Study of miniature features generated by backside patterned texturing in precision diamond machining

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**NANYANG
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**STUDY OF MINIATURE FEATURES GENERATED BY
BACKSIDE PATTERNED TEXTURING IN PRECISION
DIAMOND MACHINING**

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ABSTRACT

Structured and functional surfaces are key components in many advanced technological applications, such as electronics, information technology, energy, optics and tribology. A gamut of products has emerged where the surfaces are specially textured or engineered for a particular function. These textured surfaces rely on the control of surface characteristics to obtain the desired functional performance. Various techniques and methods have been used to develop micro-scale functional surfaces. For example, ultraprecision single point diamond turning (SPDT) and its associated processes, such as fast tool servo (FTS) and slow slide servo (SSS) have been used to fabricate various types of micro-sized surface textures. However, these techniques have limitation to produce surface features at submicron scale. In addition, the existing associated methods of SPDT require a complex tool path programming for the tool-workpiece synchronized motion for asymmetric and freeform surface generation. This thesis attempts to address the limitations of SPDT and its associated specialized techniques and to propose a potential alternative: backside patterned texturing (BPT) for submicron to micro-sized surface features generation on the diamond machined surface.

The proposed novel technique of BPT utilizes the pre-fabricated macro-features on the backside of work material, and thereafter the front side is face turned with a single point diamond tool. The pre-fabricated patterns divide the entire workpiece into thick and thin

sections. Unlike existing texturing methods of SPDT, BPT produces textured surfaces from submicron to micro-scale and without any external electromechanical system for synchronized tool-spindle motion or vibration-assisted machining. The diamond machining induces residual stresses at the surface and subsurface of the machined surface. The workpiece attached to the machine remains flat due to the displacement constraints provided by workpiece holding mechanism like a vacuum chuck. Upon removal of the workpiece from the machine, the induced residual stresses in the machined workpiece achieve a new state of equilibrium and consequently, the deformation of the overall newly formed surface is taken place. The thinner section of the workpiece experiences relatively larger deformation, which leads to the development of the associated texture on the front side of machined workpiece. The machining experiments are conducted for different backside pattern geometries and workpiece thicknesses. The effects of backside patterns, workpiece thickness and cutting speed on the texture formation are investigated. To demonstrate the efficacy of the method, various types of freeform surface textures, such as an array of convex shapes bumps, waterdrop, spiral and cylindrical freeform surfaces are fabricated.

The novelty of the proposed technique of BPT demands the explanation of the surface deformation phenomenon during texturing process. Therefore, along with the experiments, a mathematical formulation and a finite element (FE) model are developed to predict the surface deformation in BPT. The mathematical formulation requires some preliminary machining tests for an arbitrary type of surface texture, which gives an estimation of the source residual stresses in the plastically deformed layer of the

machined workpiece. The known source residual stresses are then taken as an input to predict the surface deformation for the subsequent axisymmetric and doubly symmetric texture geometries produced with similar machining conditions. The simulation results were compared with the experiments that showed a good agreement and validated the proposed methodology.

Finally, a finite element (FE) model is developed to simulate the surface deformation in the surface texture produced by BPT. The FE model was based on the arbitrary Lagrangian-Eulerian (ALE) mesh motion scheme to simulate diamond turning (DT) in order to extract the machining-induced residual stress (RS) profile as a function of workpiece thickness. Subsequently, the estimated RS profile is mapped to 2D and 3D FE models to predict the relative surface deformation. The simulated results were found promising compared to the experiments and the similar trends of surface deformation were obtained for various thicknesses of the workpiece material.

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LIST OF ABBREVIATIONS

ACT	Adaptive Control Technique
Al	Aluminum
ALE	Arbitrary Lagrangian Eulerian
BPT	Backside Patterned Texturing
CNC	Computer Numeric Control
DAQ	Data Acquisition
DT	Diamond Turning
DOE	Diffraction Optical Element
DMC	Diamond Micro Chiseling
EDM	Electric Discharge Machining
FE	Finite Element
FTS	Fast Tool Servo
LADT	Live Axis Diamond Turning
MEMS	Microelectromechanical Systems
MLA	Microlens Array
nFTS	nano Fast Tool Servo
OEM	Original Equipment Manufacturer
RS	Machining Induced Residual Stress
RMS	Root Mean Square
SCD	Single Crystal Diamond
SPDT	Single Point Diamond Turning
SSS	Slow Slide Servo

STS	Slow Tool Servo
UADT	Ultrasonically Assisted Diamond Turning
USM	Ultrasonic Machining
VAM	Vibration-Assisted Machining
XRD	X-Ray Diffraction

LIST OF SYMBOLS

α	Thermal diffusivity
ϵ	Effusivity
ρ	Density
σ_s	Source stresses
σ_{xx}	Residual stresses in x-direction
σ_{yy}	Residual stresses in y-direction
ϵ_p	Equivalent plastic strain
$\dot{\epsilon}_p$	Plastic strain rate
$\dot{\epsilon}_o$	Reference plastic strain rate
τ_p	Average shear stress
τ_f	Frictional shear stress
b	Width of cut
d_c	Cutting depth
$d_{c, min}$	Minimum cutting depth
f	Feed rate
h_c	Coefficient of heat convection
k	Thermal conductivity
m	Thermal softening coefficient
n	Hardening coefficient
q_{conv}	Convection heat transfer
r	Tool nose radius
r_e	Cutting edge radius of diamond tool
t_{ri}	Initial material thickness at thinner section

t_{rf}	Material thickness at thinner section after diamond machining
t_m	Minimum threshold material thickness at thinner section
t_d	Damage thickness at the thinner section
t_o	Thickness of stressed layer
v_c	Cutting speed
A	Constant coefficient
A	Initial yield strength at room temperature
B	Hardening modulus
C	Sensitivity coefficient
C	Specific heat
D_b	Diameter of produced bump texture
E	Modulus of elasticity
I_{zz}	Moment of inertia
M_z	Bending moment
Ra	Average surface roughness
Sa	3D arithmetic mean of surface variation
Sq	3D root mean square of surface variation
T_m	Melting temperature
T_o	Room temperature
U_{yy}	Linear displacement in thrust direction
U_{xx}	Linear displacement in cutting direction

CHAPTER 1

INTRODUCTION

This chapter outlines a summary and overview of the research work presented in this thesis. At the onset of this chapter, a brief background of mechanical micromachining processes especially single point diamond turning (SPDT) and its associated techniques for submicron to micro-sized surface texturing are presented. Subsequently, the motivation, objectives and scope of the research are summarized. In the last section of this chapter, a synopsis of the thesis is illustrated.

1.1 BACKGROUND AND MOTIVATION

Functional, textured or engineered surfaces play an important fundamental role in many advanced technological fields, such as optics, tribology, biology, microelectronics, hydrodynamics and biomimetics. These unique surfaces contain micro or nanoscale surface features that provide an environment for physical or chemical action to be happened for obtaining the desired functions. The demand of micro to nanoscale textured components for a particular function like antimicrobial effects, self-cleaning action and to achieve optimal friction coefficient is rapidly increasing due to their innovative widespread applications in the modern industry. Also, various functions can be

accomplished by designing and fabrication of different types of textured or functional surface textures as presented in [1, 2].

Recently, higher demands towards miniaturization of components lead to a vast technological development in micro-fabrication or micro-manufacturing. The accuracy of available technologies that allow the fabrication of submicron to micro-sized surface features is one of the main issues for miniaturized products. Comparatively, the textured functional surfaces at submicron-scale are more challenging to develop. The issues related to the fabrication of submicron-scale surface features have been focused in many literature articles [3].

Various microfabrication methods that involve material removals, such as lithography, laser ablation, electrical discharge machining (EDM), micro-grinding and ultraprecision diamond cutting are used for the fabrication of micro-scale textured surfaces [2]. The lithography followed by an etching process requires high capital and operational cost and it is limited to a few types of materials [3]. The laser ablation machining [4] and EDM [5] can be used for texturing of an almost whole range of engineering materials. However, these methods usually have problems when highly precise functional surfaces and structures are required. However, the ultraprecision diamond machining like single point diamond turning (SPDT) has substantial merits including high productivity, high flexibility and ability to produce excellent surface finish [6, 7].

Ultraprecision SPDT is one of the most widely used enabling technologies in the field of precision engineering for last few decades. SPDT uses ultra-sharp, highly pure single crystal diamond tool employed at an ultraprecision lathe. By virtue of numerous state-of-the-art systems integrated with the ultraprecision machine like high stiffness and hydrostatic oil bearing sideways, air bearing spindles, highly precise servo controller and ultraprecision design of machine tool, SPDT produces components with optical/mirror surface finish, high dimensional accuracy and few nanometers of surface roughness [8].

With SPDT, very high-quality flat, spherical and aspherical optical surfaces can be generated directly either with minimal or without any subsequent post-polishing. The components produced via SPDT have been used for various applications from defense to commercial as well as in consumer products. Laser scanners, optical projection systems, optical sensors, laser beam guiding system, scientific instruments, illumination systems, fusion reactor (imaging mirrors), inserts for injection molded plastic camera lenses, scanner mirrors, photocopier drum, computer memory discs, X-ray telescopes are some of the examples of the products produced by SPDT [8, 9].

In SPDT, different machine kinematics can be used depending on the required shapes of the surface feature. Aspheres and spheres are typically manufactured by a combination of one rotation axis and two linear axes. Slow tool servo (STS) mode can be used to fabricate the mirrors of large off-axis distances and without axial symmetry. However, the high inertia force causes the slowing down of tool acceleration, which makes STS less suitable to machine mirrors with high-frequency asymmetries. These types of mirrors

can be developed by using Fast tool servo (FTS) systems. In sum, many special machining techniques can be integrated into an ultraprecision diamond turning machine to make it suitable for a particular shape of the surface feature. Some of the examples like STS, FTS, SSS (Slow Slide Servo), LADT (Live Axis Diamond Turning), VQ (CNC control re-polish technique), ACT (Adaptive Control Technique), and UADT (Ultrasonically Assisted Diamond Turning) with their potential applications are summarized in Table 1-1.

Many theoretical and practical studies focusing various aspects of special techniques of SPDT have been reported in the literature, which shows their significance and versatility for functional or structured surface generations. The application of FTS and SSS assisted diamond turning to synchronize the motion of the Z- and X- axes with the spindle (C-axis) generates complex 3D axisymmetric and non-axisymmetric features like Fresnel lenses, aspheric lenses and microlens array (MLA) with micrometer form accuracy and nanometer surface finish [10]. Kong et al. [11] utilized FTS assisted SPDT to manufacture MLA and developed an analytical model to predict the surface generation of lens array during the FTS machining process. Neo et al. [12] used SSS process in 4-axis ultraprecision machine to manufacture textured surfaces with sinusoidal wave grid (SWG) and MLA and showed the significance of cutting tool trajectory optimization for accurate surface generation during diamond machining. Zhang et al. [13] utilized SSS to produce sinusoidal freeform surfaces and proposed a new method using cylindrical coordinate micromachining to improve the overall form accuracy of the created feature. Yu et al. [14] also fabricated SWG and MLA on the brittle material using FTS assisted

diamond machining. All these examples of surface texturing that use SPDT and its associated processes are limited to produce features of an order of a micrometer to tens of micrometer range.

Table 1-1: Details of special techniques used with SPDT (redrawn from [15])

Techniques	Abbreviation	Axis	Used for
Slow tool servo	STS	X,C,Z, Tool STS	Off-axis parts, High amplitude surfaces, Freeform surface
Fast tool servo	FTS	X,C,Z, Tool FTS	High-frequency, lower amplitude, discontinuities surface
Slow slide servo	SSS	R, Z, θ , Z axis oscillation	Toroids, lens arrays, cylinders, freeform, f-theta lenses, off-axis aspheres,
Adaptive control technique	ACT	X, C, Z	Mirror, aspherical or spherical surface, surfaces with quality control
CNC control re-polish technique	VQ	X, C, Z, polish head	Surface roughness and form error control, asphere
Live axis diamond turning	LADT	X, C, Z	Surfaces with large departures
Ultrasonically assisted diamond turning	UADT	X, C, Z, Z high-frequency oscillation	Precision machining for ferrous metals and glasses

The fabrication of submicron scale textured surfaces by mechanical micromachining processes is very challenging. Until now, very few attempts are made to fabricate the submicron sized surface textures by SPDT or its associated processes. Brinksmeier et al. [6, 16] developed a novel technique to produce high-resolution elements by combining diamond turning with nano fast tool servo system (nFTS) to generate fine quality submicron-scale surface structures. Zhu et al. [17] proposed a unique method by combining FTS and flywheel cutting for surface texturing and successfully fabricated submicron-scale surface features on the machined surface. The external gadgets of FTS/SSS to control the tool-spindle synchronized motion dictates the geometrical limitations of produced textures in ultraprecision machining. These special SPDT techniques require high capital for an additional attachment of electromechanical system designing and fabrication as well as long processing and cycle time.

Having considered the production limitations of diamond machining processes, a simpler innovative fabrication technique seems highly preferable that can overcome the present limitations and can permit the fabrication of micrometer and even sub-micrometer scale features with mirror surface quality. This was the overall motivation of the current research in which an attempt was made to find out some simpler, faster and cheaper alternatives for submicron to micro-scale textured surface generations without any external electromechanical gadgets that are usually used with special techniques of SPDT.

In the current research work, a novel technique, named backside patterned texturing (BPT) is proposed for the fabrication of submicron to micron-sized features by ultraprecision SPDT. In this proposed technique, firstly the backside of work sample was pre-fabricated to generate a macro scale backside pattern. Then, the front surface of the sample was diamond machined up to a certain thickness to produce miniature features on the machined surface corresponding to the pre-fabricated pattern. Unlike from conventional methods, which require additional motion control system with complex tool path programming and be suitable only for micrometer scale textures generation, BPT produces features from submicron to micro-scale without any external electromechanical system for synchronized tool-spindle motion. Figure 1-1 shows the process approach of the BPT. However, the details about the technique are discussed in Chapter 3.

Figure 1-1 Process approach of backside patterned texturing (BPT)

1.2 NEED FOR THE RESEARCH AND SCIENTIFIC CONTRIBUTION

The current research work contributes to the knowledge of texturing methods in ultraprecision SPDT. Though various texturing techniques have been used with SPDT and its associated special techniques (as shown in Table 1), there are still some challenges especially the requirement of unique tool motion synchronizer and the limitation to produce submicron-scale surface features. The current work addresses these challenges by (i) demonstrating a simpler and faster fabrication technique without compromising the surface quality of diamond machined workpieces and (ii) showing the capability of producing surface features up to submicron scale (up to 100 nm) without any external tool motion controller.

1.3 OBJECTIVES OF THE RESEARCH

The objectives of the research are outlined as follows:

- a. To explore, propose and develop a novel technique, so-called backside patterned texturing (BPT) for submicron to micro-scale surface texturing using SPDT and without any external tool motion synchronizer.
- b. To study and explain the fundamental phenomenon/hypothesis behind the surface deformation during the texturing process in BPT.
- c. To perform experiments to undertake a parametric study and to investigate the correlation of workpiece surface deformation to the material thickness and the cutting speed.
- d. Development of a prediction methodology for residual stress based surface deformation in BPT.

- e. To develop a finite element (FE) model of diamond turning process for the prediction of residual stress based surface deformation in BPT at various workpiece thicknesses.

1.4 METHODOLOGY AND SCOPE OF THE RESEARCH

The complete research work is divided into two main sections: experimental study and predictive modeling. BPT is proposed for the fabrication of precisely controlled miniature surface features with optical surface quality. The complete experimental methodology for the fabrication of different sizes of convex shape surface textures by BPT is elaborated. The created surface topography is characterized by Talyscan™ and white light interferometer. At a given machining condition, the effects of backside pre-fabricated patterns and workpiece thickness to the surface deformation of the created textures on a diamond machined surface is studied. To demonstrate the efficacy of the method, some other types of freeform surface textures, such as waterdrop freeform, cylindrical freeform, spiral freeform and integrated freeform surfaces are also fabricated on the machined surface.

In the predictive modeling, a mathematical formulation based on the machining-induced source stresses is developed for the surface deformation analysis in BPT. The proposed methodology requires some preliminary experiments for an arbitrary type of produced surface textures, which gives an estimation of the source residual stresses in the plastically deformed layer of machined surface. The known source residual stresses are then taken as an input to predict the surface deformation for the subsequent axisymmetric or doubly symmetric texture geometries produced with similar machining conditions.

Furthermore, an FE model is also developed using plain strain explicit formulation to simulate a plunge cut in diamond turning. The details of the simulation approach, thermomechanical parameters and boundary conditions of the model are illustrated. Continuous chip formation is successfully developed without defining of any prior element damage criteria. The measured cutting forces during experiments validate the developed model. The machining-induced residual stress (RS) profile at the steady state condition is obtained from the cutting simulation and is subsequently used for surface deformation prediction. Later, the effect of RS on the surface deformation is studied. The FE simulations are performed by varying the workpiece thickness and the resulted surface deformation are compared with the experimental data.

1.5 OUTLINE OF THE THESIS

The report consists of seven chapters. The current chapter (Chapter 1) illustrates the background of surface texturing techniques especially SPDT and its special associated systems. The objectives and the scope of the work underlying the topic of the research are also outlined.

Chapter 2 discusses the relevant studies available in the literature focusing the submicron to micro-scale textured or engineered surface generation techniques and their potential applications. However, the literature review specifically focuses those micro-texturing techniques in which ultraprecision SPDT or its associated special techniques like FTS or SSS are used as a fundamental development process.

Chapter 3 demonstrates the process development, system configuration and machining conditions for the experiments to fabricate an array of convex shape textures and some other freeform surfaces.

Chapter 4 reports the experimental findings of surface textures, surface quality and effects of material thickness and cutting speed on surface deformation. The fundamental concept of the surface deformation in BPT is also discussed in detail. In addition, the comparison of grain size at thin and thick sections is also shown in this chapter.

Chapter 5 describes a mathematical approach to predict the surface deformation of the produced texture by the proposed technique of BPT. The modeling approach is explained in detail followed by the development of a mathematical formulation and a comparison of experimental and simulation results.

Chapter 6 presents an FE model to simulate DT for RS profile. Subsequently, the estimated stresses are to be applied to study the surface deformation in the textures developed by BPT. The modeling approach of the model is explained in detail. The RS profile along the workpiece thickness is extracted. Subsequently, the surface deformation is modeled based on the predicted RS profile. In the end, the simulated results of surface deformation were compared to the experiments.

Finally, Chapter 7 summarizes the overall research and the recommendations for the future work.

CHAPTER 2

LITERATURE REVIEW

This chapter begins with the reviews of relevant literature about functional or textured surface generation followed by the surface deformation analysis due to machining-induced residual stresses (RS) and its process modeling. Texturing techniques using ultraprecision diamond machining processes are mainly focused in this chapter.

2.1 FUNCTIONAL AND TEXTURED SURFACES

Microtextured surfaces have become popular for controlling of mechanical as well as functional properties due to its unique texture pattern. Chris et al. [1] defined the structured surfaces as “patterned” surfaces with some regular array of features that provide some deterministic functions. Over the decades, the submicron to micro-scale textured surfaces has played a key role in the development of many advanced technologies, which have been used in microelectronics, energy systems, optical applications, X-Ray optics, MEMS, biomedical systems, mechanical, tribology and hydrodynamic usages. Due to high demand for extended functionality components, the textured surfaces are of increasing importance. Bruzzone et al. [3] classified the textured surfaces into three main groups according to their features and applications as shown in Figure 2-1.

Many keynote papers have been published in CIRP showing the long history of research and development in micromachining. The CIRP studies review the textured or engineered surfaces in detail, their functionalities, potential applications, manufacturing procedures, technique development and limitations [1-3, 6, 18-21]. Chris et al. [1] focused on structured or textured surfaces of discrete components for mass production and commercial manufacturing. A detailed study about the range of manufacturing methods for textured surfaces was discussed showing the shortage and limitation of measuring techniques of the developed micrographs. De Chiffre et al. [18] reviewed various 2D and 3D measurement methods and relevant ISO standards for quantitative characteristics of textured or functional surfaces. Masuzawa et al. [19] discussed the significance of micromachining for the development of miniaturized products and their manufacturing methods, such as micro-EDM, micro-USM, lithography, micro-molding and micro-grinding. Lonardo et al. [21] studied the emerging trends in procedures and instrumentation for surface metrology and characterization of textured and optical surfaces. Corbett et al. [22] reviewed state-of-the-art nano-scale technological developments and discussed the materials used, fabrication techniques and potential applications in biomedical, space and optical technologies.

The material removal technologies used for the fabrication of submicron or micro-scale structured and functional surfaces can be divided into three main groups: chemical [23, 24], laser [25] and mechanical. A variety of different techniques in each of these groups has been extensively reported in the literature. However, this chapter only covers the texturing techniques in which mechanical material removal method is used for surface generation.

Figure 2-1: Classification of textured surfaces, their properties and applications (Redrawn from [3])

2.2 MECHANICAL TEXTURING PROCESSES

2.2.1 ULTRAPRECISION DIAMOND MACHINING

Ultraprecision diamond machining is the key and well-established technology for machining of very high-quality optical surfaces on almost all types of engineering materials like metals, semiconductor, ceramics, glasses, plastics and crystals. Ultraprecision machining processes produce components with a very high precision equivalent to the fraction of the wavelength of light, which makes it suitable for

fabricating parts to be used in optical applications. Freeform and complex microstructured or functional surfaces are commonly developed with very high accuracy and cost-effectiveness. Many techniques have been established with diamond machining for specific applications. Some of the important methods for functional surface generation using diamond machining are discussed in ensuing paragraphs.

2.2.1.1 FAST TOOL SERVO MACHINING

The diamond turning with the combination of a fast tool servo (FTS) has become attractive for the generation of freeform and various other types of structured optical surfaces. FTS is an independently operated precise electromechanical positioning system, which is attached to SPDT machine to increase the accuracy of the tool positioning during cutting. FTS system actuates the diamond tool back and forth by a piezoelectric actuator. Conventionally, in FTS the stroke remains within the range of 10 μm to 6 mm with the frequency range of 20 Hz to 20 kHz [26]. Hence, FTS machining cannot create submicron-scale surface features. Generally, nonferrous materials like copper and aluminum alloy are used as workpiece materials, which are attached to the vacuum chuck with or without a fixture. The machining parameters: spindle speed, tool nose radius and feed rate are important variables for surface contour designing in FTS machining. Figure 2-2 shows the mechanism of FTS. The stroke in Z-direction is controlled by an electromechanical system attached to SPDT machine. The rapid actuation of the tool by FTS makes it possible to fabricates axisymmetric surface features like a microlens array (MLA) on the machined surface [11].

Figure 2-2: Fast tool servo (FTS) system attached to SPDT machine [27, 28]

A typical microlens array is composed of a series of textured micro-sized convex shape bumps distributed in a regular pattern. One microlens typically has a diameter of an order of millimeter and depth as small as $10\text{ }\mu\text{m}$. A microlens is characteristically composed of a plane and a spherical surface. The spherical convex shape surface is used to refract the incident light. With the emergence and development of SPDT, the most commonly used method for optical microlens array generation is FTS machining. Microlens array light guides are often used for display devices and scanner [29]. FTS can generate lens array with micrometer form accuracy and nanometer surface finish and the developed surface can be used as a mold for mass production. Figure 2-3 shows an example of the microlens array generated by FTS machining.

Figure 2-3: Typical microlens array (a) final created convex shape [30] and (b) mold insert fabricated by FTS [11]

2.2.1.2 NANO FAST TOOL SERVO

In order to overcome the functional limitation of FTS, Brinksmeier et al. [16] developed a novel technique: nano fast tool servo (nFTS) for the fabrication of submicron-sized surface textures. The proposed method successfully demonstrated the fabrication of diffractive optical elements (DOE), which cannot be machined by conventional FTS system due to the complex structure and miniature features of submicron scale. This

technique was designed with the tool stroke of up to 500 nm at a bandwidth of 5 kHz or more. The quality of the machined diffractive optical elements by nFTS machining mainly depends on the piezo actuator, nFTS data preprocessing and the workpiece material. This proposed nFTS method can be used for the fast generation of complex structures at one step on metallic surfaces for security applications. The blaze type diffractive structured surface generated by nFTS machining is shown in Figure 2-4.

Figure 2-4: Blaze type diffraction structures fabricated by nanometer fast tool servo (nFTS) diamond turning [6]

2.2.1.3 SLOW SLIDE SERVO MACHINING

Typically, diamond turning machine consists of two linear axes (X and Z) for position controlling and a spindle (C-axis) as a velocity controller. In slow slide servo (SSS), the spindle axis (C-axis) also acts as a position controller. The diamond tool is mounted

along the Z-axis. The workpiece is attached to the rotating spindle and the tool mounting on the Z-axis oscillates in sine wave in and out pattern to generate freeform and axisymmetric surface features. A CNC program synchronizes the relative 3D tool motion of all axes for a surface generation [31]. Figure 2-5 shows the schematic of SSS system and an example of a texture (compound eye) fabricated by SSS diamond machining.

The slow slide servo (SSS) mechanism is very much similar to the FTS, as the workpiece is attached to the machine spindle and the tool oscillates with the spindle rotations. However, in contrast to FTS system, SSS system does not use any additional axis to oscillate the diamond tool and the Z-axis slide generates the tool oscillations. Secondly, the spindle position controller (C-axis) works differently. In an FTS set-up, the spindle has an encoder that feeds the position to FTS unit without putting the spindle in position control. On the other hand, in SSS system all axes including C-axis are under fully coordinated to control the synchronized position control. Comparing with the FTS system, the SSS mechanism is relatively faster and easier to setup and consequently it has short cycle time. SSS also allows the manufacturing of highly accurate and precise parts. SSS is ideal for the fabrication of many freeform surfaces including freeform polynomials, torics and Zernike surfaces [32].

Figure 2-5: (a) Machining setup of slow slide servo (SSS) [33] and (b) 3D convex shape compound eye fabricated by SSS diamond machining [34]

2.2.1.4 SLOW TOOL SERVO MACHINING

The slow tool servo (STS) relies on the synchronous motion of tool holder and the spindle rotation by a feedback control system from the mechanical slides. In FTS, the diamond tool is usually attached to a stack of the piezoelectric actuator. Hence, the frequency response of FTS can be extremely high compared to the mechanical slides of the ultraprecision machine. Unlike to the FTS system, in STS system the diamond tool is mounted on the Z-slide and moves together by a feedback loop at much lower speed or frequency [10, 35]. The ultraprecision machine equipped with STS's capability enables the diamond machining of complex surface features, such as off-axis aspheres, torics and other freeform surfaces. STS system is more appropriate for the machining of larger diameter workpieces, whereas the FTS process is more suitable for smaller diameters.

2.2.1.5 DIAMOND MICRO CHISELING

Diamond micro chiseling (DMC) [36] is a method for the generation of micro retro-reflector and other micro-optic structures like corner cube array, which are not considered machine-able previously by diamond machining. Commonly, the retroreflectors are used for reflecting light ray into the direction of its source, independent to its incident directions. The DMC process uses the V-shaped diamond tool on a 5-axes ultraprecision machine tool that consists of three hydrostatic linear slides and two aerostatic rotational axes. Figure 2-6 shows the developed cube corner retroreflector by DMC. The surface roughness $R_a < 8$ nm was achieved for the textured surface.

Figure 2-6: Corner cube array fabricated by diamond micro chiseling [6]

2.2.2 VIBRATION-ASSISTED MACHINING

Vibrating-assisted machining (VAM) is a unique machining operation in which small amplitude; high-frequency vibration is applied to the cutting tool using an external source to enable the tool to vibrate in a controlled manner. The vibrations are often applied by an

ultrasonic transducer (frequency range: up to 40 kHz) mounted on a tool post with the cutting tool attached to it. Vibrations can be applied in a single direction (linearly) along the cutting speed to cause the tool to periodically disengage from cutting or in two directions to create an elliptic motion to the cutting tool. Figure 2-7 shows the schematic of linear and elliptical vibration of cutting tool excitation through ultrasonic transducer.

Figure 2-7: Schematic of tool cutting edge motion in (a) linear and (b) elliptical vibration assisted machining [37]

Vibration-assisted machining (VAM) in ultraprecision machining has been used for micro-sized surface texturing. Suzuki et al. [38] proposed a method for surface sculpturing and texturing using ultraprecision diamond machining. The workpieces used for experiments was made up of steel and machined with single crystal diamond (SCD) cutting tools. Elliptical vibration-assisted cutting was applied to the cutting tool during

UP machining and the variation of the elliptical vibration locus was then used for texturing. The cutting depth during elliptical vibration cutting was controlled by the vibration amplitude of the cutting tool. With this technique, high-performance surface sculpturing and various shapes of grooves were fabricated. Figure 2-8 shows the developed textured by the vibration-assisted diamond machining.

Figure 2-8: Photographs of textured surface fabricated by elliptical vibration assisted cutting in ultraprecision diamond machining. (a) various patterned grooves at varying speed and conditions (b) concave dimple pattern (c) hexagonal dimple pattern [38]

Guo et al. [39] conducted a comprehensive study to investigate the texture generation mechanics of elliptical vibration assisted cutting in precision diamond machining. The experiment was performed and an algorithm was developed to predict the surface

generation during machining. Figure 2-9 depicts the experimental textured surface and simulated pattern developed by proposed algorithm.

Figure 2-9: Textured topography by elliptical vibration assisted diamond machining (a) experimental results and (b) simulation results [40]

2.3 RESIDUAL STRESS IN THE MACHINED COMPONENTS

Residual stress (RS) can be expressed as a compression or tension of material without the existence of any external load like applied force, displacement or thermal gradient. RS remain in the processed material after the original cause of the stresses has been removed. These types of stresses can occur due to many reasons including heat treatment and cooling, inelastic deformations and phase transformation. Manufacturing processes induce RS in the material by non-uniform thermal contractions, heterogeneous plastic deformations, or phase transformations. Compressive residual stress is generally desired as it has a beneficial effect on the fatigue life and it delays crack initiation and propagation. Tensile stress, on the other hand, adversely affects the mechanical performance of the materials.

The machining process, which involves thermal and mechanical loading and generates surface and subsurface damage or deformation, alters the mechanical and metallurgical properties of the machined workpiece and induce residual stresses [41, 42]. By releasing the workpiece from the fixture, the RS 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 [43]. 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.

The magnitude of the RS and its penetrations depth into the workpiece subsurface is also important with its nature of compressive or tensile. The RS profile caused by manufacturing processes usually show very steep profile to the depth gradients. In conventional machining, RS profile as deep as 200 μm was observed when cutting AISI 4340 with the depth of cut 200 μm [44]. El-Khabeery et al. [45] found that the absolute value of the RS is initially high in the surface and decreases continuously with an increase in the cutting depth. They observed the RS until about 300 μm depth beneath the machined surface. Guo et al. [46] observed the RS is tensile at a depth of 20 μm and changes to be compressive at 100 μm in the high-speed milling of aluminum alloys. Also, the depth of residual stress (RS) is dominantly affected by the mechanical loading [47].

Jacobus et al. [44] performed a detailed analysis of the residual stress (RS) generation in the machining process and discussed the following three possible stress profile along the workpiece thickness:

Case 1: When the thermal strain is less than plastic deformation; it causes the compressive residual stress in the surface and subsurface.

Case 2: When the thermal strains dominate the plastic deformation; it causes tensile stresses at the surface and near the surface and compressive stresses at the subsurface.

Case 3: When the plastic deformation in the subsurface is less than zero; it causes the stress in the surface and subsurface to become tensile.

Figure 2-10 shows the schematic of the three possible RS profiles in the machined workpiece. At high cutting speed, the thermal load will be more dominant and cause tensile residual stresses on the machined surface, whereas mechanical load will have a greater effect for low cutting speed and consequently induces compressive residual stress [48].

Figure 2-10: Potential residual stress profile induced by machining processes [44].

2.4 SURFACE DEFORMATION DUE TO RESIDUAL STRESS

The surface deformation caused by the generation of RS is one of the major sources of the machined component distortion that leads to the component waste. Many studies have been performed in the area of machining-induced surface deformation. The primary focus of most of the available literature is on the distortion of thin-walled components and thin sheets/plates with a high strength to weight ratio, which is widely used in many advanced technologies, such as components used in aerospace applications. Such components require a fine surface quality and low dimensional tolerances. Hence, the reduction of the machining-induced part deformation has become increasingly important. However, due to the low stiffness, the thin workpieces can easily deform. The induced RS during machining in the surface and subsurface region can cause serious surface deformation after the workpiece has been finished. It has been shown that when the residual stresses are increased, or the thickness of workpiece is decreased, the surface deformation and distortion is increased [49].

The machining-induced residual stress influences the internal stress equilibrium state and in the end redistribute 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 becomes larger [50]. In the machining of webs or plates, the curvature (deflection) and dimensional instability (distortion) occurred as the compensation of the component self-equilibrates for the unbalancing of forces and moments upon removal of the material from the fixture. It is noted that the influence of the machining strategy due to machining

parameters, workpiece conditions, tool conditions and workpiece fixture are significant to the workpiece deflection and the depth of damage [51].

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 lowest reference plane. The RS affects the quality of the machined workpiece. In the case of the machining of the thin workpiece, the depth of the residual stress can be significant compared to the thickness of the machined workpiece. There are not many studies available in the literatures, which discuss the effect of the machining to the warping of the thin workpiece. Hence, there is a gap in understanding the surface deformation of the thin workpiece due to the contribution of the machining-induced stresses.

The redistribution of the RS after machining and removal from the machine brings about the potential distortion, which leads to an increase in scraped parts and cost of production. Therefore, many researchers have been given increasing efforts to predict the surface deformation caused by machining-induced RS and to optimize a strategy for its control. The predicting techniques of workpiece deformation from the introduction of RS field could be classified into two categories. The first group directly maps the ‘experimentally measured RS field’ into a finite element model for deformation analysis. On the other hand, in the second group, the RS field is obtained from an analytical model and then is mapped to an FE model for deformation prediction. Both of these categories are discussed in the ensuing paragraphs.

2.4.1 MAPPING OF EXPERIMENTALLY MEASURED RS FIELD

Many researchers attempted to develop techniques for the prediction of workpiece distortion resulting from the introduction of RS. The RS field is obtained from the measurements of the machined workpiece and subsequently mapped to a finite element (FE) model for surface deformation analyses. The mapping method can also be used to study the distortion of complex and curved parts where another method like analytical modeling is difficult to apply [52, 53]. The residual stress (RS) field can be measured from a simple shaped workpiece and then the measured RS profile is to be mapped to a complex and curved geometry. The stress field is rebalanced in the workpiece model and the relevant out-of-plane surface deformation can be predicted. For stress mapping, the mesh of the top layers in FE model, which represent the surface and subsurface of machined workpiece model should be refined enough for the acceptable accuracy of the simulation results. Hence, mesh density should be modeled with care while mapping the RS field to FE model as the stresses are rapidly changed along the workpiece thickness and usually top thin layer of the processed surface contains the larger stress values.

For surface deformation analysis, the RS from the bulk machined workpiece can be defined as initial conditions using FE modeling software of ABAQUS. Huang et al. [53] mapped the measured RS profile as an initial condition to FE models of monolithic components to investigate RS based part deformation. In this model, the technique of “element birth and death” is used to simulate the material removal in the milling process. Figure 2-11 shows the FE model in which RS is mapped across the thickness of the workpiece.

Figure 2-11: (a) Measured RS profile mapped to the test specimen and (b) FE simulation for deformation analysis [53]

Ritcher et al. [54] proposed a methodology for the prediction of plate deformation manufactured by high-speed machining. The RS profile was experimentally measured along the workpiece thickness by the classic ‘layer removal technique’ proposed by Hospers et al. [55]. The estimated RS field was then mapped as an initial condition to FE plate models at different thicknesses for elastic deformation analysis. Figure 2-12 represents the FE model of a 3D plate with the mapped RS profile along the workpiece thickness for deformation analysis.

Figure 2-12: Measured RS profile mapped to the plate model for deformation prediction (a) measured distortion on the machined plate and (b) the predicted plate deformation by FE simulation [54]

2.4.2 RESIDUAL STRESS FROM ANALYTICAL MODEL

The experimental measurement of the RS profile requires a lot of expertise, efforts and time. Therefore, instead of mapping of the measured RS field, many researchers have attempted on the analytical model to predict the RS field for the workpiece processing deformation analysis. Jiang et al. [56] proposed a hybrid model by combining mechanics of materials theory and response surface design method together to simulate the surface deformation caused by the RS profile along the workpiece depth. Fergani et al. [57] developed an analytical model for the residual stress field and its associated distortion in a thin milled plate. However, the developed model is limited to the milling process and cannot be modified for other machining operations. Liu et al. [58] developed a 3D FE

model to simulate the milling of a T-shaped structure and investigated the deflection caused by process forces. This model ignores the elastic deformation caused by RS in the machined workpiece. E. Brinksmeier et al. [59] calculated the ‘source residual stresses’ from a simple model and then mapped the stress value to a relatively complex FE model of a linear rail for shape deviation analysis.

Most of the developed analytical models for RS simulation are limited to the specific machining process mechanics and cannot be generalized or extended to other machining processes. Also, the assumptions made for the designing of analytical model carry the unwanted errors.

2.5 RESIDUAL STRESS FROM FE MODEL

All of the previous contributions mainly focused either on the experimental stress measurements or complex analytical model development. As mentioned earlier, the experimental measurement of RS profile along the workpiece depth is complex and time-consuming especially in thin workpieces because of low-stress penetration. It is well known that the maximum stress is found at the surface and near-surface region. The magnitude of the stress decreases along the thickness of the workpiece. In the case of diamond machining, the induced stresses diminish very quickly beneath the top surface and only the top thin layer up to 20 μm is significant for the stress analysis. Generally, XRD technique is used to measure the surface stresses of the machined workpieces. The measuring/absorbing depth of X-rays depends on the source and work material. For ductile aluminum alloy (like Al 6061), the X-ray absorbing depth is close to 75-80 μm (for general purpose Bruker D8 DISCOVER XRD). It means that, in the case of diamond

machining of aluminum workpieces, even with a cautious measurement strategy, it is only possible to determine an estimate of residual surface stresses (either compressive or tensile) over the absorbing depth of X-ray. However, the actual stress profile along the workpiece thickness, which could be the combination of compressive and tensile stresses, cannot be measured by XRD. Figure 2-13 shows the schematic of X-ray beam penetration, larger than the stressed layers.

Figure 2-13: X-ray penetration depth into work sample during stress measurement

This problem can be addressed by obtaining the RS depth profile from an FE model of diamond machining, rather than from experimental measurement. The simulated RS profile can be mapped then to another simple FE model for surface deformation analysis. This approach is followed in the current thesis in which the diamond turning is first simulated via a developed FE model and the RS profile across the workpiece thickness is extracted from the steady state condition. Then, the RS profile is mapped to another FE model for surface deformation prediction. The detail of the modeling approach and

simulation results is discussed in Chapter 6. However, the relevant literature about the FE modeling approaches is discussed in the ensuing paragraphs.

2.5.1 FINITE ELEMENT MODELING

The finite element (FE) modeling has been developed for the last three decades by many researchers. A lot of research into elasticity, plasticity, contact mechanics, fluid dynamics, creep, etc. has been implemented in the FE models. Many commercial and non-commercial FE codes have been developed for solving different linear and nonlinear problems like machining. FE modeling provides a useful tool for the better understanding of material flow and surface generation in conventional as well as in precision diamond machining. FE simulations can explain the physical phenomenon and it gives the scientific information, which is unreachable by analytical modeling or experiments. However, the peculiar nature of machining process, nonlinear localized stress, strain and temperature are the factors that make the numerical simulations extremely difficult.

There are three ways to simulate the cutting process for finite element analysis: Lagrangian, Eulerian and arbitrary Lagrangian-Eulerian (ALE) mesh motion schemes. All of the three modeling approaches have been used for the simulations of cutting processes. An overview of the finite element simulations can be seen from 1976 to 1996 in [60] and from 1996 to 2002 in [61]. Besides, some of the recent advancements in the FE simulation of machining process can be found in [62].

2.5.1.1 LAGRANGIAN APPROACH

The FE cutting simulation with Lagrangian approach necessarily requires a suitable chip separation criterion for continuous chip formation. The overall simulation results largely depend on the predefined chip formation criterion. Therefore, the criterion must reflect the cutting mechanics and physical mechanism of the workpiece material to produce reasonable results regarding cutting forces, chip geometry, temperature and residual stress distribution. The Lagrangian approach can simulate the cutting process from the incipient to steady state to study the various aspects of machining including cutting temperature, tool edge effects, residual stresses, tool wear, etc. In Lagrangian boundary conditions, the cutting velocity is applied to the tool and the workpiece remains stagnant. Figure 2-14 shows the schematic diagram for plain strain cutting simulation using Lagrangian approach. The tool moves at the given velocity from the incipient to steady state and the continuous chip is formed due to predefined chip formation condition. However, the workpiece is fully constrained at the bottom and left side.

Figure 2-14: Lagrangian boundary conditions for cutting simulation [63]

The chip separation criteria can be divided into two categories: geometrical and physical criteria. In geometrical chip separation, a critical distance between tool tip and the nearest node ahead of the tool (tool-workpiece distance) is given to separate the chip from the bulk material. When the tool-workpiece distance is equal to the given threshold, the chip starts to form. The geometrical criterion has a disadvantage as it does not have any physical meaning. It is hard to predict the true critical tool-workpiece distance. To run the simulation, the critical tool-workpiece distance should be as small as possible to obtain the realistic results as long as the numerical instability is avoided. Geometrical chip separation criteria have been used in many cutting simulations [64, 65].

On the other hand, the physical chip separation criterion is based on the critical threshold values of some physical parameters like equivalent plastic strain, strain energy density or stress in the elements nearest to the tool cutting edge. For the implementation of physical criterion, a pair of coincident nodes at a pre-defined parting line or sacrificial layer is defined at the onset of the simulation. The nodes are separated and the chip is started to form once the given physical condition is satisfied [66, 67]. Figure 2-15 shows the node separation due to pre-defined physical chip separation criterion. A detailed review of the chip separation criterion in FE cutting simulations can be seen in [68]. Zhang [68] argued that there is no ideal existing chip formation criterion and most of the criteria partly represents the physical mechanism of the experimental chip formation.

Figure 2-15: (a) Initial mesh and boundary condition for Lagrangian approach using physical separation criterion and (b) twin nodes separation during chip formation [66]

2.5.1.2 EULERIAN APPROACH

Due to disadvantages with pre-defined chip separation criteria, it is always desired to avoid them in the cutting simulations, which can be achieved by using Eulerian mesh motion scheme [69-72]. In the Eulerian approach, the mesh remains fixed in space and the material flows through the mesh. With this method, the large deformation can be handled properly and the mesh distortion during the simulation can be avoided. Another advantage of the Eulerian approach is that it does not require any pre-defined parting line or chip separation criterion. The material flows inside of the workpiece mesh and the cutting tool remains fixed [72]. The boundary conditions for the Eulerian mesh motion scheme are shown in Figure 2-16. Eulerian boundary conditions are applied to inflow, outflow and at the chip top surface. Hence, the material flow is bounded at the vertical position. However, other surfaces are defined by Lagrangian boundaries. As the simulation progress, the thickness of the chip and tool-chip contact length gradually settles to their final values as the steady state is reached. This approach also has some associated disadvantages. First of all, the chip shape and geometry must be known at the

onset to enter in the FE model. Secondly, the continuous elongated chip formation cannot be simulated with this approach. Also, the Eulerian mesh cannot yield residual stresses in material as the elastic behavior is not considered in this approach [73].

Figure 2-16: (a) Eulerian boundary conditions and (b) initial meshing and chip geometry [69, 70]

2.5.1.3 ARBITRARY LAGRANGIAN-EULERIAN (ALE)

The arbitrary Lagrangian-Eulerian (ALE) simulation approach is relatively a new technique compared to pure Lagrangian and Eulerian techniques. In fact, the ALE techniques combine both the Lagrangian and Eulerian formations without their disadvantages [73, 74]. In ALE formulation, different zones of the workpiece are defined either Lagrangian or Eulerian meshing regions. The regions of inflow and near tool edge are defined with Eulerian boundaries. Whereas, other regions and chip top surface represent the Lagrangian boundaries [75]. The mesh near the cutting edge remains fixed due to Eulerian meshing definition. In this way, the mesh distortion accompanied with the large material deformation can be handled without the termination of the simulation. In addition, the material flow around the cutting edge of the tool can be modeled as a close representation of actual machining condition.

An arbitrary geometry of the chip is defined at the start of the simulation. However, it just provides ease in the simulation and is not necessarily required in ALE approach. As the simulation continues, the chip geometry redefines itself and acquires a new shape and size depending on the material and machining conditions. The cutting velocity is applied on the nodes in the inflow region and the cutting tool remains fixed in ALE simulation. Figure 2-17 shows the schematic of ALE boundary conditions and chip formation.

Figure 2-17: ALE mesh motion scheme (a) initial shape and (b) continuous chip formation (Redrawn from [73])

2.5.2 NUMERICAL SIMULATION OF DIAMOND TURNING

The work reported by Carrel et al. [76] is considered a pioneer for numerical simulation of diamond turning (DT). This study covers the Lagrangian as well as Eulerian approaches for FE simulations. Subsequently, many researchers attempted to model

diamond turning using various approaches to provide realistic and robust simulation results. Some of the relevant studies for precision diamond machining simulations are highlighted here.

Mamalis et al. [77] used the Lagrangian formulation with implicit integration to model the precision hard turning to study the tool edge radius and cutting speed effects on process forces, machining temperature and residual stresses. In order to consider the tool edge radius, element-remeshing method is applied for the continuous chip formation. Zang et al. [78] used the similar modeling approach to simulate the precision diamond turning for OFHC copper. This study focused on investigating the effects of tool geometry (rake angle, clearance angle, edge radius) and cutting velocity on the RS. Though this FE model provides some insight to choose the optimal cutting tool geometry for better machining performance; there are some shortcomings in this study. The developed FE model used implicit integration for cutting simulation, which is computationally very costly compared to the explicit integration, especially when the large cutting length is simulated. Secondly, the model validation was not discussed in the study. Only the maximum stresses found at the machined surface was considered as the benchmark to optimize the tool geometry. The stress profile as a function of the workpiece thickness was not taken into account. The numerical study was based on the transient stresses near the cutting edge of the tool, rather than at the steady state.

Zone-Ching et al. [79] also utilized the Lagrangian formulation to study the residual stress induced by ultraprecision diamond machining for orthogonal cutting of NiP alloy.

To generate the continuous chip, a node-separation criterion based on a predefined critical strain energy density was used. This study ignored the rounded edge of the diamond tool tip. Compressive stresses were found at the surface and subsurface in x- and y-direction for all the testing cutting depths of 1 μm , 3 μm and 5 μm . The maximum thickness of the stressed layer was found close to 12 μm . Wu et al. [80] introduced a pure-deformation technique to simulate diamond turning using updated Lagrangian formulation and elements adaptive meshing. The study suggested that the need for the chip separation criteria or parting line, which is necessary while using Lagrangian formulation or pre-defined chip geometry in the case of the Eulerian formulation can be avoided by using the pure-deformation technique. The chip is formed as the tool advances and adaptive meshing alleviates the large element distortion occurs near the cutting tool edge. The total length of the workpiece modeled was 10 μm . With this approach, the material flow around the cutting edge can be realistically modeled. However, this method requires a number of iterations to optimize the mesh density and sweeping frequency to complete the simulation. Also, this approach is not suitable when the longer cutting length is modeled, which is generally desired when residual stresses are to be estimated. The region near the tool cutting edge requires very fine mesh and consequently results in a lot of computational costs. The suggested pure-deformation approach seems more suitable for the transient analysis only. Figure 2-18 shows the chip formation for cutting simulating using the pure-deformation technique.

Figure 2-18: Chip formation for cutting simulation using pure-deformation technique with the Lagrangian formation [80]

As discussed earlier, the FE model of diamond turning mostly uses the Lagrangian formulation with or without pre-definition of chip separation criteria and parting line. The FE simulation based on Eulerian or ALE mesh motion is hardly reported in the literature. In the current thesis, diamond turning process is simulated using ALE based formulation, which is never attempted before. In ALE formulation, the cutting simulation undergoes using adaptive meshing of elements by a pre-defined element mapping frequency and sweep. Therefore, the requirement of an element deletion criterion, which is necessary for continuous chip formation, can be avoided. Hence the cutting edge effect of the diamond tool on the surface formation can be considered. The primary purpose of the FE modeling and simulation is to support and enhance the fundamental physical understanding behind

surface deformation in the newly developed texturing technique of BPT. Furthermore, the surface deformation in thin workpieces due to SPDT is not fully understood and has not been researched thoroughly. The developed FE simulation also helps to understand the relationship of workpiece thickness and induced RS in diamond turning.

2.6 SUMMARY

This chapter reviews the ultraprecision SPDT and its associated specialized techniques, such as FTS, SSS and STS for the fabrication of textured and functional surfaces. An overview of the surface deformation based on the RS and FE modeling of diamond turning is also outlined. Some of the issues that have been noticed through the comprehensive review are as follows:

- All of the existing texturing techniques used with ultraprecision diamond machining processes require some external electromechanical devices for the precise controlling of tool contour for asymmetric and freeform surface generation. Also, the implementation of these techniques is time consuming due to complex tool path programming and longer cycle time.
- The RS profile along the workpiece depth is required for the surface deformation prediction. However, due to the very low penetration depth of the stresses, the RS profile as a function of thickness for the diamond turned workpieces cannot be measured by the conventional stress measurement techniques like XRD.

- The FE model of diamond turning mostly uses the Lagrangian formulation with or without pre-definition of chip separation criteria and parting line. The numerical model using the ALE formulation to simulate diamond turning and machining induce RS analysis is not reported in the literature.

The following chapters intend to address the aforementioned issues.

CHAPTER 3

BACKSIDE PATTERNED TEXTURING – PROCESS DEVELOPMENT AND METHODOLOGY

This chapter describes experimental development and system configuration for the proposed technique of backside patterned texturing (BPT). The process steps, system configuration and requirements are illustrated. Furthermore, the detailed machining parameters for fabrication of an array of mirror quality regular bumps and other freeform surfaces are described.

3.1 SYSTEM DEVELOPMENT

Backside patterned texturing (BPT) is a newly developed technique, which utilizes a pre-fabricated workpiece with arbitrary backside pattern for submicron to micro-scale surface texturing. Figure 3-1 shows the methodical approach of BPT. The fabrication process essentially consists of two steps. In the first step, a macro-scale pattern is pre-fabricated on one side of a workpiece. The pre-fabricated patterned side of the workpiece is referred as ‘backside of the workpiece’ in this technique. The design and geometry of the pre-fabricated pattern is associated with the desired textures formation on the final machined

surface, which is regarded as the ‘front side’. The backside pattern can be fabricated by a simple milling, drilling or EDM process. The pre-fabrication process actually divides the whole workpiece into thick and thin sections. Figure 3-2 shows the schematic diagram of a workpiece in which some holes are pre-fabricated as backside patterns.

In the second step, the front-side of the workpiece is diamond machined using consecutive face turning passes with suitable machining conditions. The machining passes gradually reduce the overall thickness of workpiece (including thick and thin sections). At the end of the diamond machining process, the workpiece is released from the machine’s vacuum chuck and all the displacement constraints provided by workpiece holding mechanism are removed. Upon workpiece removal from the machine, the induced residual stresses in the machined workpiece achieve a new state of equilibrium. Accordingly, the deformation of the overall newly machined surface is taken place. The thinner section of the workpiece experiences larger deformation, which leads to developing the associated texture on the front side of the machined workpiece.

Figure 3-1: Methodical approach of backside patterned texturing (BPT)

Figure 3-2: Schematic of pre-fabricated workpiece showing the thick and thin sections

3.2 SYSTEM CONFIGURATION OF BPT

3.2.1 EXPERIMENTAL SETUP

The experimental setup of BPT as shown in Figure 3-3 demonstrates the fabrication of submicron to micro-sized convex shape bumps on the diamond machined surface. A multi-purpose micro-machine, Mikrottools DT-110 (Figure 3-4) is used to machine the pre-fabricated patterns like holes (as shown in Figure 3-3) on the backside of the workpiece.

Figure 3-3: Experimental set-up for BPT, (a) pre-fabrication and (b) diamond machining

Figure 3-4: Micro-milling machine (Mikrotools DT-110)

The pre-fabricated workpiece is then clamped to the vacuum spindle of a 2-axis ultraprecision diamond turning machine, Precitech Nanoform[®] 200 (Figure 3-5). The ultraprecision machine uses high stiffness hydrostatic slide-ways and slot-type thrust bearing for ultraprecision control of tool movement. Nanoform[®] 200 can also support FTS and STS attachments for the machining of non-rotational asymmetric freeform surfaces. However, the proposed technique of BPT utilizes the ultraprecision machine in its simplest form and without any external attachment for motion controller. The front side of the workpiece is diamond turned by a series of consecutive face turning passes, which induce machining stresses to the surface and subsurface of the newly machined workpiece. After diamond machining, the workpiece is removed from the vacuum spindle for the surface inspections. The surface is cleaned by alcohol to remove the attached debris and chips prior surface measurement.

Figure 3-5: Ultraprecision diamond turning machine Nanoform[®] 200

The scope of the experimental study mainly covers the development of convex shape regular bumpy textures on the machined surface corresponding to the backside holes as pre-fabricated patterns. However, the similar experimental setup can also be used for other types of pre-fabricated patterns or textures geometries.

3.2.2 EXPERIMENTAL WORK

3.2.2.1 SINGLE POINT DIAMOND TURNING

Single point diamond turning (SPDT) refers to a facing operation where the length of a workpiece is reduced by single point cutting tool movement perpendicular to the axis of rotation. This definition is in contrast to the typical ‘turning’ operation for conventional machining in which a cutting tool moves parallel to the axis of rotation and reduces the diameter of a workpiece. A schematic of SPDT operation is shown in Figure 3-6. In a simplest form of SPDT, the cutting edge of the diamond tool remains perpendicular to the cutting velocity (v_c) and the tool moves towards the center of the workpiece at a given feed rate (f). The cutting depth (d_c) is applied along the axis of rotation to reduce the overall length producing the cutting chip which separates from the workpiece at the tool-workpiece interaction region.

Figure 3-7 shows the theoretical chip cross-section for DT defined between two successive positions of the cutting tool at a distance equal to the feed rate (f) for a cutting depth (d_c). Figure 3-7 (a) shows the front view of the tool’s rake face at which the relative motion between diamond tool and workpiece is normal to the direction of the cutting process. The shaded region ‘A’ is the cross-section of material removed after the tool has

been fed into the workpiece surface, while the shaded region 'B' is removed with each subsequent feed of the tool. For diamond turning, the width of cut which is represented by 'b' for a single turning pass can be expressed as shown below [77, 81].

$$b = r \left\{ \cos^{-1} \left(\frac{r - d_c}{r} \right) + \sin^{-1} \left(\frac{f}{2r} \right) \right\} \quad (3.1)$$

Where r represents the cutting tool nose radius.

Figure 3-6: 3D Schematic view of the diamond face turning

Figure 3-7: The schematic geometry of chip formation in SPDT (a) theoretical cross-section and (b) magnified view revealing the details (Redrawn from [82]). The proportion of cutting radius and cutting depth is exaggerated to show clearly the regions of material

removal

3.2.2.2 SINGLE POINT DIAMOND TOOL

The entire diamond turning experiments were performed by insert type single point diamond tools, which is made by natural single crystal diamond (SCD). The natural diamond tools are expensive but are known to produce better surface finish than synthetic diamond tools. SCD is vacuum brazed on the tungsten carbide insert, which is attached to the tool shank for machining, as shown in Figure 3-8**Error! Reference source not found..** Solid-shank diamond tools are also available in which the SCD is directly brazed on the tool shank. However, in-situ replacement of insert type tool is possible without disturbing the centering of the attached workpiece to the machine chuck. The schematic of the tool inserts with their dimensions used in the experiments is attached in Appendix A.

Figure 3-8: Insert type single point diamond tool attached to the tool shank

The radius or arc formed by the intersection of the flank and the rake faces of the diamond tool is represented by the cutting edge of the tool. The sharpness of the edge, which is referred as the ‘cutting edge radius’ (r_e), plays an important role in the surface generation in diamond machining and affects the quality of the machined surface. Very fine quality cutting edge of a tool is generally fabricated using special edge preparation process, which may include different methods like brushing, drag finishing, microblasting, wet edge honing and laser treatment, etc. [83, 84]. The cutting edge always has a defined edge radius because perfectly sharp edge tool is not possible to develop due to technological limitations. The geometry of the cutting edge and its preparation process can significantly influence the tool performance, tool life, chip formation, surface finish and surface integrity [85]. Generally, the cutting edge radius (r_e) of diamond tools used in SPDT ranges from 100 nm to 500 nm depending on its manufacturing process and material used (synthetic or natural) [86, 87], which is much smaller than the edge radius of the tools used in conventional cutting. However, tungsten carbide tool used in normal machining process, the cutting edge radius used remains in the range from 5 micron to 50 micron [88].

In conventional machining, the cutting depth (d_c) is much larger than the cutting edge radius (r_e), by at least three orders of magnitude. However, the cutting depth (d_c) may approach to cutting edge radius (r_e) in SPDT as the cutting thickness ranges from tens of micrometers to tens of nanometers [89]. Z. J. Yuan et. al. [86] experimentally and theoretically analyzed a relationship between minimum cutting depth ($d_{c,min}$) and the radius of diamond tool edge (r_e). The study described a critical point ‘A’ generally known as ‘stagnation point’ near the tool edge at cutting zone (Figure 3-9). As the tool interacts

with work material during cutting, one part of the material above point 'A' is piled up to form the chips. However, the other part underwent to burnishing/ploughing due to the finite size of edge radius. This part of the material is ultimately forms the newly machined surface. In addition, it is argued that the minimum cutting thickness ($d_{c,min}$) largely depends on the cutting edge sharpness of the tool for continuous chip formation, as shown in Eq. (3.1). From the expression, it is inferred that large edge radius (r_e) is not suitable for machining in case of low cutting thickness.

$$d_{c,min} = (0.322 \sim 0.249) r_e \quad (3.2)$$

Furthermore, the waviness of the tool edge should also be carefully controlled for mirror quality surface finish. Waviness is the amount of deviation of the cutting edge from a true circle, measured from peak to valley. All the diamond tools used in the experiments had the 'controlled waviness' with the maximum peak-to-valley deviation of 100 nm. The quality certificate of the tool cutting edge is attached in Appendix B.

Figure 3-9: Cutting tool edge geometry, where d_c and $d_{c,min}$ represent the normal cutting depth and the minimum cutting depth, respectively (Redrawn from [86])

3.2.2.3 EXPERIMENTAL CONDITIONS

A number of work samples were machined to evaluate the functionality, efficacy and suitability of the developed technique. The workpiece material was Al 6061-T6, which is commonly used for optical mold and components. The diameter and thickness of the circular workpieces were 43 mm and 3 mm, respectively. In order to proper clamping of the circular discs, the diameter of the workpiece should match with the grooves size of vacuum chuck of machine spindle.

As backside patterns, some holes with diameter of 1.5 mm, 2 mm and 2.5 mm were fabricated by carbide tools up to the depth of 2.6 mm. Hence, the workpiece thickness at thinner section after the pre-fabrication process was 400 μm , which is termed as ‘the initial workpiece thickness at thinner portion’ and represented by t_{ri} . The initial thickness (t_{ri}) of 400 μm was selected on the basis of some preliminary experimental analyses and for the material thickness $> 400 \mu\text{m}$ at the thinner section, no surface texturing was observed. The workpiece thickness at thinner section after diamond face turning passes and the deformation height of the created features are denoted by t_{rf} and t_b , respectively (Figure 3-10). The diamond machined surfaces were observed at different workpiece thicknesses (t_{rf}) in order to investigate the relationship between workpiece thickness (t_{rf}) and the deformation height of the produced texture (t_b). The diameter of the created bump is represented by D_b . Table 3-1 summarizes the experimental conditions selected for diamond machining experiments.

Figure 3-10: Schematic of workpiece cross-section (a) initial condition and (b) surface deformation after diamond machining, where t_{rf} is the workpiece thickness at thinner portion after diamond machining and t_b represents the height of created feature

Table 3-1: Experimental conditions for diamond face turning

Condition	Content
Cutting Speed (v_c)	2000 mm/s
Feed Rate (f)	10 mm/min
Cutting depth (d_c)	10 μ m
Diamond Tool	Single point natural diamond tool; nose radius (r) = 0.532 mm, r_e = 300 nm rake angle = 0° , clearance angle = 10°

3.2.3 CUTTING FORCES MEASUREMENT

A 3-axis Kistler dynamometer (model 9256C1) is used for the cutting force measurement of diamond turning. The diamond tool is attached to the dynamometer as shown in Figure 3-11. The characteristics of the dynamometer used in the experiments are attached in Appendix C. Dewetron 3010 DAQ system is used for real-time monitoring and post data analyses of cutting force signals. Kistler charge amplifier 5070AA is used to convert the

dynamometer signals into respective output voltages proportional to the cutting forces at the cutting tool. The measured cutting forces are used for the validation of the finite element (FE) model of diamond turning (as discussed in Chapter 6).

Figure 3-11: Schematic of cutting force measurement system attached to the diamond turning machine, where F_t = thrust force, F_f = feed force and F_c = cutting force

3.3 PBT PROCESS CAPABILITY

As mentioned earlier, the detailed parametric study of BPT presented in this thesis focuses on the fabrication of submicron to micro-sized convex shape bumps on the diamond machined surface. For that reason, some holes with different diameters were

pre-fabricated on the backside of the workpiece as backside patterns. However, the developed technique is not limited to one type of texturing geometry and many other freeform surfaces like waterdrop freeform, cylindrical freeform, etc. can also be developed. In order to show the efficacy and versatility of the technique, some other types of freeform surface are also textured on the diamond machined surface. In BPT, the pre-fabricated pattern dictates the geometry and design of the final profile of the produced texture. Therefore, it is inferred that the developed technique offers a liberty to the designer to control the final texture design and geometry by changing the pre-fabricated macro pattern. Figure 3-12 shows some macro-scale pre-fabricated backside patterns for the corresponding textures fabrication on diamond machined surface. The detail explanation and experimental results of the surface deformation phenomenon are discussed in the Chapter-4.

Pattern for an array of
convex shape bumps

Pattern for spiral shape
texture

Pattern for cylindrical
surface texture

Pattern for waterdrop
texturing

Pattern for integrated
freeform texture

Text script pattern

Figure 3-12: Pre-fabricated backside patterns for corresponding texture formation

3.4 SURFACE TEXTURE CHARACTERIZATION

The diamond machined surface was observed at different workpiece thicknesses (t_{rf}) by Wyko™ NT 3300 white light interferometer (Figure 3-13), which is used for surface roughness and waviness measurements on 3D structures. The white light interferometer uses a source of broadband white light to measure the surface topography. The source emits a light beam, which is divided into two parts by a beam splitter and then each of the beams illuminates the reference and sample surfaces. The reflected beams are then recombined to create an interference pattern, which is used to analyze the paths differences of the two beams traveled for surface height measurement. Due to the non-contact nature of the measurement, surface height up to few nanometers with very high precision can be measured with the optical interferometry system. For all the measurements of texture profile shown in this report, x20 magnification optical lens was used with maximum intensity to cover the overall maximum measuring area of 4.9 x 4.1 mm². The maximum height of the created texture with reference to the flat surface is referred as the deformation height of texture (t_b). A low-pass Fourier filtering with low cut-off frequency of 8 mm⁻¹ was applied to eliminate high-frequency roughness data from the measured profile and to observe the waviness pattern.

The non-contact interferometry system provides faster scanning results as compared to contact based measurement systems. However, it has a limitation of scanning area and it cannot measure the large surfaces. Therefore, for larger scanning area like for the measurement of a 3x3 array of bumps, a contact based Talyscan™ 150 surface profiling system was used. The instrument setting of the measuring system is shown in Table 3-2.

Figure 3-13: Wyko™ NT 3300 white light interferometer

Table 3-2: Specification of Talyscan scanning system

Condition	Content
Contact mode	Diamond tip (radius = 2 μm)
Resolution	$\sim 7 \text{ nm}$
Scanning speed	1000 $\mu\text{m}/\text{sec}$
x-spacing	0.5 μm
y-spacing	5.0 μm
Scanning area	12.5 x 12.5 mm^2

3.5 SUMMARY

This chapter discussed the process configuration and experimental methodology of the proposed novel technique of BPT for submicron to micro-sized surface texturing on the diamond machined surface. Firstly, the backside of work sample was pre-fabricated to

generate a macro scale pattern. Then, the front face of the sample was diamond turned up to a certain thickness to produce miniature features. Various types of backside patterns are pre-fabricated for the corresponding freeform surface generation on the diamond machined surface like an array of convex shape texture, spiral, waterdrop, integrated, cylindrical freeform surfaces, etc. The produced textures profile and roughness are observed by the white light interferometer and TalyscanTM surface profiler. The process forces are measured for the validation of the finite element (FE) model of diamond turning. The experimental results and the discussion about the texture formation are described in the next chapter.

CHAPTER 4

SURFACE TEXTURING BY BACKSIDE PATTERNED TEXTURING

This chapter presents the experimental investigation of BPT for the fabrication of submicron to micro-sized surface features. The purpose of this study is to show the efficacy of the proposed technique for the generation of various types of freeform surfaces. The chapter starts with the presentation of the experimentally developed single and an array of convex shape bumps on the diamond machined surface. Then, the detailed experimental results are shown and a relationship between material thickness and surface deformation height is illustrated. The explanation of the physical mechanism behind the surface deformation in surface texturing is discussed. In addition, some general types of freeform surface are developed using the pre-fabricated patterns shown in Chapter 3. Finally, a comparison of grain sizes at thin and thick sections of the machined work samples are discussed in this chapter.

4.1 SURFACE TEXTURING

4.1.1 FORMATION OF SINGLE CONVEX SHAPE BUMP

Figure 4-1 shows an interferometry image of surface topography for a single micro-sized bump created at the diamond machined surface at the workpiece thickness (t_{rf}) of 170 μm

for 2.5 mm diameter of pre-fabricated hole. Figure 4-1a is the 3D surface topography while Figure 4-1b shows the 2D cross-sectional trace profiles passing through the apex of the produced texture. For the said case, the average deformation height (t_b) of the created texture was measured as 1.275 μm .

Figure 4-1: (a) 3D surface topography of created feature when $t_{rf} = 170 \mu\text{m}$ and $D_b = 2.5 \text{ mm}$, (b) 2D profile in x- and y-direction corresponding to the 3D image

4.1.2 FORMATION OF AN ARRAY OF TEXTURES

To fabricate an array of submicron-sized convex shape bumps, 9 holes were pre-fabricated at the backside of the work sample in 3x3 array format (Figure 4-2a). The diameter of each hole was 2.5 mm. A pitch length of 3 mm was used in order to avoid the interferences of surface deformation by adjacent created texture. The front surface was then diamond turned until the workpiece thickness (t_{rf}) reduced to 230 μm .

Figure 4-2 (b) illustrates the mirror quality of the diamond machined surface. Figure 4-2 (c) is the expected surface profiles after diamond machining corresponding to backside patterned holes. Whereas, Figure 4-2 (d) shows the fabricated submicron-sized convex shape bumps in 3x3 format measured via TalyscanTM surface profiler. It can be observed that the formed bumps in the array are uniform in shape and size, which ensures the controllability of the BPT to produce uniform submicron-sized textures with very fine surface quality. The average deformation height (t_b) of texture was found to be 475 nm with 60 nm of standard deviation. The irregularities in the form profile of produced textures can be attributed to inhomogeneous nature of the polycrystalline material and machining error occurred during the pre-fabrication process.

Figure 4-2: Experimental results, (a) workpiece with pre-fabricated backside pattern (b) diamond machined surface (c) expected modeled surface and (d) scanned area for 3x3 array of bumps

4.2 EFFECT OF WORKPIECE THICKNESS

The detailed experimental results for different pre-fabricated patterns and workpiece thicknesses (t_{rf}) are plotted in Figure 4-3. All the measured data are shown with standard deviation. It is found that the workpiece thickness (t_{rf}) has a critical influence on the final geometry of the generated texture. The nonlinear deformation height (t_b) increases with a decrease in the workpiece thickness (t_{rf}) for all tested conditions. When the workpiece thickness (t_{rf}) is $\leq 200 \mu\text{m}$, the surface deformation height (t_b) rapidly increases. The experimental results also illustrate that no surface deformation was observed until a certain threshold thickness (t_m) of the thinner section was achieved. The threshold thickness (t_m) depends on the geometry of pre-fabricated backside macro features. For 2.5 mm backside holes, textures started appearing after diamond facing when workpiece thickness (t_{rf}) reduced to $310 \mu\text{m}$. Whereas for 2 mm and 1.5 mm pre-fabricated holes, the threshold thickness (t_m) was found to be $300 \mu\text{m}$ and $280 \mu\text{m}$, respectively. Up to this threshold thickness (t_m), surface deformation at thicker and thinner portions remains almost identical. Once the threshold thickness (t_m) was achieved and the workpiece was removed from the vacuum chuck, the miniature feature was formed on the machined surface. The minimum deformation height (t_b) of 280 nm was observed at the threshold thickness (t_{rf}) of $290 \mu\text{m}$ for 2.5 mm pre-machined holes. However, in the case of 2 mm and 1.5 mm holes, convex shape bumps of minimum heights of 170 nm and 130 nm were formed, respectively. These experimental results imply that the deformation height (t_b) of the created texture can be controlled by proper selection of workpiece thickness (t_{rf}) and the geometry of the pre-fabricated patterns.

Figure 4-3: The influence of workpiece thickness (t_{rf}) to the average deformation height of the produced texture (t_b)

4.2.1 SURFACE QUALITY

A $100 \times 100 \mu\text{m}^2$ area at the apex of the created textured was scanned to determine the surface quality. For each case of material thickness (t_{rf}), the specimens were randomly

selected to avoid the possibility of a systematic error in measurements. Fringe contrast drops off at the periphery of the produced textures due to the slope changes, which may lead to measurement errors. Therefore a small area is selected at the top of the produced miniature feature for roughness measurement. Figure 4-4 shows the roughness profile of the created textures at various material thicknesses (t_{rf}). The surface quality is shown regarding 3D roughness parameters of ‘arithmetic mean of surface variation (Sa)’ and ‘root mean square (RMS) of surface variation (Sq)’. It can be observed that the minimum Sa and Sq of 10 nm and 12 nm, respectively were obtained at the material thickness (t_{rf}) of 260 μm . Whereas, the maximum Sa and Sq reached to 38 nm and 47 nm, respectively when the material thickness (t_{rf}) was 110 μm . The measurements results imply that with an increase in the surface deformation (t_b), the surface roughness is also increased.

The surface roughness of the machined surface can further be reduced by controlling the machining parameter (such as tool nose radius, cutting speed and feed rate). Large nose radius and high cutting speed with fine feed rate produce a better surface finish in diamond turning [90].

Figure 4-4: Surface roughness profiles at different material thicknesses for 2.5 mm pre-fabricated hole

4.3 LIMITATIONS OF BPT

Based on the results obtained, it was also observed that at a certain workpiece thickness the texture profile damaged at the periphery of the developed texture because of reduction in the structure strength (i.e. due to very low thickness). The material thickness at thinner section after consecutive diamond machining passes at which the surface structural damage nucleated is referred as the damage thickness (t_d). During diamond machining, the surface damage occurred when thinner portion workpiece thickness reduced to less than 100 μm for all tested conditions. Hence, the range of the safe operational thickness of the thinner section to observe the undamaged surface features can be written as: $t_m \geq t_{rf} > t_d$. An example of the surface damage occurred at the machined workpiece is shown in Figure 4-5.

Figure 4-5: Damage of surface profile happened when t_{rf} was 100 μm for 2.5 mm diameter of hole, (a) top view and (b) isometric view

The maximum deformation height (t_b) up to 5.1 μm was measured for the undamaged machined surface in case of 2.5 mm pre-fabricated hole when workpiece thickness (t_{rf}) was 110 μm . Maximum deformation heights (t_b) for 2 mm and 1.5 mm holes were

measured as $3.3\ \mu\text{m}$ and $2\ \mu\text{m}$, respectively. This result shows the limitation of BPT and suggests the safe operational thickness of workpiece at a thinner portion (t_{rf}) ranging from threshold thickness (t_m) to damage thickness (t_d) to fabricate submicron to micro-scale surface features. Figure 4-6 shows the 2D profiles of created bumps measured at the apex for different pre-fabricated hole geometries within safe operational workpiece thicknesses.

Figure 4-6: 2D form profiles of created bumps at different workpiece thickness (t_{rf}) for 1.5 mm, 2 mm and 2.5 mm diameter of pre-fabricated hole

It is also important to observe that no significant change was observed in the deformation diameter (D_b) of the created bump and it remained the same as backside pattern for all workpiece thicknesses (t_{rf}). This result is in contrast to the deformation height (t_b) of texture which increases with a decrease in workpiece thickness. It implies that the material deformation in lateral direction replicates the backside pre-fabricated pattern. However, the shape and geometry of the pre-fabricated pattern affect the threshold workpiece thickness (t_m) and the deformation height (t_b) of the created texture.

4.4 EFFECT OF CUTTING SPEED

In order to investigate the effects of cutting speed (v_c) on the deformation height (t_b) of produced texture during BPT, some work samples were diamond faced with other constant cutting speeds (v_c) of 1 m/sec, 3 m/sec and 4 m/sec as well. Other machining conditions were the same as mentioned in Table-1 of Chapter 3. The relationship of cutting speed (v_c) and deformation height (t_b) is shown in Figure 4-7 for the cases when workpiece thickness (t_{rf}) reduced to 260 μm and 230 μm . The result depicts the direct influence of the cutting speed (v_c) on the developed textures. Higher cutting speed (v_c) produces larger surface distortion, which increases the height of generated texture.

The monotonically increasing trend of surface deformation (t_b) of Figure 4-7 can be represented by the following power law relationship:

$$t_b = A v_c^n \quad (4.1)$$

Where A is the coefficient; the power exponent n shows the slope. It can be seen that an increase of cutting speed (v_c) increases the texture profile height (t_b) by a power factor of n , which is varying from 0.6 to 0.9 with $R^2 = 95-99\%$ for all tested pre-fabricated geometries and workpiece thicknesses (t_{rf}).

Figure 4-7: Comparison of cutting speed (v_c) vs deformation height (t_b), (a) $t_{rf} = 260 \mu\text{m}$ and (b) $t_{rf} = 230 \mu\text{m}$

4.5 DISCUSSION FOR THE SURFACE DEFORMATION IN BPT

The machining-induced residual stresses (RS) are generally undesired and considered detrimental to machining accuracy. It is well understood that the cutting process induces residual stresses (tensile or compressive) on machining even when the workpiece is unleashed from the external load after processing [50, 91, 92]. Compressive stress is mostly desired as it improves the functional behavior of the machined components by influencing their fatigue and creep properties. However, the tensile stresses adversely affect the performance of the machined components. But with the perspective of the geometrical accuracy of machined parts, both the types of induced stresses directly influence the deformation of the newly developed surface and cause detrimental effects on the part geometry, which may lead to surface distortion beyond the acceptable tolerance limit [59, 93].

In machining, the possible causes of RS are plastic deformation and phase transformation. The effect of these stresses is found predominantly in the surface and subsurface of the machined components due to the limited depth of penetration in the order of some hundreds of micrometers. However, in the case of machining of the thin workpiece, the effect can be more prominent and can result in larger relevant surface deformation. In thin metallic workpieces, residual stress induces surface distortion and dimensional instability, which may lead to waste of the machined workpieces [91, 92, 94]. The formation of submicron to micro-sized textures in BPT is attributed to the effects of RS on the surface and subsurface of the diamond machined workpiece. In the proposed technique, the workpiece carries a pre-fabricated backside pattern, which divides the overall workpiece into thick and thin portions (Figure 4-8a). The initial

material thickness (t_{ri}) of the thin section remains in the order of few hundreds of micrometer. The machined surface of the workpiece clamped on the vacuum chuck remains flat during diamond machining due to the displacement constraints. The mechanical loading during the machining process generates surface and subsurface plastic deformation that induces stresses. The machining process also induces a plastically deformed layer; so-called damaged layer or stressed layer just beneath the machined surface. The depth of damaged layer depends on cutting conditions, material properties and cutting tool geometries. In the case of ultraprecision diamond machining, a very thin damaged layer up to 20 μm is expected because of low feed rate and cutting depth [95, 96]. Figure 4-8b shows the stressed layer near the cutting surface and above the ‘no strain region’ of a machined sample after diamond machining, while the workpiece is still attached to the machine. No elastic deformation of the overall workpiece is expected as the machine chuck still constrains the specimen.

The depth of RS after ultraprecision diamond machining remains the same as the thickness of the plastically deformed layer at the cutting surface and subsurface [96]. Diamond turning induces a very low level of a damaged layer and the stresses, which are not generally concerned for the large surface deformation. However, in the case of thin parts even low residual stresses can lead to relatively a high surface deformation. Hence, at the low thickness of the machined workpiece, large surface deformation can be observed. If this distortion is somehow controlled, it may be used for some beneficial outcome like surface texturing.

Once the workpiece is unleashed from the machine chuck, the workpiece becomes deformed due to redistribution of residual stresses at the surface and subsurface to achieve self-equilibrium compensating the unbalancing forces and moments produced by material removal processes. Thus the machined components contain both the strain deformations: plastic strain caused by machining and elastic strain resulting from the machining-induced plastic strain. Figure 4-8c illustrates the stress distribution in final shape after removal of the workpiece from the machine chuck. The elastic strain deformation is more sensitive to the workpiece thickness and large surface deformation arises in the case of thin workpieces [50, 96].

Figure 4-8: BPT process mechanism showing the cross-section of a workpiece, where t_{ri} and t_{rf} shows the workpiece thickness at thinner portion before and after diamond machining, respectively, whereas t_b represents the average height of created feature, (a) pre-fabricated workpiece, (b) diamond face turning at front side and (c) generated features at machined surface (dimensions are exaggerated for visibility)

In BPT, the overall diamond machined surface experiences an out-of-plane surface deformation. However, the thinner portion corresponding to pre-fabricated backside pattern experiences relatively larger surface deformation and consequently results in raising of miniature feature or texture formation. The thinner portion is constrained by the surrounding thick portion, which helps for controlled/uniform bulging of the thin portion.

The above discussion about the surface deformation in BPT is also supported by the experimental results on higher cutting speed (v_c), as shown in Figure 4-7. Cutting speed has a significant effect on the RS of the machined surface. The increase of cutting speed increases the effective residual stress and its penetration depth [97, 98]. From a mechanics point of view, the large magnitude of residual stresses causes more deformation in the machined surface. Therefore, it is concluded that the higher cutting speed causes a rise in induced stresses which ultimately produces large surface deformation (t_b) and produces surface texture.

It is important to mention that when the deformation height (t_b) of created texture was 200 nm or below, its form profile did not remain uniform and was difficult to capture. The variation in the form profile is attributed to the non-uniform elastic spring-back caused by the anisotropic nature of polycrystalline aluminum 6061-T6. The spring-back is referred to the elastic strain recovery when the rounded cutting edge of the tool passes on the machined surface and burnishes the freshly machined surface. After burnishing of the surface, the material left behind the cutting tool edge recovers or springs back. The elastic spring-back depends on the physical properties of the workpiece material [99].

The magnitude of the spring-back recovery lies in the range of few nanometers to tens of nanometers, which affects the surface quality in terms of roughness for diamond turned surfaces [100]. The effect of spring-back on the overall surface deformation of the workpiece is not significant as compared to the deformation caused by RS, especially at a lower material thickness ($t_{rf} \leq 260 \mu\text{m}$) where material deformation (t_b) up to an order of a micrometer is achieved.

4.6 BPT PROCESS CAPABILITY AND FLEXIBILITY

As discussed earlier, the backside pre-fabricated pattern and workpiece thickness (t_{rf}) determine the shape and geometry of created textures on the diamond machined surface for a given machining condition. In order to show the versatility and efficacy of the proposed technique, some other freeform surfaces are produced and presented in Figure 4-9. The backside patterns are pre-fabricated in advance according to the desired freeform surfaces or textures on the diamond machined surface. The experiments follow the same machining conditions as mentioned in Chapter 3, while the workpiece thickness (t_{rf}) after diamond machining was $200 \mu\text{m}$. The light reflected the close-up image of the whole fabricated surface is presented, which gives a good qualitative visualization of the produced texture. The thicker portion of the machined surface acts as a smooth reflecting surface that gives rise to the bright image on the screen; the thinner portion being elevated diffuses the reflection and gives a rise to the black patch on screen. For quantitative visualization, the surface deformations (t_b) are measured via Talyscan contact profiler at different locations of the developed textures. In Figure 4-9, the line x-x' refers to the location where the 2D surface deformation is measured. The measured surface deformations (t_b) for different backside patterns are summarized in Table 4-1.

These results rationalize the significance of backside pre-fabricated pattern and workpiece thickness (t_{rf}) for the final shape and geometry of created textures. Therefore, it is concluded that the developed technique offers a liberty to the designer/user to control the final texture design and geometry by changing the pre-fabricated macro pattern.

Freeform Surfaces	Backside pre-fabricated pattern	Mirror finish of diamond machined surface	Projected pattern of machined surface
Spiral Freeform
Integrated Freeform
Waterdrop freeform
Cylindrical Freeform

Figure 4-9: Typical freeform surface textures composed of various patterns ($t_{rf} = 200 \mu\text{m}$)
(Line x-x' refers to the location where the surface deformation is measured)

Table 4-1 Surface deformation measurements for freeform textures

Freeform Surfaces	workpiece thickness (t_{rf})	Deformation height (t_b)
Spiral Freeform	200 μm	1.60 μm
Integrated Freeform	200 μm	1.55 μm
Waterdrop freeform	200 μm	1.80 μm
Cylindrical Freeform	200 μm	1.60 μm
Text script pattern	200 μm	1.50 μm

4.7 MICROSTRUCTURE ANALYSIS

The quantitative characterization of the deformed grain distribution at thin and thick sections of the machined samples was analyzed using atomic force microscope (AFM). Software-based image processing of AFM data can generate quantitative information from individual grains or group of grains. Statistics on groups of particles can also be measured through image analysis and data processing. Commonly desired statistics include grain counts, grain size distribution and surface area distribution. For individual grain, size information (length and perimeter) can also be measured. The grain distribution was studied for three samples with the final workpiece thicknesses (t_{rf}) of 230

μm , 200 μm and 170 μm . The scanning was performed at the thin and thick sections at the stress-affected zone near the newly machined surface. To reveal the microstructure, the specimens were cut at the region of interest from the diamond turned workpieces and mechanically ground using a series of SiC paper with grits sizes varying from 240 to 1200 (for a period of 180 sec for each paper in wet condition). Afterwards, the samples were delicately polished with colloidal silica for a period of 600 sec in order to get a mirror finish. The polished samples were electrolytically etched using Barker's reagent with a voltage of 12V (DC) for 20 sec. This procedure permits the plastically deformed grains to be clearly revealed with a consistent high accuracy grains measurement by the AFM. The detail of sample cutting from the bulk workpiece and scan area is shown in Appendix 'F'.

Figure 4-10 shows the AFM micrographs across the thickness of the samples which describes the grains distribution at thick and thin sections. Quantitative analysis through perimeter histogram plots of grains at thick and thin sections are shown in Figure 4-11. However, Table 4-2 gives the statistical information of grain size distributions. It can be observed from Table 4-2 and Figure 4-11 that the average size of grain in thin section is larger than the grains measured at thick sections for all the examined samples. Consequently, for a given area of scanning, the thin sections have less number of grains as compared to thick sections. The observations of the micrograph suggest that the grains at thin sections are elongated and bigger in size as compared to thick sections due to the larger induced mechanical deformation. The vicinity grains in thin sections experience

relatively larger deformation, which leads to the texture formation and larger grain perimeters.

Table 4-2 Statistical information of grain size range in thin and thick sections

Sample	Material thickness t_{rf} (μm)	Grain counts (scan area = $10 \times 10 \mu\text{m}^2$)		Mean grain perimeter (μm)	
		Thin section	Thick section	Thin section	Thick section
A	230	746	892	1.480	1.318
B	200	764	834	1.470	1.390
C	170	781	805	1.456	1.402

Figure 4-10: AFM images across the thickness of the samples to represent the grains distribution at thick and thin sections

Figure 4-11: Quantitative analysis Grain size distribution at thin and thick section

4.8 SUMMARY

The experiments were conducted to fabricate submicron to micro-sized convex shape bumps and other freeform texture on the diamond turned surface. A relationship between workpiece material thickness (t_f) and deformation height (t_b) of the produced textures is explored. It is found that the deformation height (t_b) is very sensitive to the material thickness (t_f) at the thinner section; t_b increases with a decrease of t_f for all tested machining conditions and backside pattern geometries. Surface roughness increases at the

larger surface deformation (t_b) and surface roughness (S_a) value as small as 10 nm was achieved when the material thickness (t_{rf}) was 260 μm for 2.5 mm diameter of produced texture. The limitation of the process can be seen at higher deformation height (t_b). The results suggested that each backside pattern geometry had a safe operating material thickness (t_{rf}) that ranged from minimum threshold thickness (t_m) at which the minimum texture height was achieved to the damage thickness (t_d) at which the fracture occurred at the texture periphery. This chapter implies that various types of texture profiles having the deformation height (t_b) from submicron to micro-scale can be fabricated by controlling the user-defined backside pattern geometry and the material thickness (t_{rf}) at the thinner section. In the end, grain size distributions at thin and thick sections were scanned using AFM, which shows the elongated grain at thin sections as compared to thick section for all the tested samples.

CHAPTER 5

PREDICTIVE METHODOLOGY OF SURFACE DEFORMATION IN BACKSIDE PATTERNED TEXTURING

This chapter describes a mathematical approach to predict the surface deformation in the backside patterned texturing (BPT). The proposed methodology is based on the surface deformation caused by the plastically deformed layer in the machined workpieces. The modeling approach is explained in detail, followed by the development of a mathematical formulation. Finally, a comparison of experimental and simulation results is presented.

5.1 SOURCE RESIDUAL STRESS

As explained earlier, machining process induces a ‘plastically deformed layer’ or sometimes known as ‘stressed layer’ at the surface and near-surface region of a newly developed surface. This induced stressed layer acts as a ‘source of residual stresses’ and is represented by ε_s . The stresses presented in a plastically deformed layer are known as the source stresses (σ_s). These types of stresses are sometimes known as fictitious stresses as well [50]. The concept of source stresses (σ_s) in plastically deformed layer was first introduced by H. ReiBner [101]. Later, Brinksmeier et al. used source stress (σ_s) for the shape deviation analysis of a grinded linear rail guide [59].

Figure 5-1 shows the schematic diagram of a diamond machined workpiece with non-uniform thickness attached to the machine. The removal of top part of the workpiece induces a stressed layer and disturbs the internal workpiece equilibrium. As a consequence, once the workpiece is set free from the displacement constraints provided by the workpiece holding mechanism, the overall workpiece has to react to achieve a new equilibrium by an out-of-plane surface deformation.

Figure 5-1: Cross-section of the machined work sample with residual stress source (ϵ_s)

5.2 MODELING APPROACH

The proposed prediction methodology is based on the estimation of source residual stresses (σ_s) which is caused by the formation of a plastically deformed layer after diamond machining. The proposed modeling approach aims to provide a simple method

to predict the surface deformation in textures produced by BPT. The modeling approach is shown in Figure 5-2. The source residual stress (σ_s) is estimated by the proposed model directly after some preliminary machining tests for an arbitrary type of pre-fabricated texture geometry. The known source residual stress (σ_s) is then used as input to predict the surface deformation of other axisymmetric and doubly symmetric pre-fabricated backside patterns.

Figure 5-2: Simulation approach for surface deformation prediction

It is important to note that the source stresses (σ_s) used in the proposed model do not truly represent the actual residual stress (RS) state in the machined workpiece. Actually the true RS is not required in the proposed simulation approach. In fact, the source stress (σ_s) simplifies the varying RS profile along the workpiece thickness into a single value, which can represent the similar surface deformation or distortion potential as the

actual RS profile carries for particular machining conditions and workpiece geometry. The reason is that the source stress (σ_s) is directly determined by the deformed surfaces after some initial experiments. Therefore, the calculated source stress (σ_s) in stressed layer can be used for surface deformation analysis without the need of the true RS profile along the thickness of the workpiece. In this way, the valuable time and efforts for a range of geometrical textures can be reduced significantly.

To develop the model, some circular holes are considered as pre-fabricated pattern to generate convex shape submicron to micro-sized convex shape bumps on the diamond machined surface. The diameters of the holes were set to 2.5 mm, 2.0 mm and 1.5 mm. The machining conditions and experimental results have been shown in the previous chapters. Any one of these pre-fabricated pattern geometry can be considered for initial source residual stresses (σ_s) calculations. For instance, it is considered that 2.5 mm diameter bumpy textures are produced initially as preliminary tests run. The resulted surface deformation (t_b) is to be used then for source residual stress (σ_s) estimation using the proposed mathematical model. Subsequently, the known stresses can be used for the surface deformation (t_b) analysis for 2 mm and 1.5 mm diameter of textures produced by similar machining conditions. Finally, the simulation results are compared with the experiments.

5.3 ESTIMATION OF SOURCE RESIDUAL STRESS

The 2D cross-section at the center of the thinner section (i.e. diameter of the produced bump) is considered as a beam like structure with machining-induced bending moment

(M_z) generated by source residual stresses (σ_s). Figure 5-3 shows the schematic diagram of the workpiece attached to the machine spindle and at free-state after diamond machining. The surface profile of the developed texture presented in Chapter 4 shows that the produced bump was found uniform about its vertical axis. Therefore, it is considered that the surface deformation is symmetrical along the vertical axis; this assumption simplifies the prediction formulation and a 2D beam model can be used to represent the bump formation. The length of the beam is represented by ' L ' which actually shows the diameter of the produced texture.

Figure 5-3 (a) Schematic of pre-fabricated workpiece attached to precision machine vacuum spindle (b) generated bump on the machined surface at a free state and (c) beam model to represent 2D cross-section of thin section.

The source residual stresses (σ_s) produced by the material removal process provide a measure of bending moment (M_z) that leads to the surface deformation (t_b). The elastic theory of a beam describes that the applied moment (M_z) on a beam as a function of stresses can be written as:

$$M_z = - \int \sigma_x t(y) dA \quad (5.1)$$

Where $t(y)$ and dA represent the thickness of the beam and integrated cross-sectional area, respectively. However, the maximum deformation (t_b) of the beam as a function of bending moment (M_z) acting on the beam can be simplified as:

$$t_b = \frac{M_z L^2}{8 E I_{zz}} \quad (5.2)$$

Where E represents the modulus of elasticity and I_{zz} shows the second moment of inertia.

Appendix D shows the detailed derivation of Eq. (5.2).

The plastically deformed layer produced by machining processes also causes a bending moment (M_z) that lead to surface deformation in the machined surface. The bending moment (M_z) can be described by machining-induced source residual stresses (σ_s) [59] as:

$$M_z = \int_0^{t_o} b \sigma_s (t - t_{rf}/2) dt \quad (5.3)$$

Where σ_s is the machining-induced source stresses up to the penetration depth (t_o). The source residual stress (σ_s) is assumed to be constant along the penetration depth (t_o) of plastically deformed layer.

After combining Eq. (5.2) and Eq. (5.3) and replacing I_{zz} by $(1/12)bt_{rf}^3$, the source residual stresses (σ_s) for the surface deformation and texture formation can be estimated as:

$$\sigma_s = \frac{4 t_b E t_{rf}^3}{3 t_o (t_o - t_{rf}) L^2} \quad (5.4)$$

It can be seen that the width of the beam (b) has been canceled out in the final formulation (Eq. (5.4)). The developed mathematical formulation provides the estimation of source residual stress (σ_s), which causes the surface deformation (t_b) for an arbitrary pre-fabricated pattern. These estimated stresses are to be used then to predict the surface deformation (t_b) for other pre-fabricated geometries.

5.4 MODEL VALIDATION AND PREDICTION

As discussed earlier, to validate the modeling approach, 2.5 mm of convex shapes bumpy textures are fabricated as initial test run at different workpiece thicknesses (t_{rf}) and the measured surface deformation (t_b) is shown in Figure 5-4. Using the measured data with the proposed mathematical formulation (Eq. (5.4)), the source residual stresses (σ_s) are calculated and summarized in Table 5-1.

Figure 5-4: Experimental surface deformation for the diameter (L) of 2.5 mmTable 5-1: Calculated source stress at different material thickness (t_{rf}) for 2.5 mm diameter of bumps

Material thickness t_{rf} (μm)	Measured deformation height t_b (μm)	Source stress σ_s (MPa)
110	5.100	-56
140	3.025	-51
170	1.275	-31
200	0.950	-32
230	0.475	-21
260	0.440	-24
290	0.300	-27

It is to be noted that the depth of the plastically deformed layer (t_o) mostly depends on machining conditions and material characteristics [96, 102]. In diamond turning, the

machining-induced residual stresses decay very quickly along the thickness of the workpiece as a very thin layer of the workpiece is plastically deformed. The stress profile in the machined workpiece does not remain constant and varies along the thickness of workpiece. However, calculated source stresses (σ_s) are assumed to be constant throughout the penetration depth of the stressed layer (t_o). The actual depth of the penetration for RS can be determined by experimental measurements of residual stress or micro-hardness. However, these methods are very time-consuming and difficult to implement especially for very low penetration depth, such as in diamond machined workpieces. As mentioned earlier, in diamond turned workpiece the surface and subsurface region up to the depth of approximately 20 μm significant for stress profile. Therefore, for the calculation purpose, the thickness of plastically deformed layer (t_o) was taken as 20 μm [96]. Any error in the penetration depth (t_o) estimation will affect the magnitude of source stresses (σ_s). However, the total bending moment would remain same as it is defined by the measured surface deformation (Eq. (5.2)).

The calculated source stresses (σ_s) are used then as input to predict the surface deformation height (t'_b) for 2 mm and 1.5 mm diameter of pre-fabricated pattern. Hence, the Eq. (5.4) is rearranged for further calculation as follows:

$$t'_b = \frac{3 t_o (t_o - t_{rf}) L^2}{4 E t_{rf}^3} \cdot \sigma_s \quad (5.5)$$

Where the deformation height of the predicted texture is represented by t'_b .

The simulated surface deformations (t'_b) of textures were compared to the experimental results for different material thicknesses (t_{rf}) for 1.5 mm and 2 mm diameter of textures and shown in Figure 5-5 and Figure 5-6, respectively. The predicted results were almost identical to the experimental results for all cases of material thicknesses (t_{rf}). These results validate the proposed methodology and imply that the stresses at the top stressed layer of machined surface predominantly affect the surface deformation in the produced textures by BPT.

Figure 5-5: Comparison of measured and simulated results for the diameter (L) of 1.5 mm

Figure 5-6: Comparison of measured and simulated results for the diameter (L) of 2.0 mm

In addition, the proposed mathematical formulation is also validated for square shape doubly symmetric backside patterns. The dimensions of the square shape cavities were set to $3 \times 3 \text{ mm}^2$, $2.5 \times 2.5 \text{ mm}^2$ and $2 \times 2 \text{ mm}^2$. The geometries of the patterns are shown in Appendix 'G'. After diamond turning experiments, the surface deformations (t_b) were measured at the workpiece thicknesses (t_{rf}) of 230 μm , 200 μm , 170 μm and 140 μm . For initial source stress (σ_s) calculation, $3 \times 3 \text{ mm}^2$ square patterns are considered as preliminary tests run. The observed surface deformation (t_b) for $3 \times 3 \text{ mm}^2$ square patterns at different material thicknesses (t_{rf}) are shown in Figure 5-7. Using the equation of Eq. (5.4), the source stresses (σ_s) was estimated and summarized in Table 5-2. In the case of square patterns, the length of the beam model (as shown in Figure 5-3) represents a side of the square pattern and represented by ' L '. Subsequently, the calculated source stresses

(σ_s) are used as input to predict the surface deformation height (t'_b) using Eq. (5.5) for other square patterns of $2.5 \times 2.5 \text{ mm}^2$ and $2 \times 2 \text{ mm}^2$.

Figure 5-7: Experimental surface deformation for square shape pattern ($3 \times 3 \text{ mm}^2$), where $L = 3.0 \text{ mm}$

Table 5-2: Calculated source stress at different material thicknesses (t_{rf}) for $3 \times 3 \text{ mm}^2$ square shape patterns

Material thickness t_{rf} (μm)	Measured deformation height t_b (μm)	Source stress σ_s (MPa)
140	3.540	-42
170	2.620	-39
200	0.700	-16
230	0.545	-13

The simulated surface deformations (t'_b) were compared to the experimental results for different material thicknesses (t_{rf}) as shown in Figure 5-8 and Figure 5-9. It can be seen

that the predicted results were well in agreement with the experimental results for all the cases of material thicknesses (t_{rf}) of square shape backside patterns.

Figure 5-8: Comparison of measured and simulated results for square shape pattern ($2.5 \times 2.5 \text{ mm}^2$), where $L = 2.5 \text{ mm}$

Figure 5-9: Comparison of measured and simulated results for square shape pattern ($2.0 \times 2.0 \text{ mm}^2$), where $L = 2.0 \text{ mm}$

5.5 SUMMARY

The primary objective of this study is to propose a prediction methodology for submicron to micro-sized surface texturing developed by BPT. The developed model utilizes the estimated source residual stress (σ_s) using the measured surface deformation for an arbitrary backside pattern. Then the known source stresses is used for surface deformation of subsequent texture geometries on diamond machined surface. The proposed methodology shows a good agreement with the experiments for the backside patterns of holes and square shape cavities. With a few initial experimental tests, the developed mathematical formulation can significantly reduce any further trial and error experiments for precise texture formation in BPT. One of the advantages of the proposed method is that it does not require prior measurement of residual stress (RS) depth profile either via experiments (like XRD) or FE model for deformation analysis. In this way, the machining time and efforts can greatly be reduced.

CHAPTER 6

FINITE ELEMENT SIMULATION FOR RESIDUAL STRESS AND SURFACE DEFORMATION ANALYSIS

This chapter presents a computer simulation of diamond turning using ALE formulation for residual stress estimation. Subsequently, the estimated stresses are to be applied to study the surface deformation and textures formation in backside pattern texturing (BPT). The current finite element (FE) model focuses on the simulation of convex shape bump formation on the diamond machined surface. In this chapter, the modeling approach is explained in detail. The machining-induced residual stress (RS) as a function of workpiece thickness is extracted first. Subsequently, the surface deformation is modeled based on the predicted RS profile. The developed model is validated by the comparison of cutting forces. Finally, the simulated results of surface deformation were verified and validated with the experimental results.

6.1 NUMERICAL MODELING

6.1.1 EXPLICIT DYNAMIC ANALYSIS

A plane strain finite element (FE) cutting model is developed using ABAQUS/Explicit 13.1 to simulate a plunge cut in diamond turning (DT). The explicit dynamic formulation is used for the cutting simulation mainly because of its usefulness to simulate highly nonlinear problems, which involve large localized deformations as happens in machining. Also, the explicit formulation is more efficient than the implicit integration approach. The reason is that the computational cost associated with explicit integration increases linearly with the model size. However, in the case of implicit integration, the solution cost increases more rapidly than linearly with the size/scale of the problem. Explicit integration provides a more computationally efficient solution than implicit for the problem involving stress wave propagation [103].

To ensure the numerical stability, explicit integration uses many small time increments (Δt) that must be smaller than a critical value (Δt_{m-cr}) for pure mechanical simulation.

Mathematically, Δt_{m-cr} can be shown as:

$$\Delta t_{m-cr} \sim \frac{L_{min}}{c_d} \quad (6.1)$$

$$c_d = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (6.2)$$

Where L_{min} represents the smallest element dimension in the model and c_d is the stress wave speed which depends on the mechanical characteristics of the workpiece material (Eq. (6.2)).

In case of pure thermal analysis, the critical value (Δt_{T-cr}) shows the time required for the thermal waves to cross the smallest element in the model mesh as:

$$\Delta t_{T-cr} \sim \frac{L_{min}^2}{2\alpha} \quad (6.3)$$

$$\alpha = \frac{k}{\rho \cdot C} \quad (6.4)$$

Where α shows the thermal diffusivity of the material. The parameters ρ , k and C describe the density, thermal conductivity and specific heat of the material, respectively.

For fully coupled temperature-displacement analysis, the stable time increment (Δt) satisfies the following equation:

$$\Delta t \leq \min(\Delta t_{m-cr}, \Delta t_{T-cr}) \quad (6.5)$$

Hence, the overall time efficiency of the explicit dynamic simulation depends on the smallest mesh dimension in the model (L_{min}), which governs by the mesh size near the cutting edge region where a fine mesh is generally desired.

6.2 NUMERICAL SIMULATION OF DIAMOND TURNING

For realistic equivalent orthogonal 2D plain strain approximation, the width of cut should be at least five times to the cutting depth; this condition is satisfied in DT [80]. One of the important aspects of the diamond turning simulation is to consider the round cutting edge of the tool, which is generally ignored in macro scale cutting simulations [104]. During diamond machining, the cutting depth remains in the order of cutting edge radius. Therefore the burnishing, rubbing or ploughing effects may significantly affect the characteristics of the formed surface.

In the present developed FE simulation, both the tool and workpiece are modeled as deformable parts. However, the diamond tool is considered to be rigid as its deformation is expected to be negligible compared to very large deformation subjected to the workpiece. The very large elastic modulus of the tool as compared to the workpiece supports the assumption of the ‘rigid-tool’. The workpiece is meshed by four-node plane strain thermally coupled elements (CPE4RT) with automatic hourglass control and reduced integration. The diamond tool is also meshed by CPE4RT elements but only the heat transfer analysis is performed for the tool.

6.2.1 MESH MOTION SCHEME AND BOUNDARY CONDITIONS

Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing is used to model the cutting step of the FE simulation. ALE formulation combines the advantages of both Lagrangian and Eulerian mesh motion techniques. In the Lagrangian formulation, the mesh is attached to the material and is deformed as the material moves/undergoes a large deformation. This

is one of the main disadvantages while using Lagrangian mesh motion scheme for cutting simulations. Secondly, a chip separation criteria or parting line must be defined while using Lagrangian formulation. Large element distortions, especially near the cutting-edge of the tool, cause the abortion/termination of the simulation. On the other hand, in the Eulerian formulation, the mesh is fixed in space and the workpiece material moves through the mesh avoiding the termination of the simulation due to large deformation. Also, the material flow around the cutting edge can be modeled correctly without defining any chip separation criterion or parting line. However, the continuous elongated chip formation cannot be simulated using the Eulerian meshing scheme. Secondly, the chip geometry must be known at the onset of the simulation to make the model realistic. In addition, the residual stress analysis for cutting simulations cannot be modeled using pure Eulerian formulation as it does not consider the elastic behavior of the material [105]. The shortcomings of the pure Lagrangian and pure Eulerian formulation can be avoided by using ALE adaptive meshing. ALE can avoid excessive element distortions due to the remapping of the nodal points and apply continuous remeshing at the pre-defined sweeping and frequency. Besides, the chip geometry is not required in advance and the chip is automatically formed due to the remapping of adaptive meshing as the simulation continues. ALE based boundary conditions and mesh motion scheme has been successfully used in cutting simulation for residual stress studies by Nasr et al. [106] and by Miguelez et al. [107].

In ALE formulation, different regions of an FE model can be defined either with Eulerian or Lagrangian meshing scheme as per the design requirement. By using the Eulerian

meshing near cutting region and adaptive remeshing in other regions, which are defined as Lagrangian zones, there is no need to define a parting line or element deletion criterion to form a continuous chip. By virtue of this, the material flow around the round cutting edge of the tool and simultaneously rubbing or burnishing effects can be realistically modeled. In ALE formulation, the cutting tool remains fixed and the cutting velocity is applied to the workpiece; this condition is necessary while using ALE formulation as the Eulerian zone defined in the workpiece requires some nodal velocity.

The schematic of the ALE based cutting model with boundary conditions and round edge of the tool is shown in Figure 6-1. The left side nodes and the bottom surface of the FE model are fixed with displacement constraints in the vertical direction only, i.e. $U_{yy} = 0$ and $U_{xx} \neq 0$. Whereas, the cutting velocity is defined in the x-direction i.e. $v_c = v_{xx} = 2000$ mm/sec. Hence, the elements and nodes can freely move in the x-direction as the simulation continues. The mesh density around the cutting tool edge is refined enough to represent the edge effects in the analysis. The large distortion occurs at the chip formation zone where the material leaves the bulk workpiece in the form of a continuous chip. This zone is modeled as a Eulerian region where the material moves through the fixed mesh. Nonetheless, the other zones including the pre-defined chip section are modeled by Lagrangian meshing scheme for unconstrained material flow on the free boundaries, which determine the final chip geometry. In all Lagrangian zones, the underlying material follows the attached mesh as the simulation continues.

The cutting step starts by assuming initial predefined chip geometry. Nevertheless, as the simulation progress, the Lagrangian zone mesh motion redefines the shape and size of the

chip, which is actually governed by the deformation process. Thus, the final chip geometry at the steady state differs significantly from the initial arbitrarily assumption and insensitive to the pre-defined chip geometry [105, 108, 109]. The dimensions of the 2D model were set as $400\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$; the model size is large enough to avoid the x- and y-axis boundaries effects on the simulation's results.

Figure 6-1: (a) Schematic of SPDT process and (b) ALE simulation boundary conditions

6.2.2 WORKPIECE MATERIAL CONSTITUTIVE MODEL

The cutting process possesses high strain and strain-rate (10^2 - 10^6 s⁻¹) material deformation. The high strain parameters increase the hardness of the material. On the other hand, the temperature at the cutting edge causes the work material softening. Hence, the material model, which represents the workpiece in FE simulation, should be capable of incorporating these different characteristics. Johnson-Cook (J-C) [110] material model, (Eq. (6.6)) is often used to model the thermal-visco-plastic behavior of workpiece material as it has shown its efficacy for the modeling of high strain-rate and temperature dependent cutting [17]. The constitutive material model incorporates the high strain, strain rate, strain hardening, nonlinear material properties and heat transfer analysis [94]. The J-C model describes the flow stress (σ_{eq}) in machining as:

$$\sigma_{eq} = [A + B(\bar{\epsilon}_p)^n] \cdot \left[1 + C \ln \left(\frac{\dot{\epsilon}_p}{\dot{\epsilon}_o} \right) \right] \cdot \left[1 - \left(\frac{T - T_o}{T_m - T_o} \right)^m \right] \quad (6.6)$$

Where A [MPa] is the initial yield strength at room temperature, B [MPa] is the hardening modulus, C is the rate sensitivity coefficient, n is the hardening coefficient, m is the thermal softening coefficient, T_m [K] is the melting temperature and T_o [K] is the room temperature. ϵ_p [1/s], $\dot{\epsilon}_p$ [1/s] and $\dot{\epsilon}_o$ [1/s] represents the equivalent plastic strain, plastic strain rate and reference plastic strain rate, respectively. The J-C material parameters used in the simulation are listed in Table 6-1. Other physical and thermal properties of Al 6061-T6 and SCD is reported in Table 6-2.

Table 6-1: Johnson-cook constitutive model parameters for Al 6061-T6 [13, 14, 111]

A (MPa)	B (MPa)	C	n	m	$\dot{\epsilon}_0$ (s ⁻¹)	T_m (K)	T_o (K)
324	114	0.002	0.42	1.34	1	925	293

Table 6-2: Thermal and physical properties of workpiece and cutting tool [99]

Parameters	Al 6061-T6	SCD
Young's modulus (GPa)	70	1050
Poisson ratio	0.2	0.1
Density (kg/m ³)	2700	3520
Specific heat (J/kg °C)	900	420
Thermal conductivity (W/m °C)	170	1000
Melting temperature (K)	925	-
Thermal expansion (1/K)	23x10 ⁻⁶	1.1x10 ⁻⁶
Inelastic heat fraction	0.9	

6.2.3 HEAT TRANSFER MODEL

In machining, material plastic deformation and tool-workpiece contact friction are considered as two major sources of heat generation [112]. The current FE model includes both the types of heat generations: by friction as well as by plastic deformation. Heat conduction between tool and workpiece is considered as a primary mode of heat transfer in the present work. The fraction of adiabatic plastic work converted into heat is known as inelastic heat fraction and is represented by Quinney-Taylor coefficient. Most of the plastic work up to 95% is converted into heat flux during machining [110]. In the current work, a value of 0.9 is used and assumed to be constant throughout the machining simulation; many researchers have used this value for FE cutting simulations [77, 112]. Remaining 10% of the plastic work is devoted to strain hardening effects.

The heat flux produced by the contact friction is dissipated at the tool-workpiece contact interface. The fraction of the heat flux (represented by ' H ') is shared between the tool and workpiece depends on effusivity ratio (ϵ) as shown in Eq. (6.7) [44, 110, 113].

$$H = \frac{\epsilon_{wp}}{\epsilon_{tool} + \epsilon_{wp}} \quad (6.7)$$

Where $\epsilon = \sqrt{k \rho C}$; k : thermal conductivity (W/m °C); ρ : density (kg/m³); C : specific heat (J/kg K). Based on the material a property (Table 1), 35% of the friction heat flux is transmitted to the workpiece and remaining 65% to the diamond tool.

Convection and radiation heat transfer are not considered in cutting step of the simulation. However, the convection heat transfer (Eq.(6.8)) is modeled in Step-2 of the simulation where the workpiece is left to cool down to room temperature.

$$q_{conv} = h_c (T - T_o) \quad (6.8)$$

Where, h_c is the coefficient of heat convection (10 W/m² °C, for air) and T is the transient temperature at the workpiece free surfaces.

6.2.4 TOOL-WORKPIECE INTERACTION AND FRICTION MODEL

The true modeling of frictional phenomena around the cutting tool and workpiece interface at secondary shear zone and in rubbing/burnishing zone is complicated, if not

impossible since it is influenced by many factors including machining conditions, temperature and pressure. For realistic and reliable FE simulations, the accuracy of the friction model plays a vital role. Many researchers have attempted to improve the understanding of tool-workpiece interaction mechanics and have developed several friction models and formulations [70, 110, 114].

Zorev [115] described the interfacial friction along the tool rake face as a function of frictional as well as normal stresses. Figure 6-2 shows the schematic of the tool-workpiece interface to describe the Zorev's friction model. The highest value of the normal stress can be found at the edge of the tool, whereas it steadily decreases and reaches to zero when the chip loses contact with the tool rake face. The frictional shearing stress (τ_f) remains constant and is equal to the average shear stress (τ_p) in the sticking region (l_p). However, in the remaining contact length, the frictional shearing stress (τ_f) is calculated using a coefficient of friction (μ) as shown in Eq. (6.9) and Eq. (6.10).

$$\tau_f = \tau_p \quad \text{when} \quad \mu\sigma_n(x) \geq \tau_p \text{ (sticking region)} \quad (6.9)$$

$$\tau_f = \mu\sigma_n(x) \quad \text{when} \quad \mu\sigma_n(x) < \tau_p \text{ (sliding region)} \quad (6.10)$$

The implementation of Zorev's model in FE simulations requires shear stress in the sticking region and coefficient of friction (μ) in sliding region, which makes the model complicated to define. In fact, the frictional shearing stress (τ_f) depends on the strain, strain rate and temperature [116]. However, many researchers assumed a constant value

equal to the shear strength of the material and ignored the variability of the τ_f on temperature and strain. These assumptions accumulate the errors in the simulation results.

On the other hand, Coulomb's friction model provides a simple tool-workpiece interaction conditions; that's the reason why it is mainly used in many FE simulations [117, 118]. In this model, the frictional stresses (τ_f) are assumed to be proportional along the rake face of the tool with a constant coefficient of friction (μ) throughout the contact length as:

$$\tau_f = \mu\sigma_n \quad (6.11)$$

Due to simplification of the Coulomb's model, it has been widely used by many researchers for machining simulations to provide the acceptable results [119, 120]. In low-speed machining like diamond turning where the temperature and pressure at the tool-workpiece interaction is not very high, the Coulomb's friction model is quite effective [121].

Figure 6-2: Zorev's friction model to represent the stress distribution on the cutting tool rake face

The developed FE model in this report uses Coulomb's friction model and a number of trial runs were performed using a range of constant friction coefficient (μ) from 0.05 to 0.2 to match the experimental cutting forces. However, reasonable numerical results regarding cutting forces were achieved at $\mu = 0.07$; therefore, all the simulation analysis shown here was performed using a constant friction coefficient (μ) of 0.07.

6.2.5 CUTTING CONDITIONS

The aim of the cutting simulation is to extract the machining-induced residual stresses (RS) profile and subsequently to use it for surface deformation analysis. The round edge radius (r_e) of the diamond cutting tool should not be ignored in diamond turning due to

the low cutting depth and feed rate and therefore r_e is considered in the current simulation work. The cutting and thrust forces were extracted when the simulation reached to steady state. The term steady state refers to the condition at which there is no significant variation in the process variables like cutting forces and temperature.

For the cutting FE simulation step, following cutting conditions were used:

Cutting speed (v_c) = 120 m/min, Tool edge radius (r_e) = 300 nm, Rake angle = 10° ,

Clearance angle = 0° , Cutting depth (d_c) = 10 μm

6.3 SIMULATION APPROACH

The proposed FE simulation consists of two stages: the residual stress profile extraction and its uses for the surface deformation analysis. In the first stage, the continuous chip formation is modeled at a constant cutting speed. An explicit dynamic method is used for cutting step as it is computationally efficient for large deformation and nonlinear problems like cutting. Machining is a coupled thermo-mechanical process in which the generated heat due to friction and plastic work may influence mechanically. Therefore, the cutting simulation must use fully coupled temperature-displacement analysis, which performs the thermal as well stress analysis concurrently. The flowchart for the complete cutting simulation/analysis is depicted in Figure 6-3. The input file for the cutting simulation is attached in Appendix E.

Figure 6-3: Flow chart for residual stress extraction from cutting simulation

When the steady state condition is achieved during chip formation, the workpiece is to be cooled down to room temperature. The cutting tool is no longer required in the cooling step or for further analysis and it increases the computational time. Hence, only the workpiece deformed mesh was imported to Abaqus/Standard with material properties, stresses and temperature at all elements and nodes and was used as an initial condition for

cooling step. The sink temperature was set to 293 K. The cooling step is also modeled with fully coupled temperature-displacement analysis. After cooling down of model to the room temperature, the RS profile was extracted at an appropriate distance from the cutting edge to avoid the transient response. For the stable FE solution, it would be important to obtain the RS profile at steady state condition, rather at the transient condition. Figure 6-4 shows the steady state location at which RS profile is extracted.

Figure 6-4: RS components extraction region from cutting model

In the second stage of simulation, the steady state residual stress (RS) profile obtained from the cutting simulation was mapped into a 2D FE model that represents the cross-section of the developed texture. The thicker portion of the pre-fabricated workpiece after diamond turning remains flat compared to the large deformation of the thinner portion, which is responsible for texture formation. Therefore, only the deformation of the thinner portion is studied here. The length of the 2D model represents the cross-section diameter of the created circular bump where the maximum deformation height is achieved. It is important to mention that the mesh density of the new 2D model was similar to the one of

the cutting simulation model used in the first stage. Therefore, any mesh sensitivity effect can be avoided.

Figure 6-5 shows the 2D FE model before and after the deformation. The bottom corner nodes were constrained in the vertical direction. One additional node is also constrained horizontally to avoid rigid body motion. The applied constraints had very little reaction forces and hence their influence on the results is insignificant. The extracted RS profile from the cutting simulation is implemented across each layer of elements as the initial condition. The simulations were run in Abaqus/Standard with similar material specifications as mentioned in Table 6-2.

Figure 6-5: 2D model to represent the thinner section of the workpiece (a) before deformation and (b) after deformation

6.4 RESULTS AND DISCUSSION

6.4.1 CONTINUOUS CHIP FORMATION

The continuous chip was successfully developed using the ALE formulation as shown in Figure 6-6. The material flow in the machined workpiece and around the cutting edge of the diamond tool represented by the velocity vector is shown in Figure 6-7. It can be observed that during the simulation the material flows smoothly within the Eulerian region defined near the tool edge. The chip separates along the cutting tool rake face from the bulk material due to excessive plastic deformation, which creates a fracture. However, the remaining fraction of the workpiece material undergoes ploughing underneath the round cutting edge and forms the newly machined surface. The region where the chip leaves the bulk material is also known as stagnation zone [122] or dead metal zone [108]. In conventional machining simulations, the large uncut chip thickness justifies the assumption of using the infinitely sharp cutting tool. However, when the uncut chip thickness remains in the order of cutting edge radius, the ploughing force component becomes very significant and cannot be ignored. As discussed earlier, in ALE the chip forms due to plastic deformation and therefore any prior definition of material fracture criteria or parting line is not required for chip formation. Hence, the effects of cutting edge on the machined surface, ploughing effects and other valuable information (which are normally lost due to element deletions) can be retained using ALE formulation.

Figure 6-6: Chip morphology in the FE simulation

Figure 6-7: Material flow around the cutting edge of the tool

The initial chip thickness is assumed and defined at the onset of the simulation. Figure 6-8 shows the initial and machined chip shape and thickness in the FE simulation. It can be seen that the steady state chip shape and thickness differs significantly to the initial assumption and hence, it does not affect the simulation results. The meshing elements in the Eulerian region near the cutting edge of the tool remain fixed and therefore, no any mesh and element distortion can occur. In other regions, the mesh follows the underlined material and conclusively forms the chip as the simulation continues and reaches to steady state.

Figure 6-8: Predefined and simulated chip in the ALE formulation

6.4.2 COMPARISON OF CUTTING FORCES

The developed FE model is validated by comparing the predicted cutting forces with the experimentally measured forces. The predicted cutting forces are extracted from the FE model at the cutting tool once the simulation reaches a steady state. The cutting forces increase from the incipient stage and approach to a constant value at the steady state. Generally, the FE simulation gives larger cutting forces compared to experimental results due to plain strain approximation, which restricts the material flow in the direction of the chip width. The diamond turning model is approximated to the equivalent orthogonal 2D FE model by normalizing the width of cut to one unit. Therefore, the width of cut (b) should be compensated first before the comparison of the cutting forces. For diamond turning, the width of cut (b) for single turning pass can be expressed as shown in Eq. (3.1). In accordance with experimental conditions mentioned in Table 3-1, the width of cut (b) is estimated as $\sim 110\text{ }\mu\text{m}$.

Figure 6-9 shows the comparison of measured and simulated cutting forces at steady state. It can be seen that the simulated thrust force is very close to the measured values. However, the simulated cutting forces are little over-predicted. Though the simulated forces do not perfectly match the experimental results, it still shows the reasonable accuracy for further surface deformation analysis.

Figure 6-9: Experimental and numerically simulated forces at cutting and thrust directions

6.4.3 RESIDUAL STRESS PROFILE ESTIMATION

Figure 6-10 shows the variation of the RS profile at the surface and subsurface across the thickness of the workpiece when the cutting has reached its steady state. It can be seen that the RS component in cutting direction (x-direction) seems to be significant, while the stress component in thrust direction (y-direction) is negligible. Therefore, the current work will focus on stress component in the cutting direction for further discussion.

It is to be noted that the stress profile contains both the compressive stress as well as tensile stress components. The resulting maximum compressive stress was found at the surface and near-surface, which gradually reaches to zero at a certain thickness (i.e. $5\text{ }\mu\text{m}$ in the present case). This result confirms that the residual stress in diamond turning diminished very quickly along the thickness of the workpiece [96].

Figure 6-10: Steady state residual stress contour in x- and y-direction of cutting model as a function of workpiece depth

As discussed earlier, the possible reasons for the surface residual stress during machining are the plastic deformation, phase transformation and thermal stress due to uneven heating [123]. The effect of phase change on RS is expected to be negligible as the maximum temperature at the cutting zone near the round edge of the tool was approximately 365 K. The developed temperature profile is not sufficient to produce the phase transformation on the machined surface. Therefore, it is justified to neglect the phase transformation as a source of RS. Figure 6-11 shows the variation of temperature near the cutting zone and at the steady state location.

Figure 6-11: Temperature variation across the thickness of workpiece at transient (near the cutting edge) and steady state condition

The mechanical deformation is considered to produce compressed RS on the machined surface. However, the thermal gradients during machining result in tensile residual stresses [124]. The heat generated in DT is much less as compared to conventional machining. Secondly, the Aluminum 6061-T4 alloy has high thermal conductivity. Therefore, the generated heat during cutting dissipated quickly to nearby sub-surface of the material, rather than entrapping of heat energy to the near-surface region, which normally happens in the case of low thermal conductivity material, such as stainless steel AISI 304 [124, 125]. Hence, the mechanical effects are the dominant source of RS on the machined surface in DT, which produces predominantly compressive stresses on the surface and near-surface of the machined surface.

6.4.4 EFFECT OF MATERIAL THICKNESS ON SURFACE DEFORMATION – 2D FE MODEL

The surface deformation obtained from FE simulation are shown and compared in Figure 6-12, Figure 6-13 and Figure 6-14 for the thinner portion diameter (L) of 2.5 mm, 2 mm and 1.5 mm, respectively. It is shown that the trends of the two curves for all tested condition of cross-section length are identical. The magnitude of the deformation height (t_b) for larger material thickness (when $t_{rf} \geq 170 \mu\text{m}$) is very well predicted with good accuracy. However, the discrepancy between the FE prediction and the experimental measurement increase much for lesser material thickness when $t_{rf} \leq 140 \mu\text{m}$. The deviation of the simulated results from the experiments at the low material thickness (t_{rf}) can be attributed to the increasing number of cutting passes during experiments. As discussed in the experimental section, the workpiece material thickness is gradually decreased by a series of face turning passes with a constant cutting depth. Hence, in order to obtain the low material thickness (t_{rf}), more number of turning passes is required. Each turning pass disturbs the internal equilibrium of stresses in the workpiece. In diamond turning, only the top stressed layer (up to 10-20 μm) near the machined surface contains all the significant information about the RS field. Most of the stressed layer near the surface and sub-surface created by previous cutting pass is removed by the sequential cut with the cutting depth of 10 μm and a new plastically deformed layer is fabricated. However, when the number of turning passes increases, the error from each cut can be accumulated and the FE simulation for a single cutting pass may carry an accumulated error for higher number of sequential cut. Consequently, a discrepancy in the simulated results is observed at a lower material thickness (t_{rf}).

Also, an exact match with the experiments in FE modeling is hardly expected due to some inherent approximation. The possible sources of the errors could be the approximations in friction model, material characteristics modeling, elements remeshing or remapping errors, etc. In addition, the workpiece material is assumed to be pure homogenous in FE model. However, polycrystalline alloy (Aluminum 6061-T6) was used in the experiments. Despite the approximations made in the FE simulation approach, the comparison shown in Figure 6.12-14 indicate the good agreements between predictions and measurements for the material thicknesses (when $t_{rf} \geq 170 \mu\text{m}$).

Figure 6-12: Surface deformation heights from experiments and simulations when thinner portion length was equal to 2.5 mm

Figure 6-13: Surface deformation heights from experiments and simulations when thinner portion length was equal to 2.0 mm

Figure 6-14: Surface deformation heights from experiments and simulations when thinner portion length was equal to 1.5 mm

6.4.5 EFFECT OF MATERIAL THICKNESS ON SURFACE DEFORMATION - CIRCULAR PLATE MODEL

The 2D FE model can be extended to a 3D circular plate model, which represents the thinner section of the workpiece corresponding to the backside pre-fabricated hole. The 3D plate model is shown in Figure 6-15. The machining-induced RS profile obtained from the cutting simulate is mapped along the thickness of the plate for the relevant deformation analysis as shown in Figure 6-16.

For the implementation of the 2D stress profile from plain strain cutting simulation to 3D plate structure, following assumption is made:

$$\sigma_{xx} = \sigma_{yy} \quad (6.13)$$

This assumption seems oversimplified. However, as discussed earlier, the experimental results show that the developed convex shape profiles were uniform around the vertical axis passing through the center of the texture. Therefore, the assumption can be accepted at least for the qualitative analysis of the surface deformation in order to study the effects of machining-induced RS on the texture produced by BPT.

The bottom edge of the 3D plate was constrained in x- and y- directions. The extracted RS profile from the cutting simulation is mapped to the each layer of elements as an initial condition. The simulations were run in Abaqus/Standard at different material thicknesses (t_{rf}), similar to the 2D simulation as mentioned earlier in section 6.3. Figure 6-17 shows the deformed plate and line trace profile measured at the apex of the plate.

Figure 6-15: 3D circular plate representing the thinner section of workpiece

Figure 6-16: Mapping of the RS profile along the thickness of the circular plate

Figure 6-17: (a) 3D deformed plate and (b) corresponding profile measured at the center of the texture, when $t_{rf} = 200 \mu m$ and $L = 2.5 mm$

Figure 6-18 shows the comparison of 3D simulation and experiments results for 2.5 mm diameter of created texture on the machined surface. It is found that the simulation results are very much similar to 2D simulation results. The 3D plate model predicts well for the surface deformation when $t_{rf} \geq 170 \mu\text{m}$. However, for lesser material thickness ($t_{rf} \leq 140 \mu\text{m}$), the simulated results are underpredicted. The trend of the simulation result is identical with the experiments for all material thicknesses (t_{rf}). Therefore, the 3D model with the simulation approach presented in this chapter can provide a better pictorial representation of the textured profile in BPT.

Figure 6-18: 3D simulation results compared with the experiments for 2.5 mm diameter of created texture

6.5 SUMMARY

This chapter provides an FE modeling approach for surface deformation simulation in backside patterned texturing for submicron to micro-sized features generation. A coupled thermo-mechanical plain strain cutting model is successfully developed based on the arbitrary Lagrangian-Eulerian formulation to simulate diamond turning. The induced residual stress across the workpiece thickness is analyzed via ALE based FE cutting model and is subsequently utilized in the surface deformation prediction of textures produced BPT.

ALE formulation for simulation avoids the needs of elements deletion criteria and prior definition of the parting line. Therefore, the material flow around the cutting edge of the diamond tool can be realistically modeled. The developed cutting model is validated by comparing the experimental and simulated cutting forces, which show the acceptable agreement. The estimated RS profile is mapped to 2D models of various thicknesses for deformation analysis. The relationship between the workpiece material thickness (t_{rf}) and surface deformation (t_b) is developed and compared to the simulation results. For the larger material thickness (when $t_{rf} \geq 170 \text{ } \mu\text{m}$), the FE modeling approach accurately predicts surface deformation compared to the experimental results. However, in the case of lower material thickness ($t_{rf} \leq 140 \text{ } \mu\text{m}$), the simulation results are slightly underestimated.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

This chapter provides the concluding remarks and summarizes the research work presented in this thesis. In addition, the potential future work, which may lead to improvement as well as an extension of the current work, is presented in the last section of this chapter.

7.1 CONCLUDING REMARKS AND RESEARCH CONTRIBUTIONS

The objectives and contributions of this thesis consist of a novel process development for submicron to micro-sized surface texturing followed by a mathematical formulation and a finite element (FE) model to predict the surface deformation in the texture produced by BPT.

7.1.1 DEVELOPMENT OF THE TECHNIQUE OF BPT

A novel technique: backside patterned texturing (BPT) was developed for the fabrication of submicron to micro-scale miniature features using 2-axis ultraprecision single point diamond turning (SPDT). For this purpose, many work samples were machined using diamond face turning for 1.5 mm, 2 mm and 2.5 mm diameter of pre-fabricated holes in order to produce single as well as an array of 3x3 convex shape bumps. Later, some other types of freeform surfaces like waterdrop freeform, cylindrical freeform, spiral freeform

and integrated freeform surfaces were also fabricated with mirror surface quality. The proposed method has been shown to fabricate user-defined submicron to micro-sized features over a large area of machined surfaces. Following conclusions can be drawn from the study:

- BPT can be employed to fabricate miniature surface features with mirror surface quality for user-defined macroscopic backside pre-fabricated patterns
- Unlike the other ultraprecision machining processes (like FTS or SSS etc.), which use a diamond tool to fabricate the desired features sequentially, BPT allows to fabricate multiple features with different shapes and geometries simultaneously.
- In contrast to conventional mechanical micromachining methods, this technique has a potential to provide a simpler and faster solution as it does not require any complex tool-workpiece path programming and additional aid for motion synchronization. The technique also provides flexibility for the fabrication of various types of features like freeform and asymmetrical surfaces with mirror surface quality.

7.1.2 EFFECTS OF BACKSIDE PATTERN GEOMETRY AND WORKPIECE THICKNESSES

The effects of process parameters, such as backside pattern geometry and material thickness (t_{rf}) on the deformation height (t_b) of created textures were investigated. It is found that the workpiece thickness (t_{rf}) has a critical influence on the final geometry of the generated texture. The nonlinear deformation height (t_b) increases with a decrease in the workpiece thickness (t_{rf}) for all the tested conditions.

For each backside pattern geometry, there is a safe operating material thickness (t_{rf}) from minimum threshold thickness (t_m) at which the minimum texture height is achieved to the damage thickness (t_d) at which the fracture occurs at the texture periphery. For example, in the case of 2.5 mm diameter of the pre-fabricated hole, the material thickness (t_{rf}) should be in the range of $310 \mu\text{m} \geq t_{rf} > 100 \mu\text{m}$ for the undamaged texture profile. Hence, it is concluded that various texture profiles can be fabricated by controlling backside pattern geometries and the material thicknesses (t_{rf}).

7.1.3 EFFECTS OF CUTTING VELOCITY TO THE SURFACE DEFORMATION

The experimental result suggested that the cutting speed directly influences to the developed textures. Higher cutting speed produces larger surface distortion, which increases the height of generated texture (t_b). The reason is that the higher cutting speed causes an increase of the level and penetration depth of residual stresses, which lead to induce more surface deformation at thinner portion. As a result, the higher cutting speed produces larger surface deformation height (t_b).

7.1.4 SURFACE DEFORMATION PREDICTION BY A MATHEMATICAL FORMULATION

A mathematical formulation was developed to predict the surface deformation in the produced texture by BPT. The proposed methodology does not require the true RS profile along the workpiece thickness via experimentally measurement or FE model. The model estimates the source residual stress (σ_s) using the measured surface deformation for an

arbitrary backside pattern. Then the known source stress (σ_s) is used for surface deformation estimation of other axisymmetric and doubly symmetric texture geometries on diamond machined surface. The proposed methodology shows a good agreement with the experiments. With a few initial tests, the source residual stress (σ_s) based proposed methodology can significantly reduce time and efforts requires for further trial and error experiments for subsequent precise textures formation in BPT.

7.1.5 SURFACE DEFORMATION PREDICTION BY AN FE MODEL

To provide a better understanding of the surface deformation process in BPT, an FE model is also developed to simulate the surface deformation in the produced surface texture by BPT. The arbitrary Lagrangian-Eulerian (ALE) formulation was used to simulate diamond turning and the RS profile across the workpiece thickness was obtained at the steady state. ALE mesh motion formulation avoids the need of elements deletion criteria and prior definition of parting line for continuous chip formation. Therefore, the material flow around the cutting edge of the diamond tool can be realistically modeled. The developed cutting model is validated by comparing the experimental and simulated cutting forces, which show the acceptable agreement. The simulated RS profile was subsequently mapped to another 2D and 3D models to predict the surface deformation at various material thicknesses (t_{rf}). The simulation results show that for the larger material thickness (when $t_{rf} \geq 170 \mu\text{m}$), the FE modeling approach accurately predicts surface deformation compared to the experimental results. However, in the case of lower material thickness ($t_{rf} \leq 140 \mu\text{m}$), the simulation results are underestimated even though the trend of the simulation results is similar to the trends of the experiments.

In sum, the proposed texturing method contributes to the capability improvement of ultraprecision diamond machining techniques and opens a new domain in miniaturization of the component.

7.2 RECOMMENDATIONS FOR THE FUTURE WORK

The present thesis contributed both in the practical as well as theoretical aspects of the developed technique of BPT. However, there are other possible ways to extend the research work presented in this thesis to enhance the performance and capabilities of the proposed method.

- (a) The current experimental work used polycrystalline ductile Aluminum 6061-T6 as workpiece material. The study of the effects of other materials, such as brass, OFHC copper and NiP alloys, which are also used in optical components fabrication, would enhance the flexibility of the proposed technique for other materials. The elastic behaviors of the other materials are different from Al 6061-T6; it means that the resultant surface deformation, surface finish and the form profile of the generated texture will also vary.
- (b) The developed ALE based FE model of diamond turning can be generalized to study the surface deformation/distortion of thin diamond machined workpieces. The RS profile obtained via FE cutting simulation as a function of workpiece thickness can be used to study the surface flatness and form error, which are the general concerns associated with diamond turned workpieces [126].

- (c) The proposed mathematical formulation using a beam model for surface deformation prediction in the produced texture shows the good agreement with the experimental results. However, it would be interesting to extend the model to a 3D structure representing the similar geometry as the developed texture.
- (d) The textured surface can be used directly as a reflective medium or as a mold for mass production of optical components. The structural strength of the specimen should be able to sustain the molding pressure. The thinner section in the current machined workpieces may not withstand the high molding pressure. Hence, it is important to enhance the strength by filling the backside pattern by some suitable epoxy resins that can solidify at room temperature.
- (f) The tool geometry (like nose radius, rake angle etc.) and tool wear influence the induced stresses during machining. Hence, it is worthwhile to extend the research to study the effect of new and worn tool with different geometries on the surface deformation mechanism of BPT.

APPENDIX A

Schematic of the single point diamond tool insert

(Dimensions are in millimeters)

APPENDIX B

Quality certificate of the diamond tool cutting edge

APPENDIX C

Characteristics of the dynamometer ‘Kistler 9256C1’

Sensitivity	F_z (pC/N)	-26.11
	F_x , (pC/N)	-25.61
	F_y (pC/N)	-13.02
Resonant frequency	~ 5.5 kHz	
Maximum Force Measuring Limit	$F_x=F_y=F_z$	250 N
Rigidity	250 N/ μ m	

APPENDIX D

DEVELOPMENT OF EFFECTIVE SOURCE RESIDUAL STRESS EQUATION

L = diameter of produced bump

b = width of beam

t_o = plastically deformed layer

T = workpiece material thickness (t_{rf})

According to the elastic beam theory, the differential equation for bending moment (M_z) can be written as

$$\frac{d^2y}{dx^2} = -\frac{M_z}{EI} \quad (1)$$

$$\frac{dy}{dx} = -\frac{M_z}{EI}x + C_1 \quad (2)$$

The deflection (y) at any point of the beam with respect to x is

$$y = -\frac{M_z}{2EI}x^2 + C_1x + C_2 \quad (3)$$

Boundary conditions (BC):

BC1: at $x = 0$, $y = 0$

BC2: at $x = L$, $y = 0$

After the adding of BCs to equation (3)

$$y = -\frac{M_z}{2EI} x^2 + \frac{M_z L}{2EI} x \quad (4)$$

The maximum deflection (y_{max}) of the beam can be found at the center i.e. $x = L/2$

Therefore,

$$t_b = y_{max} = -\frac{M_z}{2EI} \left(\frac{L}{2} \right)^2 + \frac{M_z L}{2EI} \left(\frac{L}{2} \right)$$

Note: Deformation height (t_b) of beam is represented by y_{max} .

$$t_b = \frac{M_z L^2}{8EI} \quad (5)$$

Rearranging the equation for bending moment (M_z)

$$M_z = \frac{t_b 8EI}{L^2} \quad (6)$$

The bending moment (M_z) can be represented as a function of effective induced source stresses (σ_s) as:

$$M_z = \int_0^{t_0} b \sigma_s (t - t_{rf}/2) dt \quad (7)$$

After integration,

$$M_z = \frac{b \sigma_s t_0}{2} (t_0 - t_{rf}) \quad (8)$$

Combining the Eq. (6) and Eq. (8) gives as follows

$$\frac{t_b 8EI}{L^2} = \frac{b \sigma_s t_0}{2} (t_0 - t_{rf})$$

Rearranging the equation for effective source stresses (σ_s)

$$\sigma_s = \frac{16EI t_b}{t_0(t_0 - t_{rf})b L^2} \quad (9)$$

This is the final equation to show the relationship between effective source stresses (σ_s) and workpiece deformation (t_b).

APPENDIX E

*Heading

** Job name: Job-24-32-29B6-MN4 Model name: Diamond Turning_ALE_MN11-43-2

** Generated by: Abaqus/CAE 6.13-1

*Preprint, echo=NO, model=NO, history=NO, contact=NO

** MATERIALS

*MATERIAL, NAME="ALU 6061"

*CONDUCTIVITY

167.,298.

*DENSITY

2.7E-09,

*ELASTIC

68900., 0.3

*EXPANSION, ZERO=298.

2.52E-05,298.

*INELASTIC HEAT FRACTION

0.9,

*PLASTIC, HARDENING=JOHNSON COOK

324., 114., 0.42, 1.34, 900., 298.

*RATE DEPENDENT, TYPE=JOHNSON COOK

0.002,1.

*SPECIFIC HEAT

8.96E+08,298.

*MATERIAL, NAME=SCD

*CONDUCTIVITY

2000.,298.

*DENSITY

3.52E-09,

*ELASTIC

1.05E+06, 0.1

*EXPANSION, ZERO=298.

1.18E-06,298.

*SPECIFIC HEAT

5E+08,298.

**

** INTERACTION PROPERTIES

**

*SURFACE INTERACTION, NAME=INTPROP-1

*FRICTION

```
0.07,  
*GAP HEAT GENERATION  
1., 0.35  
**  
** PREDEFINED FIELDS  
**  
** NAME: PREDEFINED FIELD-1  TYPE: TEMPERATURE  
*INITIAL CONDITIONS, TYPE=TEMPERATURE  
WORKPIECE-1.WP_WHOLE, 298.  
** NAME: PREDEFINED FIELD-2  TYPE: TEMPERATURE  
*INITIAL CONDITIONS, TYPE=TEMPERATURE  
SCD-1.WHOLE_TOOL, 298.  
** -----  
**  
** STEP: CUTTING  
**  
*STEP, NAME=CUTTING  
*DYNAMIC TEMPERATURE-DISPLACEMENT, EXPLICIT  
, 0.00025  
*BULK VISCOSITY  
0.06, 1.2  
**  
** BOUNDARY CONDITIONS  
**  
** NAME: BC-TOOLRIGHT TYPE: DISPLACEMENT/ROTATION  
*BOUNDARY  
TOOL-RIGHT, 1, 1  
TOOL-RIGHT, 2, 2  
** NAME: BC-TOOLTOP TYPE: DISPLACEMENT/ROTATION  
*BOUNDARY  
TOOL-TOP, 1, 1  
TOOL-TOP, 2, 2  
** NAME: BC-WP-BOTTOM TYPE: DISPLACEMENT/ROTATION  
*BOUNDARY  
SET-30, 2, 2  
** NAME: TOO-EDGES TYPE: DISPLACEMENT/ROTATION  
*BOUNDARY  
SET-29, 1, 1  
SET-29, 2, 2  
** NAME: WP-LEFT TYPE: VELOCITY/ANGULAR VELOCITY
```

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*BOUNDARY, TYPE=VELOCITY, REGION TYPE =EULERIAN
WORKPIECE-1.VELO-LEFT, 1, 1, 2000.
*ADAPTIVE MESH CONTROLS, NAME=ADA-1, CURVATURE REFINEMENT=3.
1., 0., 0.
*ADAPTIVE MESH, ELSET=WORKPIECE-1.WP_WHOLE, CONTROLS=ADA-1,
FREQUENCY=1, MESH SWEEPS=2, OP=NEW
**
** ADAPTIVE MESH CONSTRAINTS
**
** NAME: ADA-CONS-3 TYPE: DISPLACEMENT/ROTATION
*ADAPTIVE MESH CONSTRAINT
WORKPIECE-1.CENTERNODES, 1, 1
WORKPIECE-1.CENTERNODES, 2, 2
** NAME: ADA-CONS-4 TYPE: DISPLACEMENT/ROTATION
*ADAPTIVE MESH CONSTRAINT
WORKPIECE-1.RIGHTNODES, 2, 2
** NAME: ADA-CONS-5 TYPE: DISPLACEMENT/ROTATION
*ADAPTIVE MESH CONSTRAINT
WORKPIECE-1.LEFTNODES, 2, 2
** NAME: LEFT-EU TYPE: DISPLACEMENT/ROTATION
*ADAPTIVE MESH CONSTRAINT
WORKPIECE-1.VELO-LEFT, 2, 2
**
** INTERACTIONS
**
** INTERACTION: INT-1
*CONTACT PAIR, INTERACTION=INTPROP-1, MECHANICAL
CONSTRAINT=PENALTY, CPSET=INT-1
TOOL_CUT_EDGE, WP-CUTEDGE
**
** OUTPUT REQUESTS
**
*RESTART, WRITE, OVERLAY, NUMBER INTERVAL=50, TIME MARKS=NO
**
** FIELD OUTPUT: F-OUTPUT-1
**
*OUTPUT, FIELD, TIME INTERVAL=1E-06
*NODE OUTPUT
NT, RF, U
*ELEMENT OUTPUT, DIRECTIONS=YES
```

EVF, PE, PEEQ, PEVAVG, S, STATUS, SVAVG, TEMP

*CONTACT OUTPUT

CSTRESS,

**

** HISTORY OUTPUT: H-OUTPUT-1

**

*OUTPUT, HISTORY, TIME INTERVAL=2.5E-06

*NODE OUTPUT, NSET=SCD-1.WHOLE_TOOL

NT, RF1, RF2

*ELEMENT OUTPUT, ELSET=SCD-1.WHOLE_TOOL

TEMP,

*ENERGY OUTPUT, ELSET=SCD-1.WHOLE_TOOL

ALLAE, ALLCD, ALLDMD, ALLFD, ALLHF, ALLIE, ALLIHE, ALLKE, ALLPD,

ALLSE, ALLVD, ALLWK, ETOTAL

*END STEP

APPENDIX F

Cutting of sample from the machined workpiece for microstructure analysis

APPENDIX G

Schematic of axisymmetric backside pattern for model validation

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