for the case of 260 μm mold thickness (t_l) (Figure 8-4). The ratio is considered as being high because the depth of cut is comparable to the final machined thickness. The machining time for one embossing mold is less than 30 minutes which is considered as being fast when compared to other fabrication processes, while the time to enter the input parameters and code to the machine was about 2 hours. The comparison study between micro-machining (micro-milling) compared to other methods such as MEMS (DRIE and electroplating) have been conducted by Kang [16]. The micro-machining process is faster and produces cheaper mold when compared to MEMS based processes. The workpiece was held using 30 μm thick adhesive on workpiece holder at the bottom, in order to avoid slip-off. The adhesive is subsequently removed by dipping in to the *acetone*. Subsequently, the hot embossing and hot roller embossing process are conducted to study the performance of the different mold thicknesses.

8.2.2 Effect of the Tapered Tool Angle for Various Workpiece Thicknesses

Figure 8-5. Micro-features dimensions to represent common microfluidic devices.

In this part, the channels were manufactured by slot micro-milling process using the same tools and workpiece as in Chapter 7. Micro-milling of slots under dry conditions is undertaken at a spindle speed of 10,000 rpm and a feed rate of 25 $\mu\text{m}/\text{rev}$ resulting in a cutting speed of 261 mm/s. The micro-features micro-milled in the experiments is shown in Figure 8-5. The designs were selected to represent a typical feature seen in microfluidic devices. The tapered feature consists of a trapezoidal cross section straight protruded wall with a top width of 200 μm and

depth of 50 μm . This is connected to a conical frustum protrusion with the same depth. The wall angle is varied by varying the taper angle of the micro milling tool from 15 to 50 degrees.

Four different channel features were made for each tool in order to observe the effects of taper angle and on the burr formation and surface quality. The micro-features are fabricated at three different starting thicknesses of workpiece: 500, 220 and 110 μm . The total axial depth of cut is selected in order to analyze the significant effect of the workpiece thickness on the burr formation which is about 50 μm resulting in the ratio of the total depth of cut (t_0) to the machined thickness (t_w) of 0.11, 0.29 and 0.83 for 500, 220 and 110 μm workpiece thicknesses respectively. All the workpieces, were held using uniform adhesive holder at the bottom with the thickness of about 30 μm . The adhesive is removed by dipping in to the *acetone* upon machining. Subsequently, the hot embossing process is conducted to study the performance of the different mold thicknesses consisting of micro-features produced by various taper angle.

The machined embossing molds produced by micro-milling were visually analyzed using a Scanning Electron Microscope (SEM) JEOL 5600 to observe the quality of the micro-features. Surface roughness is also measured on the machined embossing molds using a Taylor Hobson Talyscan 150 surface profiler whereas the height and profile measurements of the molds and embossed polymer are conducted using Confocal Image Profiler.

8.3 Comparison of the Thick Mold vs. Thin Mold

8.3.1 Visual Observations

Figure 8-6. The 500 μm machined mold (left) and 260 μm (right).

The thick and thin molds were successfully produced using micro-milling. In the macroscopic view, the thin mold shows relatively little warping compared to the thick mold (Figure 8-6). The surface conditions and the micro-feature shapes are relatively similar as well. During the milling process, large amounts of material are removed and leaving the remaining channel features around the centre region. This removal and the stress induced by the milling process disturb the equilibrium state and furthermore induce warping or deflection if the workpiece is too thin especially when the depth of cut is comparable to the workpiece thickness. In addition, if the stresses are high enough this can cause damage or slip off during the milling process. However, the application of the uniform adhesive to hold the workpiece was seen to avoid the occurrence of any slipping during the milling process.

Figure 8-7. Locations of the observed micro-features taken by SEM.

The locations chosen for observation on the milled mold micro-features are as shown in Figure 8-7 and the SEM micrographs for different mold thicknesses are shown in Figure 8-8. The channels produced on the 500 μm thick mold show better surface and edge quality. In contrast the channels on the 260 μm thick mold show a little rough surface especially in the wall of the channel (location #2, #3 and #4) with no sign of burrs seen in the edges of viewed locations. These results show that the use of a diamond milling tool improved significantly the results as compared to the use of straight carbide milling tool.

Figure 8-8. SEM pictures of the top view of the channels for two different mold thicknesses.

8.3.2 Surface Roughness

Figure 8-9. Locations of the measurement surface roughness.

The surface roughness measurements were conducted at four different locations chosen to represent different areas of the milled surface (Figure 8-9). The three dimensional arithmetic average roughness (S_a) of the milled surfaces was measured using a Taylor Hobson Precision Talyscan 150 surface profiler. Surface roughness measurements of the milled surfaces revealed that the 260 μm thick mold has comparable values with the 500 μm thick one (Table 8-2).

In most of the measured areas, the S_a value of the thin workpiece is higher than the thick workpiece, except in region #3 where the S_a value was lower. In the thick mold, region #3 has the highest surface roughness compared to other region. In contrast, region #3 has the lowest surface roughness value in the thin mold. The differences of surface roughness value of region #3 can be occurred due to the different milling strategy used in that region [97]. In the smaller area such as region #3, milling tool moves in the path parallel with the length of the channel and has smaller step in between each line of the tool path. This strategy may give different surface roughness values. The surface roughness values of four different locations selected to be measured show no major variations for thick and thin molds.

Table 8-2. Surface roughness measurements (S_a) of the molds in μm

Region	Thick (500 μm)	Thin (260 μm)
1	0.039	0.059
2	0.047	0.072
3	0.101	0.033
4	0.044	0.049
Average roughness	0.058	0.053

The results show the use of carbide milling tool with a diameter of 1 mm is sufficient to remove large areas of the part in the pocketing process with correct machining parameters. The adhesive as the fixture method is sufficiently strong to hold the thin workpiece. In addition, embossing molds do not require very fine surface roughness [15] especially on the floor in order to provide good bonding between the flat polymer plate and the embossed polymer plate to obtain a good polymer microfluidic devices set.

8.3.3 Profile Measurements

Figure 8-10. Locations selected for the measurement channel profile.

In addition, the surface profile measurements were conducted using a Confocal Imaging Profiler at two different locations selected on the channel features (Figure 8-10). The measurement results are presented both in three dimensional and two dimensional views (Figure 8-11). In the location C1 on the 260 μm thick mold, the 3-D profile shows that the wall surface is not smooth but contains some uneven features also confirmed with the qualitative SEM observations. From the 2-D views, the height of the channel feature for the thickness mold is seen to be about 100 μm whereas the height of the thin mold is relatively higher at about 110 μm for both the locations.

The higher profile of the channel might occur because of the high axial force experienced by thin workpiece during milling process. The adhesive is not rigid enough at certain locations to withstand the axial forces exerted by the milling tool resulting in the thin workpiece getting pushed down by the tool. However, the results indicate that the machining of the thin workpiece is very sensitive to the uniformity of the fixturing forces and strength of the fixture.

Figure 8-11. Channels profile of the thick (500 μm) and thin (260 μm) molds.

8.3.4 Hot Plate Embossing and Hot Roller Embossing

Hot plate embossing and hot roller embossing experiments were performed to emboss the molds on to a 1 mm thick PMMA (*Polymethylmethacrylate*) sheet. PMMA is the most commonly used polymer for molding applications because of its biological compatibility, its optical properties and ease of molding [165]. The hot plate embossing Carver Manual Press 4386 is used for embossing of polymer microfluidic devices using the thicker mold (Figure 8-12). The hot plate embossing results depend on the temperature, time and pressure [6, 48]. The embossing was

conducted with the plate temperature of 110 °C, with the applied pressure 2 tons for about 10 minutes. The hot roller embossing using the thin mold was conducted using lab scale hot roller embossing machine (Figure 8-12). The thin mold (260 μm) is wrapped and attached to the roller. The hot roller embossing process was conducted with the following parameters: pre-heat PMMA to a temperature of 125 °C for about 60 seconds, the pressure applied is 0.6 MPa, the roller speed is 9.31mm/s and the mold is at room temperature.

Figure 8-12 The hot plate embossing Carver Manual Press 4386 (left) and the lab-scale hot roller embossing machine [54] (right).

In general, the embossed PMMA reveal similar features resembling its embossing molds. As seen in Figure 8-13, the PMMA embossed using the 500 μm thick mold exhibits replication of milling marks on the floor of the channel side. In contrast, PMMA embossed using the 260 μm thick mold exhibits good results with no sign of milling mark.

Figure 8-13 Optical Microscope pictures of the channel section on the embossed PMMA produced by 500 μm mold (left) and 260 μm mold thicknesses.

Figure 8-14. Channel profiles of the embossed PMMA produced by thick (500 μm) and thin (260 μm) molds.

The channel depths are measured using a Confocal Imaging Profiler. As shown in Figure 8-14 the channels on the PMMA produced using the 500 μm thick mold visually have a better shape than the channels on the PMMA produced using the 260 μm thick mold and replicate similarly with the features in the mold. In addition, the depth of the channel on the PMMA formed using the thick mold is about 100 μm whereas the depth of the channel formed using the thin mold is only about 20 μm depth. The shallow channel depths on the embossed PMMA produced

using hot roller embossing may be occurred because of the parameters used for the process are not optimized. The channel depth in the hot roller embossing process can be increased by optimizing the embossing process and reducing the roller speed [54]. Accordingly, further roll embossing studies are needed (out of scope of current thesis) in order to find these optimum conditions to increase and improve the replication results on the embossed PMMA.

8.4 Effect of the Tapered Tool Angle for Various Workpiece Thicknesses

8.4.1 Visual Observation

The effect of the taper angle in reducing the side burr formation during slot micro-milling of 500 μm , 220 μm and 110 μm thick workpieces can be observed in Figure 8-15, Figure 8-16 and Figure 8-17 respectively. The figures show the top view of the micro-features. In general, the burrs are seen to be most severe with dimensions comparable to the wall height in the slot milled using 15° micro end-mill for all three thicknesses. In the slot milled using 15° micro end-mill, the milling process generates top burrs as the oblique cutting edge of the milling tool is fed in. Burrs are seen to be severe both in the conical frustum protrusion and in the trapezoidal cross sectioned straight protruded wall channel. The burrs size is severe enough to deteriorate the embossing process and mold condition.

Figure 8-15. Effect of taper angle on top burr formation during slot milling of the 500 μm thick workpiece. The top row shows the conical frustum protrusion section and bottom row shows the trapezoidal cross sectioned straight protruded wall channel section. The reduction in top burr formation with increasing taper angle is evident.

In the case of 500 μm thick workpiece, as the taper angle is increased from 15° to 50° , the side burrs formed both in the conical frustum protrusion channel

section and in the trapezoidal cross sectioned straight protruded wall, decreased substantially (Figure 8-15). Higher the taper angle, lesser are the top burrs formed during the slot micro-milling process.

Figure 8-16. Effect of taper angle on top burr formation during slot milling of the 220 μm thick workpiece. The top row shows the conical frustum protrusion section and bottom row shows the trapezoidal cross sectioned straight protruded wall channel section.

The burrs are seen to be severe when using the 15° taper angle tool even in 220 μm thick workpiece (Figure 8-16). The features produced using 40° taper tool have more burrs compared to that produced using the 30° taper angle tool. No significant presence of burrs is observed in the features created using the 30° milled slot. Similarly, the micro-features produced by 50° taper angle tool also exhibit very less burrs formation in the sections.

Figure 8-17. Effect of taper angle on top burr formation during slot milling of the 110 μm thick workpiece. The top row shows the conical frustum protrusion section and bottom row shows the trapezoidal cross section straight protruded wall channel section.

Figure 8-17 shows the micro-features produced in the 110 μm thick workpiece. In this workpiece, the burrs produced using 15° taper angle tool are less severe compared to other thicknesses. Similar to the 220 μm thick workpiece, the micro-features made by the tool 30° has less burrs compared to the micro-features produced by 40° taper tool angle. In the micro-features made using the 50° taper tool, some burrs are observed especially in the trapezoidal cross sectioned straight protruded wall channel section.

8.4.2 Burr Height Quantification

The burr height is quantified using a Taylor Hobson Precision Talyscan 150 surface profiler using a mechanical stylus probe. The burr height values obtained are plotted in Figure 8-18. The burr height measurement results show that as the taper angle increases the burr size become less, especially for the case of 500 and 110 μm . The burr height dimension is comparable not only with the feature size but also with the thickness of the workpiece especially for the case of 110 μm thick workpiece.

Figure 8-18. Burr height vs. taper tool angle at different workpiece thickness.

The burr height is the largest for features made using the 15° taper tool and is significantly larger compared to other taper angle tools especially for 220 μm and

500 μm thick workpieces with a height of about 80 μm , while the 110 μm thick workpiece has the lowest burr height about 30 μm . The burr heights for features machined using the 30°, 40° and 50° taper angles are less than 10 μm . Using the 30° taper angle tool on the 110 μm thick workpiece, lowest burr height was observed which is almost zero suggesting presence of no burrs, which is also confirmed in SEM micrographs. Burrs in features machined using the 40° taper angle tool in 500 μm thick workpiece have the lowest height of about 1 μm while the burr heights in 220 and 110 μm thick workpieces are about 8 μm . The 110 μm thick workpiece has the largest burr size while the 220 and 500 μm show no burrs for the case of 50° taper angle.

These experiments also imply that the fixturing method using an adhesive is sufficiently strong to hold the thin workpiece providing similar result for thick and thin workpieces even when the ratio of the axial depth of cut to the machined workpiece thickness (t_w) is about 0.83 (axial depth of cut 50 μm , machined workpiece thickness 60 μm for the 110 μm thick workpiece).

8.4.3 Hot Embossing Trial

The machined mold features are transferred onto a PMMA sheet by hot embossing in order to observe the performance and quality of the features produced with various taper angles at different workpiece thicknesses. The embossing process is performed using a hot plate embosser (Carver Manual Press 4386). The PMMA was embossed with the following parameters: 10 minutes time, base and top plates temperature 99 °C, and pressure 14 MPa. The top view of the embossing results is shown in Figure 8-19. In general, the embossed PMMA reveal similar geometrical features as the embossing mold.

Figure 8-19. Embossed features on PMMA produced by the molds of various taper angle at different mold thicknesses.

As seen in Figure 8-19, the embossed PMMA with 15° wall exhibits replication of burrs on the micro-features with the most severe embossed features for the 500 μm thick workpiece. There is no replication of burrs seen in other taper angles for this mold thickness. Replication of burrs is observed in the 40° taper wall in addition to 15° taper wall for the mold thickness of 220 μm . The micro-features of the 30° and 50° taper wall are observed to be smooth with no presence of burrs. The micro-features of the embossed PMMA produced by the mold thickness of 110 μm exhibit good results with no sign of burrs for the case of 30° and 50° taper wall. In contrast, the 15° and 40° taper wall show presence of burr replication especially

in the channel section. The tapered channel shape also improved the de-embossing process of hot plate embossing. The taper angle provides easy mold release and avoids sticking between the embossing mold and PMMA. Hence, the tapered mold design may have potential advantages in mass manufacturing the microfluidic devices.

8.5 Summary

The fabrication of thin embossing mold produced by micro-milling and followed by hot roller embossing has been conducted to understand the mold performance. A thin mold with the machined thickness of about 160 μm with feature height of about 100 μm has been produced successfully using the micro-milling process. Visual observations, surface roughness measurements and profile measurements on the thick mold and thin mold show that the surface quality of the thin embossing mold produced by micro-milling and held using adhesive is comparable with the thick mold. The embossed PMMA shows that the thin mold produced by micro-milling is capable to be used in the hot roller embossing applications. Although, the features are not perfectly transferred to the embossed PMMA due to the non-optimized roller process parameters the results prove the capability of the micro-milling process to create the features necessary for a microfluidic in thin embossing mold. The importance of the workpiece holder to produce good quality thin embossing molds by micro-milling is also pointed out in this work. The application of the adhesive as the fixture method is necessary to avoid the vibration problems and to obtain the uniformity of the surface and features quality of the thin machined molds.

It has been shown that the micro-features fabricated in different thicknesses using such tapered tool micro-milling geometry are successfully used for hot embossing without the need for any secondary de-burring operations.

Chapter 9.

CONCLUSIONS AND FUTURE RESEARCH STUDY

This chapter summarizes main findings of the thesis covering the fundamental study of micro-machining thin workpieces and application to making thin embossing molds. Projected future research studies related to findings are also presented.

9.1 Conclusions

Some of the main findings of this thesis are stated below.

a. Challenges in micro-machining thin workpiece

1. Effect of the reduced workpiece thickness in the cutting process.
 - The experimental results show that the cutting forces and chip thicknesses remain more or less the same as the workpiece is machined from thick to thin conditions; it can be inferred that the cutting energy needed is the same for thick and thin workpieces.
 - The thinnest Al6061-T6 workpiece machined using orthogonal micro-cutting process and fixtured using a 54 μm thick UV-curing adhesive is about 28 μm . The limitation to achieve thinner workpiece is attributed mainly due to the detachment of the thin workpiece by peel-off which occurs in the initial chip formation as the tool engages with the workpiece. The detachment is induced by adhesive fracture mode that occurs in the interface between the thin workpiece and adhesive.
 - The peeling of thin workpiece occurs when the tensile stress induced by tool during initial chip formation exceeds the tensile strength at break of the adhesive. Simulation result shows that the tensile stress induced by the tool at the top of the adhesive is higher for a thinner workpiece (45 μm) than a thicker workpiece (150 μm) and higher at the entrance. Hence, a thinner workpiece is more susceptible to peel off.

- Through thickness stress profiles across the thickness of the adhesive extracted from simulations indicate that higher tensile stresses are experienced when the workpiece is thinner and are highest in the interface of the thin workpiece-adhesive rather than middle section of the adhesive confirming that the peel-off occurs in the adhesive failure mode.
2. Machining induced residual stress and warping in thin workpiece.
 - Machining process exacerbates warping of the thin workpiece; curvatures are larger as thickness is reduced.
 - The residual stress measured using curvature and XRD methods show significantly different values implying that the residual stress in the warping of thin workpiece occurs due to the machining induced stress and elastic relaxation.
 3. Effect of the substrate elastic properties in the micro-machining of thin workpiece.
 - The workpiece thickness and the substrate properties significantly affect the stress profile in the micro-cutting process and hence are likely to affect warping of the thin machined workpiece.
 - The stress profiles across the thickness of the machined workpiece are broader as the ratio of the depth of cut to the machined workpiece thickness is increased implying that as the machined workpiece become thinner, the stress is more significant not only on the machined surface but also on the subsurface of the workpiece.
 - A stiffer substrate produces less variation of the stress across the workpiece thickness while a compliant substrate produces broader stress variation. The small residual deformation in the compliant substrate and shallow residual stresses can still induce warping.
 4. Microstructural changes in the work material.
 - Machining of thin work materials using diamond face turning method generates microstructural changes in the form of grain refinement through the workpiece thickness and modifies the grain orientation.

- The microstructures of machined thin workpieces become more random, denser, and finer with the shape of the grains less elongated as compare to the bulk and thick machined sample.
- These changes are induced by significant plastic deformation in the form of localized large strains experienced by the thin workpiece. The magnitude and duration of the heat due to the temperature rise in the shear zone is shown to have a smaller effect in the grain refinement of the machined thin workpiece.

5. Burrs reduction.

- Side edge angle and taper angle were seen to affect the top burr formation; a combination of largest taper and largest side edge angle produced the smallest burr
- As the side edge angle increases the top burrs reduced at all taper angles; this effect was seen to be more prominent at larger taper angles. Hence it can be concluded that the side edge angle strengthening affects top burr formation. Analogies with exit angle burr studies, conical indenter studies, and recent related finite element simulation studies in literature help come to a conclusion that higher side edge angle can effectively help in reducing the burrs.
- As taper angle increases the top burrs are seen to reduce significantly; the taper angle is seen to affect the velocity, normal and effective rake angles of the tool, with higher taper angle tools having a higher effective rake. This can explain the formation of smaller burrs at higher taper angles.

b. Application of micro-machining in producing thin embossing molds

A thin mold with the ratio of the features height to the machined thickness of about 0.625 has successfully been produced using micro-milling process. The surface quality of the thin embossing mold produced by micro-milling and held using adhesive is comparable with the thick mold. The results prove the capability of the micro-milling process to create the features necessary for microfluidic devices in thin embossing mold.

9.2 Future Research Study

The thesis reported some findings that have potential for further study. The following work can be conducted in the future to extend the understanding of machining thin workpieces.

- a. ***Study of grain size effect.*** Based on the findings, it is observed that material properties of the thin workpiece is altered especially the microstructure. The grain size could be in the same order as the thickness of the machined workpiece. A study of the initial grain size effect on the cutting mechanism and the machining result is worthy of study. Modification of the microstructures through heat treatment can be conducted in order to get different variation in the initial grain size.
- b. ***Study of the residual stress profiles measurement method.*** Further residual stress measurements techniques are needed to measure the residual stress profile of the thin workpiece. The challenge is the selection of or development of an appropriate method to measure the residual stress on the delicate thin workpieces.
- c. ***Study of deformation of the micro-features.*** In the thin embossing mold used for hot roller embossing, the features such as protruded channel or orifice have sizes comparable to the mold thickness. Therefore, a study of the deformation of the features created in the micro-machining of thin workpieces can be conducted in the future.
- d. ***Numerical study of the effect of the fixturing force on the warping of the thin workpiece upon releasing the workpiece from the substrate.*** A study of workpiece deflection performed after the tool is retracted from the workpiece and boundary conditions are released in order to allow natural stress-relief process is important to understand the effect of the thickness and substrate properties.

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APPENDIX A. Multi-Cure Dymax® 6-621 Product Data Sheet

DYMAX CORPORATION

PRELIMINARY PRODUCT DATA SHEET

7 May 2003

PHENOLIC & FILLED PLASTICS TO GLASS & METAL MULTI-CURE® 6-621 SERIES

DESCRIPTION

DYMAX 6-621 Series adhesives are high tensile strength, UV/Visible curing resins that are especially well suited for when rigid adhesive bonds are desired. Multi-Cure 6-621 Series adhesives form clear, hard, bonds to glass, metal, phenolic, filled Nylon, ferrite, ceramic and other materials. Multi-Cure 6-621 Series can be cured with UV light, heat or pre-applied activator. Visible light can penetrate through many UV-blocked and colored plastics and glasses to cure the adhesive. DYMAX adhesive activator bonding systems comply with the Montreal Protocol and U.S. Clean Air Act of 1990.

TYPICAL UNCURED PROPERTIES (not specifications)

Solvent Content	None - 100% Reactive Solids	
Chemical Class	Urethane Acrylate	
Appearance	Clear/Straw Liquid	
Flash Point	>93°C (200°F)	
Solubility	Alcohols/Chlorinated Solvents/Ketones	
Toxicity	Low	
Viscosity (20 rpm)	6-621 750 cP (nominal)	ASTM D-1084
	6-621-T 3,500 cP (nominal)	ASTM D-2556
	6-621-VT 11,000 cP (nominal)	ASTM D-2556
	6-621-Gel 25,000 cP (nominal)	ASTM D-2556

TYPICAL CURED PROPERTIES (not specifications)

Durometer Hardness	D75	ASTM D-2240
Tensile at Break	5,200 psi (35.9 MPa)	ASTM D-638
Elongation at Break	35%	ASTM D-638
Modulus of Elasticity	320,000 psi	ASTM D-638
Tensile Lap Shear (steel to steel)	3,600 psi	ASTM D-1002
Tensile Compression Shear		
Glass-to-Glass	4,000 psi (exceeds strength of glass)	DSTM D-250*
Glass-to-Steel	5,000 psi (exceeds strength of glass)	DSTM D-251
Water Absorption (24 h)	1.1%	ASTM D-570
Boiling Water Absorption (2 h)	3.0%	ASTM D-570
Linear Shrinkage	3%	DSTM D-101
Coefficient of Linear Thermal Expansion	90 x 10 ⁻⁶ in/in/°C	ASTM D-696
Thermal Limit (brittle/degrades)	-43° to +177°C (-45°/+350°F)	DSTM D-200

*DSTM refers to DYMAX Standard Test Method

ELECTRICAL

Dielectric Strength	1,600 V/mil	ASTM D-1304
Volume Resistivity	7.5 x 10 ¹³ Ω*cm	ASTM D-1304
Surface Resistivity	2.2 x 10 ¹⁴ Ω	ASTM D-1304
Dissipation Factor, 1 MHz	0.06	ASTM D-1304
Dielectric Constant, 1 MHz	4.10	ASTM D-1304

CURE DATA – Using 365 nanometer UV light:

	Cure Time (Seconds)	Intensity (mW/cm ²)	DYMAX Light-Welder® Lamps
Tack-free cure (1/8-inch bead)	10	150	5000-EC
Depth of cure (1/4 inch)	20	150	5000-EC
Fixture between glass slides	1	50	2000-EC

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DYMAX®
Adhesives and Light Curing Systems

DYMAX CORPORATION

PRELIMINARY PRODUCT DATA SHEET

6-621 Series, 7 May 2003

Shadowed areas can be cured with activator or heat.

Activator is placed on one surface and the adhesive on the mating surface. Curing takes place at room temperature when the parts are mated. Activator requires well-mated parts (up to 0.010-inch gap). Well-mated parts fixture (achieve handling strength) in less than a minute. See DYMAX Technical Bulletin "Guidelines for Activator Curing" for complete instructions for all activators.

Heat may be used after UV cure to cure shadowed areas or after activator cure to accelerate cure. The following guidelines depend on the amount of adhesive:

<u>Minimum Adhesive Temperature</u>	<u>Time</u>
110°C (225°F)	60 Minutes
120°C (250°F)	30 Minutes
150°C (300°F)	15 Minutes

DISPENSING AND HANDLING ADHESIVE

Multi-Cure6-621 Series adhesives are available in various packages such as syringes, cartridges, bottles, and pails. They may be dispensed with a variety of automatic bench-top syringe applicators or other equipment as required. Direct questions relating to dispensing and curing systems for specific applications to the DYMAX Technical Center at 860-482-1010.

Wear impervious gloves and/or barrier cream. Repeated or continuous skin contact with liquid adhesive will cause irritation and should be avoided. Do not wear absorbent gloves. Remove adhesive from skin with soap and water. Never use solvents to remove adhesive from skin or eyes.

STORAGE AND SHELF LIFE

Store material in a cool, dark place when not in use. Do not expose to UV light or sunlight. Material may polymerize upon prolonged exposure to ambient light. Replace lid immediately after use. Product has a one year shelf life when stored below 90°F in the original, unopened container.

CAUTION

For industrial use only. Avoid breathing vapors. Avoid contact with eyes and clothing. In case of contact, immediately flush with water for at least 15 minutes; get medical attention. Wash clothing before reuse. Keep out of reach of children. Do not take internally. If swallowed, induce vomiting at once and call a physician. Repeated or continuous skin contact with liquid adhesive will cause irritation and should be avoided. For specific information, refer to the product Material Safety Data Sheet.

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DYMAX®
Adhesives and Light Curing Systems

APPENDIX B. Activator Dymax® 501-E Product Data Sheet

INDUSTRIAL ADHESIVES
501-E Product Data Sheet

Wipe-On® Activator 501-E Environmentally Safe for Fast, Reliable, Structural Bonding

INTRODUCTION

Wipe-On® Activator 501-E, when pre-applied to metallic, plated, ceramic, or glass substrates, rapidly and completely cures high-strength Dymax 800 and 600 Series structural adhesives in gaps from less than 1 mil to 20 mils. Pre-applied parts can be joined immediately or after up to 24 hours of open time.

Wipe-On® Activator 501-E is environmentally safe because it is completely free of solvents (VOCs) and ozone-depleting chemicals (ODCs). Activator 501-E's low volatility and high flash point also enhances safety in the workplace. This product is in full compliance with the RoHS Directives 2002/95/EC and 2003/11/EC.

KEY BENEFITS

- Strong structural bonds. Fixtures in seconds. No solvent flash-off time.
- No volatile organic compounds (VOC's). No ozone-depleting chemicals (ODC's).

THE BENEFITS OF COLD BONDING

Cold bonding increases efficiencies, consistency, and reliability. Dymax's ODC-free formulations provide a broad range of process control advantages by matching the cure speed with assembly needs, thereby increasing total process efficiency. Process design is made simpler and cheaper due to the long open times available, no pot life concerns or waste, and rapid room-temperature fixture. Activator 501-E provides on-part cleaning action and broad tolerance of adhesive-to-activator ratios. Rapid, on-demand curing to fixture or handling strength allows in-line quality control and increased production thru-put.

TECHNICAL DATA

TYPICAL LIQUID PROPERTIES

Color	Yellow to Amber
Solvent Present	None
ODC Present	None
Solvent Flash Time	None
Toxicity	Moderate TLV=None
Flash Point (Closed Cup)	245°F
Specific Gravity	1.0
On-Part Activator Life	24 hours
Viscosity	30-40 cP

TYPICAL CURING PROPERTIES (Per ASTM D1002 method)

	DYMAX Structural Adhesive 846	Multi-Cure® Adhesive 602
Fixture Time (2 Mil Gap)	15-20 Seconds	10-15 Seconds
5 Minutes	1,100 psi	2,400 psi
10 Minutes	1,300 psi	2,700 psi
30 Minutes	1,800 psi	3,100 psi
24 Hours	3,000 psi	3,600 psi
72 Hours	3,500 psi	3,600 psi
1 Hour at 200°F	3,500 psi	3,800 psi
10 Mil Gap	3,000 psi	2,600 psi
20 Mil Gap	2,500 psi	800 psi
20 Mil Gap - 1 Hour at 200°F	2,500 psi	2,800 psi

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INDUSTRIAL ADHESIVES
501-E Product Data Sheet

USE & APPLICATION

For most bonding applications, activator is applied to one bonding surface and adhesive to the other. Spraying, dipping, brushing, or pad transfer are all acceptable techniques for application.

Recommended Technique:

1. Apply a thin film of activator to one of the surfaces to be bonded. Activator should not stand in pools. Surfaces will have an oily appearance. Activating both surfaces may produce better results on some porous surfaces or if bond-line gaps exceed 0.15".
2. Apply a single drop or small bead of adhesive (DO NOT SPREAD) onto the mating surface. When the parts are joined the adhesive spreads, mixing with activator to completely fill the joint.
3. Assemble parts and clamp or leave undisturbed until fixture (handling strength) occurs. Assembled parts should be held immobile until adhesive fixture occurs. Movement of parts relative to each other prior to achieving fixture or handling strength can result in weaker bond lines.

Additional Technical Considerations:

Adhesive Application: Adhesive should only be applied as a drop or bead that squeezes from the center to the edges of the bonding surfaces. This technique promotes mixing and assures maximum contact of adhesive and activator over the entire bond area. Use the optimum amount of adhesive to COMPLETELY FILL the joint. Apply just enough adhesive so that a ring of liquid becomes visible when the parts are pressed together. Do not overfill. The "fillet" should cure if the proper ratio of adhesive to activator has been used.

Adhesive/Activator Ratio: Dymax 600 and 800 Series structural bonding adhesive systems are formulated to allow a wide tolerance of adhesive-to-activator ratios. The same approximate strength results when using ratios from 5:1 to 30:1. The critical factor is that a thin film of activator on one mating surface contact adhesive bead(s) on the other mating surface and that both mix during assembly. With these criteria met, the actual adhesive-to-activator ratio may vary with assembly design and adhesive/activator dispensing systems. It should be noted that flooding or over-activation (less than 5:1 adhesive-to-activator) may result in weaker ultimate bond strengths.

Applying activator to wooden surfaces: Two-sided activation may be preferable to activating only one of two mating surfaces depending on the porosity of the wood.

Surface preparation: Most substrates require little if any surface preparation, though adhesion is frequently enhanced by clean, mechanically roughened surfaces. Follow the manufacturer's instructions for cleaning plastic surfaces. Grease, wax, and some mold-release agents are barriers against adhesion.

Activator dispensing: Activator is easily applied with dispensing equipment for automated assembly. Best methods are spraying or pad printing. Natural felt, lambswool, horsehair, or chemically resistant polyurethane and silicone foams are suitable. Spray application is also satisfactory. Proper ventilation must be provided, as well as proper design of spray nozzles to prevent overspray. Overspray on surrounding surfaces does not dissipate. Activated surfaces have an oily appearance. Pressurize dispensers only with nitrogen, never with air.

TWO-SIDED ACTIVATION

Two-sided activation is recommended when bonding porous surfaces and for larger bond-line gaps exceeding .015". Parts must be assembled as quickly as possible once adhesive is applied over activator, since curing begins in seconds. Movement of parts upon assembly promotes mixing of adhesive and activator and may help to ensure complete cure through large bond-line gaps. Parts should then be left until the fixture or handling strength is obtained. VT and GEL formulations of adhesive should be used for large bond gaps.

CLEAN UP

Excess activator and adhesive may be cleaned with alcohol, esters, and other common solvents. Ketones, eg. acetone, should not be used on surfaces to be bonded as they sometimes leave a harmful residue.

PACKAGING AND SHELF LIFE

Activators are available in 8.3-mL glass vials or 8-ounce, 1-quart, 1-gallon, and 5-gallon metal containers. Activator has a minimum 12-month shelf life from date of shipment, unless otherwise specified, when stored in original, unopened, and undamaged containers. No shelf life is stipulated once opened. Activator is oxygen sensitive. Containers should be closed immediately following dispensing. Resealing container under nitrogen extends shelf life. If activator turns black, run the fixture test (on following page) to determine its potency.

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INDUSTRIAL ADHESIVES
501-E Product Data Sheet

HANDLING AND PRECAUTIONS

Activators are oxygen sensitive. Containers must be kept closed or stored under nitrogen when not in use in order to maintain shelf life. Remove only enough activator from the container that can be used in a short period of time.

RECOMMENDED "SPEED OF CURE" FIXTURE TEST

This test is recommended for inspection of incoming adhesive and activator and for in-line process control. Production parts are ideal for in-line inspection and QC. Alternatively, microscope slides or steel laps may be used as the test substrate. It is recommended that this test be performed at the beginning of each shift and the results charted. This will ensure the adhesive and activator are in good working order.

Step 1: Apply a thin film of activator to one part. Cover about one square inch.

Step 2: Apply a thin, 1/16" BEAD of adhesive (do not spread) to the other part.

Step 3: With a 3/4" to 1" overlap, press the two parts together and hold for 5 seconds. (Note -- as the adhesive bead rolls across the activator, it picks up the activator -- this is how they mix.)

Step 4: Every 5 seconds, gently tap the end of one part while holding the other part still. Fixture time is when the parts resist movement with light finger pressure.

Step 5: Record the fixture time. Fixture time should be +/- 50% of the average for our combination of adhesive and activator. If outside these limits, repeat, check method, and check with different lot of activator or adhesive.

CAUTION

Avoid skin and eye contact. Non-porous protective gloves or barrier hand cream should be used. Do not wear jewelry. Protective eye goggles should be worn when handling activator. Avoid breathing of vapor. Use positive ventilation to remove vapors. For industrial use only. Avoid contact with eyes and clothing. In case of contact, immediately flush with water for at least 15 minutes; for eyes, get medical attention. Wash clothing before reuse. Keep out of reach of children. Do not take internally. If swallowed, vomiting should be induced at once and a physician called. For specific information, refer to the product Material Safety Data Sheet before use.

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APPENDIX C. Measured Curvature Using Taylor Hobson Talyscan 150 Laser Probe

Workpiece #1

Workpiece #2

Workpiece #3

Workpiece #4

Workpiece #5

Workpiece #6

Workpiece #7

APPENDIX D. Phase Analysis (Intensity vs. 2theta) from Thin Film XRD Measurement

Workpiece #2

Workpiece #3

Workpiece #6

Workpiece #7

APPENDIX E. Epsilon vs. $\sin^2\psi$ for Determining Residual Stress Using Thin Film XRD Method

Workpiece #2

Workpiece #3

Appendix E. Epsilon vs. Sin²psi for Determining Residual Stress Using Thin Film XRD Measurement

Appendix E. Epsilon vs. Sin²psi for Determining Residual Stress Using Thin Film XRD Measurement

Workpiece #6

workpiece#7

Workpiece #7

APPENDIX F. Development of Mean Temperature Equation

The mean temperature in the shear plane in the workpiece side ($\overline{\theta}_S$) can be calculated using metal cutting concepts explained in [18], such as:

$$\overline{\theta}_S = \frac{(1 - R_1)u_S}{C_1\rho_1} + \theta_0 \quad (D.1)$$

where θ_0 is the ambient workpiece temperature, R_1 is the fraction of the heat which leaves the shear zone with the chip, u_S is the shear energy per unit volume of metal cutting, C_1 is specific heat of the workpiece and ρ_1 is the density of the workpiece. R_1 is calculated as:

$$R_1 = \frac{1}{1 + 1.328 \left(\frac{K_1 \gamma}{Vt} \right)^{1/2}} \quad (D.2)$$

where K_1 is diffusivity of the workpiece material at temperature $\overline{\theta}_S$ and calculated using equation below:

$$K_1 = \frac{k_1}{C_1\rho_1} \quad (D.3)$$

γ is strain in the chip, V is cutting speed and t is the depth of cut and k_1 is conductivity. The shear energy per unit volume (u_S) of metal cutting for oblique cutting process is calculated using:

$$u_S = \frac{F_S \cos(\eta_S - \delta_S) V_S}{btV} \quad (D.4)$$

In the single point diamond turning, the shear strain is calculated using equation below:

$$\gamma = \frac{\cot \phi_n + \tan(\phi_n - \alpha_n)}{\cos \eta_S} \quad (D.5)$$

where F_S is the component of force along the shear plane, η_S is shear flow angle, δ_S is angle of force in the shear plane (F_S) with the normal to the cutting edge. V_S is the shear velocity, b is cutting width. F_S is calculated as:

$$F_S = \left[(-F_x \cos i + F_y \sin i)^2 + (F_y \cos \phi_n \cos i - F_z \sin \alpha_n)^2 \right]^{1/2} \quad (D.6)$$

where F_x is the feed force, F_y is the cutting force and F_z is the thrust force. i is the inclination angle, where for the turning tool geometry it is calculated as:

$$\tan i = \tan \alpha_b \cos C_s - \tan \alpha_s \sin C_s \quad (D.7)$$

whereas α_n is normal rake angle which calculated as:

$$\tan \alpha_n = \tan \alpha_v \cos i \quad (D.8)$$

and α_v is velocity rake angle, calculated as:

$$\tan \alpha_v = \tan \alpha_s \cos C_s + \tan \alpha_b \sin C_s \quad (D.9)$$

η_s is calculated using this equation:

$$\tan \eta_s = \frac{\tan i \cos(\phi_n - \alpha_n) - \tan \eta_c \sin \phi_n}{\cos \alpha_n} \quad (D.10)$$

ϕ_n is normal shear angle calculated using:

$$\tan \phi_n = \frac{\left(\frac{t}{t_c}\right) \cos \alpha_n}{1 - \left(\frac{t}{t_c}\right) \sin \alpha_n} \quad (D.11)$$

α_b is back rake, C_s is side cutting edge, and α_s is side rake that measured from the cutting tool geometry. The shear velocity is calculated as:

$$V_s = \frac{\cos i \cos \alpha_n}{\cos \eta_s \cos(\phi_n - \alpha_n)} V \quad (D.12)$$

$$\tan \delta_s = \frac{-\cos i F_x + \sin i F_y}{\cos \phi_n \sin i F_x + \cos \phi_n \cos i F_y + \sin \phi_n F_z} \quad (D.13)$$

t_c is the chip thickness and η_c is chip flow direction which is equal to i .

VITA

Kushendarsyah Saptaji was born on 21st July 1977 in the west side of Java Island Indonesia called Bandung to Sarengat and Sukmi. His schooling and university days were mostly spent in Bandung. After he finished his Senior High School from the top ranked high school in Bandung, he was accepted in the Metallurgy Engineering Department in the Institute Technology of Bandung (ITB). He obtained his B. Eng. in 2000 with cum laude predicate with a GPA of 3.58; his final year project was in the area of optimizing steelmaking production in PT. Krakatau Steel. He then worked as a technical service engineer in 2001 for a Spanish based company, PT. Torrecid Indonesia, which has a business in the raw materials for ceramics. He received the ASEAN Graduate scholarship in 2006 to pursue his M.Sc. degree at the Nanyang Technological University with a major in Mechanics and Processes of Materials. He finished the study in one year and joined Matcor Technology and Services Pte. Ltd., as an engineer in the field of failure analysis and corrosion. He worked there for about 8 months when he was offered admission for pursuing his Ph.D with an NTU scholarship. He married Evi Nafisah Zakaria and having a daughter, Naila Fathiyya and a son, Roojhan Alfathi.