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Hybrid Processes in Material Removal of Hard and Brittle Materials

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HYBRID PROCESSES IN MATERIAL REMOVAL OF HARD AND BRITTLE MATERIALS

by

Hossein Mohammadi

A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy
Department of Mechanical and Aerospace Engineering
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DEDICATION

To my wife, Zahra, my newborn daughter, Elsa, and my parents.
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Hossein Mohammadi
HYBRID PROCESSES IN MATERIAL REMOVAL OF HARD AND BRITTLE MATERIALS

Hossein Mohammadi, Ph.D.
Western Michigan University, 2018

New technologies demand new materials with better mechanical, optical, and thermal properties. Materials that are light weight, strong with high resistance to high temperatures, and compatible with a predetermined condition. Such materials usually are challenging to manufacture and process compared to widely available materials such as metals. Ceramics and semiconductors are considered extremely hard and brittle, making them very difficult to cut and manufacture. The other major and fast-growing type of materials are composites (including Ceramic Matrix Composites, CMC) that are also considered very challenging to machine. All these materials have many applications in major industries (i.e. electronics, aerospace, optics, automotive, etc.) due to their superior properties, such as those indicated above. To make a final product from raw material in most cases at least one or a combination of machining processes, such as cutting, turning, milling, and drilling is necessary. Machining, or turning, of hard and brittle materials such as ceramics and semiconductors, has been a challenge for many years. Achieving good surface finish, avoiding surface and subsurface damages, and achieving a high material removal rate are extremely challenging for these materials. High tool wear is one of the main drawbacks of machining these types of materials. It not only increases the cost of the tooling but also increases the total cost of a finished workpiece because of the downtime of the process. Mechanical drilling of hard, brittle and challenging materials as a major material removal process poses many problems
as well. Rapid tool wear and damage to materials are common obstacles. Developing new techniques to overcome the obstacles in machining new materials is necessary to keep up with the invention of them. Hybrid processes that combine at least two methods of material removal (or material processing) are a possible solution for these challenges. A combination of a mechanical material removal process with a heat source such as laser to get benefit both of these techniques can help overcome these obstacles. Two novel techniques of mechanical-thermal methods are investigated in this dissertation. One of them, Micro Laser Assisted Machining (µ-LAM) which is a process used for turning the hard and brittle materials and is investigated in Part A of this dissertation. The µ-LAM has been under development over the past decade. However, to be able to use it in the actual machining world and in the industry environment, it needs to be improved and optimized. The chapters in part A of this dissertation are mainly focused on the investigation of different aspects and optimization of parameters of the µ-LAM technique. In part B, a novel technique for drilling challenging materials, Laser Augmented Diamond Drilling (LADD), is introduced and studied. In the LADD mechanical drilling combined with a heat source such as laser to get benefit from both to increase the productivity by improving the quality, precision, and tool life. Two different types of materials were drilled with the aid of this technique, and results were analyzed. Cutting forces were particularly evaluated and the quality achieved is discussed in the chapters of part B.
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<th>Description</th>
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<tbody>
<tr>
<td>µ-LAM</td>
<td>Micro Laser Assisted Machining</td>
</tr>
<tr>
<td>3D</td>
<td>Three-Dimensional</td>
</tr>
<tr>
<td>BDO</td>
<td>Beam Delivery Optics</td>
</tr>
<tr>
<td>CMC</td>
<td>Ceramic Matrix Composites</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical Vapor Deposition</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
</tr>
<tr>
<td>DBT</td>
<td>Ductile To Brittle Transition</td>
</tr>
<tr>
<td>DI water</td>
<td>Deionized Water</td>
</tr>
<tr>
<td>DoC</td>
<td>Depth Of Cut</td>
</tr>
<tr>
<td>DOE</td>
<td>Design Of Experiment</td>
</tr>
<tr>
<td>ECD</td>
<td>Electrochemical Drilling</td>
</tr>
<tr>
<td>ECM</td>
<td>Electrical Chemical Machining</td>
</tr>
<tr>
<td>EDM</td>
<td>Electrical Discharge Machining</td>
</tr>
<tr>
<td>FRP</td>
<td>Fiber-Reinforced Plastics</td>
</tr>
<tr>
<td>HPPT</td>
<td>High Pressure Phase Transformation</td>
</tr>
<tr>
<td>HV</td>
<td>Vickers Hardness</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>LADD</td>
<td>Laser Augmented Diamond Drilling</td>
</tr>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>MMC</td>
<td>Metal Matrix Composites</td>
</tr>
<tr>
<td>mN</td>
<td>Millinewtons</td>
</tr>
<tr>
<td>MRR</td>
<td>Material Removal Rate</td>
</tr>
<tr>
<td>nm</td>
<td>Nanometer</td>
</tr>
<tr>
<td>OD</td>
<td>Optical Density</td>
</tr>
<tr>
<td>OMS</td>
<td>Odorless Mineral Spirits</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions Per Minute</td>
</tr>
<tr>
<td>RUM</td>
<td>Rotary Ultrasonic Machining</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>SiC</td>
<td>Silicon Carbide</td>
</tr>
<tr>
<td>SLAM</td>
<td>Selective Laser-Assisted Milling</td>
</tr>
<tr>
<td>SPDT</td>
<td>Single Point Diamond Turning</td>
</tr>
<tr>
<td>UMT</td>
<td>Universal Micro-Tribometer</td>
</tr>
<tr>
<td>USM</td>
<td>Ultrasonic Machining</td>
</tr>
<tr>
<td>W</td>
<td>Watt</td>
</tr>
<tr>
<td>μm</td>
<td>Micrometer</td>
</tr>
<tr>
<td>Ψ</td>
<td>Include Angle</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

Machining is one of the most common, and usually the last, process on a material to shape it to a final form for industrial use. This technique has been used since humans discovered that a softer material can be carved with the aid of a harder one. Mechanical machining follows a simple rule: a harder tool can cut a softer material. In other words, the cutting tool should be much harder than the workpiece material (a rule of thumb is five times [5x] harder). This is difficult and not possible when machining the hardest materials such as silicon carbide. Materials can be categorized into two major types, metallic and nonmetallic. Nonmetallic would include plastics, polymers, glasses, ceramics, semiconductors, and composites [1]. All these materials have a wide range of properties and chemical structures that make them suitable for different conditions and applications. High strength, hardness, toughness, thermal, and wear resistivity, along with desirable optical characteristics, are considered good properties that make a material ideal for advanced technologies.

Although these properties make them desirable, it can also make them difficult to process and to cut and/or machine. Ceramics and semiconductors have many applications in modern technologies due to their properties. Their fast-growing applications emerge from their ability to perform under extreme conditions such as high temperatures, and abrasive and higher loads. In addition, they have better performance compared to other current widely available materials [2]. They are lightweight, inert, biomedical compatible, wear resistant, and have desirable optical
characteristics. For instance, ceramics can be used at high temperatures. As an example, the efficiency of an engine is directly related to the highest temperature that it can reach. A limiting factor is the temperature where metal alloys start to deform thermally. For example, an aluminum alloy has a melting point <800 °C (although the coolant fluid circulates around the engine and reduces the temperature). A material that can resist substantially higher temperatures can be an advance material such as silicon carbide with a melting point of >2800 °C. Therefore, ceramics which have high temperature stability and excellent corrosion resistance can be ideal materials for this purpose [2].

Despite their many desirable properties, ceramics and semiconductors are hard and brittle which classify them as materials with poor machinability. Their hardness makes them difficult to cut by traditional techniques since there is a limited number of harder materials that can be used as the cutting tool (ceramics are being used as the cutting tool for machining of other materials because of their hardness [3]). Even if diamond, the hardest known material [4], is used as the cutting tool, wear is unavoidable in the machining of these materials. Rapid tool wear increases the cost of production as such a cutting tool is usually very expensive, and tool replacement takes time, resulting in longer downtime of equipment.

Ceramics and semiconductors are also very brittle materials, which make their machining inefficient and time consuming. The tendency of these materials to fracture during machining and their low fracture toughness stem from their covalent bonding and crystal structure [5]. Machining them needs to be performed in a very cautious manner which means a higher process time. Achieving a good surface finish, avoiding surface and subsurface damages, and at the same time achieving a high material removal rate (MRR) are extremely difficult [6]. Grinding and abrasive machining are the main processes used for shaping the ceramics [7]. In grinding fixed abrasives
(loose abrasives are used in lapping and polishing), removing the material from the surface in small amounts and the mechanism can be classified into the brittle fracture or plastic deformation depending on the cutting condition. Surface and subsurface damage left behind after grinding are the major drawbacks of the process [8]. Single point diamond turning (SPDT), or in short form diamond turning, is one of the main techniques used to produce optics [9], [10]. In this process a diamond tool moves across the workpiece and removes the material to create a high-quality surface. A very precise spindle (air bearing) is used in this process to rotate the part.

Other advanced materials discussed are composites, which have very fast-growing applications in various industries. Composite materials are generally fabricated from at least two different materials with different properties [11]. Mechanical properties in composites are usually different than components. Three main types of composites are Fiber-reinforced plastics (FRP), Metal matrix composites (MMC), and Ceramic matrix composites (CMC) [12].

Despite many superior properties such as their light weight and strength, machining them is challenging. Products made of the composite are usually produced in near net shape [13], [14], however, further processes such as milling and especially drilling [15] are needed to finalize them. Problems such as delamination and rapid tool wear are prevalent in the machining of composites [16]. For these materials a process that can help to increase the tool life (less tool wear) and improve the quality of the final product is in high demand as well.

There have been many attempts in recent decades to solve the challenges in the machining of hard, brittle and difficult to cut materials. Nontraditional machining processes were introduced to overcome obstacles such as machining extremely hard or brittle materials. One of these processes, electrical discharge machining (EDM), erodes material with the aid of sparks while there is a small gap between the tool and workpiece. EDM is only useful for conductive materials
as to make small sparks for eroding materials, and the tool needs to be one electrode and workpiece
the second one. Such a process is not suitable for ceramics as they are not conductive in general.
Also, EDMed surfaces are full of small craters left behind because of small sparks and not smooth
enough for many applications. For brittle materials, ultrasonic machining (USM) is available to
remove material with the aid of fine abrasive particles floating in a slurry, and vibrated by a high
frequency, low amplitude tool. This process is very slow, not able to provide very smooth surfaces,
and leaves many undesirable effects such as surface and subsurface damages to the material. Many
other methods are available for machining ceramics and semiconductors. However, to achieve very
smooth surfaces with minimal damages, still traditional machining processes such as diamond
turning are used in industry [17, p. 336]. For drilling, in particular, noncontact laser ablation is
widely used for making a hole in different materials but it suffers from many drawbacks such as
overheating, inaccuracy, recast layer, etc.

Hybrid processes that combine at least two methods of material removal (or material
processing) are the possible solution for these challenges [18, p. 5]. A combination of mechanical
and thermal processes to overcome the tool wear and improve the final product quality has been
used extensively over the last decades [19]–[21]. Thermal softening decreases the hardness and
brittleness of the materials and makes them easier to cut. One of the novel techniques of
mechanical-thermal methods is micro laser assisted machining (µ-LAM) [22]. µ-LAM is a process
for satisfying the demands in machining hard and brittle materials. It also has been under progress
and development for the last decade [23], [24]. However, to be able to use it in the actual machining
world and in the industry environment, it needs to be improved and optimized. The studies related
to this technique are presented in Part A of this dissertation.
Using hybrid processes for other machining processes, i.e., drilling that is in high demand and mechanical drilling of hard and brittle materials, is also tricky. Laser Augmented Diamond Drilling (LADD), which combines laser softening and mechanical drilling, is introduced and studied in Part B of this dissertation.

1.1 Experimental Setup - Testing Platform

Experimental testing was primarily conducted on a tribometer made by the Center for Tribology Research Inc. (CETR) with a commercial name of Universal Micro-Tribometer (UMT). UMT is designed for performing tribology tests, and it has three programmable axes similar to a small CNC machine. This system can work in two different control modes: position controlled and load controlled. Each of these modes can be used to perform tests depending on the experiment’s goals. For example, to keep the cutting load at a certain amount, the controlling program keeps the force constant during the test.

The position control mode is very similar to other regular machining equipment which means the position of the tool with respect to the workpiece can be fixed or changed based on a program. The resolution of movement of the axes is as small as 1 μm/sec. UMT is equipped with different accessories such as load cell in different ranges of applicable loads from 50 g to 25 Kg. Vertical and lateral axes of the UMT are fixed to equipment, but the third axis is removable and can be replaced by an air bearing spindle. Depending on the type of test, this axis can be changed. For example, for a scratch test the linear stage can be used, and for the turning tests, the spindle can be mounted on the UMT.
1.2 Laser Sources

For the laser source, three types of lasers were used for the studies performed in this dissertation; two of them were green and IR lasers with the wavelengths of 532 and 1480 nm as low power units, and a medium power laser with a wavelength of 1070 nm. All of them are continuous wave (CW) laser units. The green laser is made by Shanghai Laser & Optics Century Co., Ltd. (SLOC) with the maximum deliverable power of 250 mW. The low power IR laser (1480 nm) is made by Furukawa with a maximum power of 400 mW. The medium power IR laser unit is made by IPG with a maximum power of 100 W. Most experimental tests were performed by using an IPG laser that had a Gaussian beam profile. Laser power was measured and adjusted before each test by the aid of a power meter, made by New Focus, based on the experimental plan.

1.3 Laser Focusing and Alignment

In both techniques studied in this dissertation laser alignment is a very crucial step. Since the cutting is occurring in a very small region at the tip of the diamond cutting tool, the laser beam is also focused to a small size to increase the power density. The laser beam travels through the diamond, and it may diffract depending on the angle of incident to the back of the diamond. Aligning the beam before each test to make sure the laser is heating the cutting zone is necessary. In the following chapters, the laser alignment technique and the setup is discussed in detail.

1.4 Characterization

Achieved results should be analyzed to determine the effect of the process and its parameters on the outputs. Characterization of the specimen after performing the tests helps to get
enough information for this purpose. To characterize the samples, different types of measurements were utilized as follows.

1.4.1 Optical Microscopy

Processed samples and diamond tools were observed under an optical microscope to evaluate the results and condition of the tool. The primary objective of using the microscope to evaluate the samples was to visually check the surfaces of turned or drilled samples for the ductile or brittle mode of the cut and other damages that possibly occurred. Cutting tool monitoring is a vital step before and after the experimental tests to evaluate the tool sharpness and determine if it needs to be sent for re-lap.

1.4.2 White Light Interferometry

The other main technique used in this dissertation to evaluate the samples was White Light Interferometry. The equipment used for this purpose was a Wyko surface profiler developed by Wyko Corporation, which now is owned by Bruker Corporation. The Wyko Interferometer is a non-contact optical profiler capable of surface integrity characterization. It operates in two modes: the vertical-scanning mode for rough surfaces and the phase-shifting mode for very smooth surfaces.

1.4.3 Scanning Electron Microscopy (SEM)

Observing the small defects on the surface are not possible using an optical microscope. For the features that a high depth of focus is needed, using a regular optical microscope is not the best option. For the steep planes and surfaces that are not smooth and reflective enough, white
light interferometry is limited as well. Therefore, a powerful tool like SEM can give a good insight into the surfaces or small features like the cutting edge of a very sharp diamond tool.

1.4.4 Raman Spectroscopy

The crystal structure of materials such as ceramics and semiconductors undergoes changes depending on the machining conditions. The nature and cause of these changes cannot be evaluated by regular microscopies. Raman spectroscopy is a non-contact, non-destructive technique; among many applications that this method has, it can be used to analyze the structure of processed materials in sub-micron scale. Many researchers used this technique to analyze the material deformation occurring during machining and other processes such as indentation of ceramics and semiconductors [25]–[30]. In the following chapters, this technique will be discussed in more detail.
CHAPTER 2

RESEARCH BACKGROUND

Machining advanced materials such as ceramics, semiconductors, and composites has always been a challenge. Ceramics and semiconductors are hard and brittle, properties that make any material hard to machine, and composites are anisotropic with a non-homogeneous structure reinforced with highly abrasive components [31], [32, p. 1578]. Ceramics and semiconductors are considered nominally hard and brittle, mainly due to their covalent chemical bonding and crystal structure [33]. They are very important materials with many engineering applications such as tribological, biomedical, MEMS, optics and optoelectronics. However, they are among the most challenging to machine in traditional manufacturing processes [32, p. 927], [34]. This challenge is due to their extreme hardness, brittle characteristics and poor machinability [35].

In the mentioned applications, products require a high-quality surface finish and close tolerances to function properly. Machining ceramics and semiconductors without causing any surface and subsurface damage is extremely challenging due to their low fracture toughness. Brittle fracture during the material removal process results in excessively rough surfaces and causes detrimental subsurface damage, which must be removed in subsequent processing steps. These additional processing steps reduce the overall productivity and increase the manufacturing cost associated with machining these nominally brittle materials [34]. Despite all their desirable characteristics, the difficulty during machining and manufacturing them has been a major obstacle that limited their broader application in different industries [35].
For instance, machining mirror-like surface finishes of ceramics and semiconductors contribute significantly to the total cost of a part. In some cases, grinding alone can account for 60-90% of the final product cost [24], [36], [37]. The actual challenge is to produce an ultra-precision surface finish or desired feature sizes (like hole diameter) in these materials at low machining cost by reducing the tool wear and decreasing machining time (increased production rate) [38].

2.1 High Pressure Phase Transformation (HPPT)

Single point diamond turning is one of the primary methods to shape ceramics and semiconductors such as silicon, zinc selenide, sapphire, quartz, etc [39]. As discussed earlier, these materials are very hard and brittle because of their chemical structure. Due to their high brittleness and low fracture toughness, damage such as surface and subsurface occur frequently. It has been known for decades that machining them and achieving proper results is possible by ductile mode machining. Researchers have studied different brittle materials that behave ductile under high pressure. Ductile mode machining, which is one of the main precision machining techniques, has been continuously studied during the last two decades [39]–[48]. The ductile response of ceramics and semiconductors which occurs during mechanical contact and deformation is related to the High Pressure Phase Transformation (HPPT) or possibly direct amorphization of the material [37], [47], [48]. One of the earliest works that discussed the ductile response of brittle materials was published by Bridgman in 1952 [49]. In this work, it was mentioned that under hydrostatic pressures, in most cases brittle materials become relatively ductile [49], [50]. The other initial works by Bifano et al. [51] showed the possibility of machining brittle materials by controlled infeed rates in the range of several nanometers. This early work was focused on grinding different
brittle materials such as germanium, silicon, silicon carbide, etc. The study, including an analytical and experimental investigation, was concentrated on establishing the infeed rates necessary for ductile regime grinding. The correlation between the grinding feed rate and the properties of materials is also discussed in this work and a measure of the brittle transition the depth of cut is introduced. This depth is also called the critical depth of cut and is the amount of infeed that by increasing it, material removal mechanism changes from ductile to brittle.

\[ d_c \propto \left( \frac{E}{H} \right) \left( \frac{K_c}{H} \right)^2, \]  

where \( d_c \) is the critical indentation depth which defines the depth that material fractures during indentation, \( H \) is the hardness, \( E \) is the elastic modulus, and \( K_c \) is the fracture toughness.

The critical depth of cut in the diamond turning process is equivalent with chip thickness. In diamond turning as shown in Figure 1, chip thickness varies along the nose of the cutting tool, starting from theoretically zero at the tip of the cutting tool. If the depth of the cut and feed rate are bigger than a certain amount of critical chip thickness, \( t_c \), then the mode of the cut changes from ductile to brittle, and will be somewhere in the middle of the chip cross section. Damage depth, \( y_c \), should not extend beyond the cut surface plane to avoid a brittle mode cut and a damaged surface left behind [52]. Since cutting passes overlapping each other, to have a surface machined in ductile mode, feed rate, \( f \), should be small enough to remove the brittle fractures from the previous pass by succeeding passes [53]. This feed rate, which is usually small, is a limitation for the machining of the brittle materials as it increases the machining time. Longer machining time increases the length of tool cutting track and leads to higher tool wear. Critical chip thickness for
various materials is different as well as for different directions [54] and even directions of cutting of materials with anisotropic behavior [6].

![Chip cross section along the tool nose](image1)

**Figure 2.1** Chip cross section along the tool nose

In work by Blake and Scattergood [40], the effect of the feed rate in single point diamond turning (SPDT) on surface roughness was studied. They proposed an equation for peak to valley height ($\delta$) based on cross feed rate and tool geometry, Figure 2.2 [34].

$$\delta = \frac{f^2}{8R},$$  

(2.2)  

assuming $f \ll R$ where $f$ is cross feed rate, and $R$ is tool nose radius.

![The effects of the feed rate in SPDT on surface roughness](image2)

**Figure 2.2** The effects of the feed rate in SPDT on surface roughness [40]
In previous research, it has been demonstrated that the ductile regime machining of ceramics and semiconductors is possible due to the high pressure phase transformation (HPPT) occurring in the material caused by the high compressive and shear stresses induced by the single point diamond tool tip [24], [37], [42], [55]–[60]. Plastic deformation of these brittle materials is possible in small sizes in the range of about or less than 100 nm [48], [61].

Gilman [62] showed how for a semiconductor, such as silicon and germanium with cubic diamond structures, at 50% compression along a four-fold axis due to high pressure causes a β-tin or metallic structure. Figure 2.3 shows how cubic diamond and β-tin structure are very similar, but their difference is due to compression. In this work it is stated, “shear gives direct access of the bonding electrons to the antibonding states, so they become delocalized, and can rearrange at electronic frequencies, instead of being limited to atomic vibrational frequencies” [62]. Therefore the metallic state of the material is due to a change in its structure.

Figure 2.3 Cubic diamond structure and tetragonal β-tin structure by compression along the four-fold axis [62]
After a rapid pressure release that usually occurs in machining, an amorphous phase remains on the surface. The high pressure phase only exists when pressure is applied to the material [48].

Single crystal silicon is the main material processed in this dissertation for most of the experiments. Si-I is the most thermodynamically stable phase of silicon at room temperature with the cubic diamond structure at atmospheric pressure [63]. Eleven other phases have been recognized for the silicon at high pressure, and is summarized in table 1. Many of these phases are thermodynamically stable and appear in some level of pressure; others form on decompression, though [64]–[66]. Phase transformation cycles in silicon under loading and unloading are shown in Figure 2.4.

The recrystallization of the silicon after undergoing high pressure while a laser is used is possible, and it is investigated using scratch tests on the silicon in a previous work [67]. Silicon experiences compression and decompression during SPDT, and it is expected that amorphous silicon is left behind.

Figure 2.4 Phase transformations cycle in silicon under loading and unloading [66]
Table 2.1 Crystalline phases of silicon [64], [68]

<table>
<thead>
<tr>
<th>Designation</th>
<th>Structure</th>
<th>Pressure region (GPa)</th>
</tr>
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<tbody>
<tr>
<td>Si-I</td>
<td>diamond cubic</td>
<td>0–12.5</td>
</tr>
<tr>
<td>Si-II</td>
<td>body-centered tetragonal (β-Sn)</td>
<td>8.8–16</td>
</tr>
<tr>
<td>Si-III (or BC8)</td>
<td>body-centered cubic (basis of 8 atoms)</td>
<td>2.1-0</td>
</tr>
<tr>
<td>Si-IV</td>
<td>diamond hexagonal (lonsdaleite)</td>
<td>-</td>
</tr>
<tr>
<td>Si-V</td>
<td>primitive hexagonal</td>
<td>14–35</td>
</tr>
<tr>
<td>Si-VI</td>
<td>unidentified</td>
<td>34–40</td>
</tr>
<tr>
<td>Si-VII</td>
<td>hexagonal close-packed</td>
<td>40–78.3</td>
</tr>
<tr>
<td>Si-VIII</td>
<td>tetragonal (~30 atoms per unit cell)</td>
<td>14.8-0</td>
</tr>
<tr>
<td>Si-IX</td>
<td>tetragonal (12 atoms per unit cell)</td>
<td>12-0</td>
</tr>
<tr>
<td>Si-X</td>
<td>face-centered cubic</td>
<td>78.3→230</td>
</tr>
<tr>
<td>Si-XI (or Imma)</td>
<td>body-centered orthorhombic</td>
<td>13/15</td>
</tr>
<tr>
<td>Si-XII (or R8)</td>
<td>trigonal (8 atoms per unit cell)</td>
<td>12-2.0</td>
</tr>
</tbody>
</table>

2.2 Diamond Cutting Tool

Single crystal diamond, the hardest known natural material on Earth [69], has many desirable characteristics that make it ideal for machining ceramics and semiconductors. The high hardness of the diamond is the first and most crucial factor as ceramics and semiconductors are extremely hard materials. Each carbon atom in diamonds has four neighbors and atoms are in four-fold (sp³) coordination. Therefore, the crystal is supported in all directions [69], [70]. The second characteristic is the ability to make a tool with very sharp, in the nanometer range, edge radius. As discussed earlier, machining in ductile mode occurs in small sizes due to HPPT. Pressure is needed for silicon to undergo HPPT. This pressure is reported in the literature in the range of 10 to 16 GPa [71]. For other materials such as SiC this number is even higher. To achieve such a high pressure, the tool needs to have a very small cutting radius. Otherwise, increasing the cutting force to generate that pressure is not practical nor helpful. The tool’s edge radius provided by the tool...
manufacturer used in this work was as small as 50 nm. The other significant advantage of the
diamond tool is its high transparency to the laser beam. The synthetic diamond tools used in the
experiments, which are more consistent in properties compared to natural diamonds, have
transmission of about 70% at the 1 μm wavelength [72]. The remaining 30% is being reflected and
absorbed in the body of the diamond.

2.3 Laser Augmentation

As discussed in previous sections, ductile mode cut occurs in small sizes. To further
augment the ductile response of these materials, traditional SPDT is coupled with the μ-LAM
technique, which is studied in part A of this dissertation. It has demonstrated the feasibility of
using an IR fiber laser to preferentially heat and soften the high pressure metallic phase of material
during cutting, which is the essence of the μ-LAM system. This method can be adapted to
machining other semiconductor and ceramic materials by choosing a laser with a suitable
wavelength and a sufficient power level for each material and processing condition [34], [73]–
[75].

In this process, the laser beam is transmitted through a diamond (cutting tool) and into the
workpiece. The laser beam intensity is of Gaussian distribution, with the maximum intensity in the
center of the beam. This distribution can be expressed as the following equation based on Figure
2.5.

\[
E(r, z) = E_0 \frac{\omega_0}{\omega(z)} \exp \left[-i[kz - \eta(z)] - r^2 \left(\frac{1}{\omega^2(z)} + \frac{ik}{2R(z)}\right)\right],
\]  
(2.3)
where \( r \) is the radial distance from the axis, \( z \) is the axial distance from the beam's narrowest point. \( E_0 \) is the electric field amplitude on axis \((r = 0)\) and at \( z = 0\), \( \omega_0(z) \) is the distance \( r \) from the optical axis at which the field amplitude is reduced by a factor of \( 1/e \), \( \omega_0 = \omega(0) \), which is called the beam waist because it is defined as the minimum radius of the beam. Also, \( k \) is the wavenumber, where \( k = 2\pi/\lambda \), \( R(z) \) is the radius of curvature of the near-spherical wavefronts, and \( \eta(z) \) is a phase factor found in Gaussian beams.

![Diagram](image)

**Figure 2.5 Parameters in Gaussian beam propagation**

The intensity of distribution is also as follow:

\[
I(r,z) = \frac{2P_0}{\pi \omega^2(z)} \exp \left[ -2 \frac{r^2}{\omega^2(z)} \right],
\]

(2.4)

where \( P_0 \) is the total power in the beam.

Due to the nature of the laser beam, as shown in Figure 2.5, the beam’s smallest radius when focused is called the waist. The shape of it is entirely different of regular lights that can be
focused in one point. The equation for the beam size in function of the distance from the beam waist \((z = 0)\) can be expressed as equation 2.5 [76].

\[
\omega(z) = \omega_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2},
\]

Understanding the behavior of the Gaussian laser beam is beneficial in knowing how to design the cutting tool and its relation to the laser that is going through it. The capability of working material to absorb the energy delivered by the beam in the machining region depends on the wavelength of the laser, since absorptivity in solids is a function of wavelength [34], [77].

### 2.4 Optical Refraction

The diamond tool plays two major roles in the techniques studied in this dissertation, first as the cutting tool and second as an optical component. The laser beam is traveling through the diamond to reach the cutting zone at the tip of the tool. The geometry of the tool can determine the path of the beam inside the diamond. Diamond is a dense material with an index number of 2.41 for visible light. If the incident angle of the beam is 90 degrees, no refraction occurs, while any other angle can cause the beam to refract from the straight line. The refraction phenomenon follows the Snell’s Law as below.

\[
n_1 \sin(\theta_1) = n_2 \sin(\theta_2),
\]

---

1 Some content of this section were presented in a term paper for the ECE-ME 6360 course on spring 2014 with title of “Maximizing laser throughput and decreasing unwanted heating effect(s) by preventing back reflection of a diamond tool in a laser assisted machining process”, other group members were Robert Makin and Ata Ur Rahman Mohammed
where \( n_1 \) is the refractive index of the medium the light is initially traveling through, and \( n_2 \) is the refractive index of the medium that the light is incident upon. \( \theta_1 \) is the angle that the light makes with the outward normal to the incident surface, as shown in Figure 2.6, and \( \theta_2 \) is the angle that the light makes with the inward normal to the incident surface.

\[
\theta_2 = \sin^{-1} \left( \frac{n_1}{n_2} \sin \theta_1 \right) ,
\]  

(2.7)
However, when a beam wants to leave a dense medium like a diamond to a thin medium like air, there would be a limitation. Total internal reflection occurs when light strikes a surface above the critical angle, which is the angle where incident light is refracted at 90° to the normal of the incident surface. Thus, all the light is reflected at the boundary. The critical angle at an interface is given by:

\[ \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right), \quad (2.8) \]

where \(\theta_c\) is the critical angle with respect to the normal of the surface, \(n_1\) is the medium that the light is traveling through and \(n_2\) is the incident surface.

Calculating the critical angle for an interface between diamond and air, Equation 2.8 becomes:

\[ \theta_c = \sin^{-1}\left(\frac{n_{\text{air}}}{n_{\text{diamond}}}\right), \quad (2.9) \]

where the refractive index of diamond is reported to be 2.419 and the refractive index of air is 1.000293.

Using these values and Equation 2.9, the critical angle for a diamond-air interface is found to be 24.43°. In Figure 2.7, \(\Theta'_1\) is the internal incident angle that when it is more than critical angle, it internally reflects with same amount angle respect to normal of the surface. When \(\Theta'_1\) is less than the critical angle, it transmits through with an angle of \(\Theta'_2\) that can easily be calculated by Snell’s law.
Figure 2.7 Transmission and/or internal reflection between two mediums
PART A
CHAPTER 3

SINGLE POINT DIAMOND TURNING OF SINGLE CRYSTAL SILICON (100)

3.1 Introduction

In this chapter, the machining of unpolished single crystal silicon with a crystal orientation of (100) by using Single Point Diamond Turning (SPDT) coupled with the Micro-Laser Assisted Machining (µ-LAM) technique is studied. The main reasons SPDT was chosen as the material removal method is that it offers better accuracy, quicker fabrication time, and lower cost when compared to grinding and polishing methods [78]. The µ-LAM system is ideally suited for demanding applications in the field of precision engineering and precision manufacturing due to its compatibility with SPDT. The focus of this study is on the machining of unpolished single crystal silicon (100) wafer by using this hybrid process and improving the surface finish. Different machining conditions and parameters are investigated, and advantages and disadvantages are discussed. Previous works in the research group on scratching and machining silicon were on polished silicon specimens to proof the concept [67], [79]. In the current study, using the µ-LAM technique to overcome an industrial challenge which is decreasing the process time to achieve a smooth surface of a hard and brittle material is investigated. The polishing stage is one of the most time-consuming steps in silicon wafer manufacturing [80]. Accelerating the surface finish improvement and consequently reducing the processing time is of high interest.

SPDT of silicon can be an extremely abrasive process due to the hardness of this material. Silicon is increasingly being used for industrial applications as it is strong, inert, lightweight, and
has desirable optical and electrical properties. Manufacturing this material without causing surface and subsurface damage is extremely challenging due to its high hardness, brittle characteristics and poor machinability. However, ductile regime machining of silicon is possible due to the high pressure phase transformation (HPPT) occurring in the material caused by the high compressive and shear stresses induced by a single point diamond tool tip [81]. Due to the limitation in chip thickness during SPDT of these types of materials (discussed in research background chapter), achieving a desirable result is extremely difficult, time consuming, and expensive. Enhancing the process in order to decrease the machining time and tool wear and at same time damage to the workpiece can make a significant advancement in machining of hard and brittle materials such as silicon. For this purpose, the μ-LAM technique is used to preferentially heat and thermally soften the workpiece material in contact with the diamond cutting tool. The strategy proposed in this chapter is to bring down the roughness of unpolished silicon wafers to an acceptable level before a final polishing step. Different outputs such as surface roughness (Ra, Rz) and depth of cut (DoC) for different sets of experiments were analyzed.

### 3.1.1 Single Crystal Silicon – Wafer Manufacturing

Single crystal silicon is the most important semiconductor with many applications in the electronic and optic industry with approximately $12 billion in revenue [80]. To manufacture a silicon wafer as one of the wide products made of silicon, different sequential processes such as slicing, grinding, lapping, etching, and polishing are needed as shown in Figure 3.1. The process starts with slicing the ingot by wire sawing as shown in Figure 3.2. The next major steps are grinding and the lapping processes which are the most time consuming and expensive steps in this
process [80]. In some cases, grinding and lapping can account for 60-90% of the final product cost [36]. Decreasing this time and cost can significantly reduce the final product price.

Figure 3.1 Processes for preparation of wafers (a) without and (b) with fine grinding [80]

Figure 3.2 Silicon wafer manufacturing steps a: silicon ingot [82] b: multi-wire sawing [83] c: grinding [80] d: lapping [80]
3.2 Setup Preparation
3.2.1 Micro Laser Assisted Machining (μ-LAM) technique

A schematic of the basic concept of the μ-LAM technique is shown in Figure 3.3. In this process, the laser beam is transmitted through a diamond (cutting tool) and into the cutting zone. The laser beam intensity is of Gaussian distribution, with the maximum intensity in the center of the beam. Since absorptivity in solids is a function of wavelength, the capability of working material to absorb the delivered energy by the beam in the machining region depends on the wavelength of the laser. This hybrid method could potentially increase the critical depth of cut (DoC) which means larger ductile to brittle transition (DBT) depth in ductile regime machining, resulting in a higher MRR.

![Figure 3.3 A schematic cross-section of the μ-LAM process](image)

Throughout this chapter, different strategy to decrease the roughness of unpolished silicon wafers are presented and discussed. At first, machining in one pass with an approach of minimum tool tracking to minimize the tool wear is presented. For the second approach two passes of
machining are compared with only one pass and finally, for the first time, utilizing cutting fluid to decrease the tool wear is practiced, and results are discussed. It needs to be clarified that the results of each approach are discussed independently. The reason is that many parameters are present in a thermo-mechanical machining method like µ-LAM and it is almost impossible to keep the machining condition identical while the tool is replaced and setup is changed. Specimen is also not identical in their as-received surface quality although they are from the same batch.

3.2.2 Laser Alignment

Laser alignment is the most critical step of the setup preparation in both LADD and µ-LAM processes. Since machining occurs in a very small area of the cutting tool, the laser should be precisely aligned on that spot to achieve the desirable results. The actual IR laser beam cannot be used as it is dangerous for the operator and could also burn the alignment camera. In previous research works [79] in the research group, the visible red guide beam was used to align the beam. However, this beam causes overexposure, and it is very difficult to determine if it is aligned in the right spot. Figure 3.4 shows the tool under the portable microscope when the beam is off and on. Previously the diamond tool used to be coated and then by touching the tool and removing the coating from the tip of the tool, alignment of the beam was achieved. Such a procedure is very time consuming and not practical for the industrial use of the technology. ProScope HR2 made by Bodelin Technologies is used as the portable camera to align the laser beam. The wavelength spectrum that this camera can detect is not provided by the manufacturer, but it can perceive and show some level of IR laser. This was figured out after experiments showed that with no filter IR laser could be detected, although overexposure occurs as shown in Figure 3.4. It is discovered that if a proper filter between the camera and the diamond tool is used as shown in Figure 3.5 to filter
out the actual beam, it is possible to use it for aligning as it is much finer than the guide beam. The filter helps to avoid over exposure and a fine beam spot size can be seen.

Figure 3.4 diamond tool under portable microscope (left), over exposure occurring when: guide beam is used for alignment (middle) IR laser with no filter (right)

Figure 3.5 Beam alignment setup while a laser goggle is used to filter the laser (courtesy of Anthony Bootka and Hans Avildsen)
3.2.3 Beam Alignment With Respect To Contact Point

The laser should be aligned precisely on the contact point of the cutting tool and the workpiece. If the tool is straight, the furthest point of the tool touches the surface. A typical test for alignment is to increase the laser power to leave a mark and burn the surface on a scratch test. Figure 3.6 shows such a test, and it is evident that the laser beam is not precisely at the center of the cut which means alignment is not perfect. To avoid this misalignment, the touching point of the tool needs to be recognized. Since the scratch width is around 80±30 µm for a cutting thrust load of 35 g applied to the tool, a misalignment of more than approximately 25% of this width can decrease the efficiency of the process significantly. In experiments to increase productivity, two to three different places of the nose of a tool can be used. To achieve that, the whole system needs to be tilted. Therefore, it is crucial to find the contact point of the cutting tool. A simple method to identify the contact spot is a small touch and performing a scratch on a sample that can leave a stain or chip on the cutting tool as shown in Figure 3.7. The diamond tool lasts for a while before it needs to be replaced and sent for re-lapping.

Figure 3.6 Scratch test on silicon sample with a burn to check the alignment
In industrial applications, most diamond turning machines are equipped with a tool setting camera which is mainly for finding the tip of the tool and center it with respect to the spindle. This gadget can be used for laser alignment, and the scratch test would not be necessary.

For the initial tests, glass type safety goggles were used with the Optical Density (OD) of 3+ for the 980-1070nm wavelength. The glass type was used because the acrylic safety goggles melted due to high temperature. The relationship between the transmission and OD of safety glass is based on the equation 3.1. Calculations show that 99.9% of the laser power is absorbed by the safety goggles. The remaining 0.1% of the beam that can go through the filter is still visible for the camera. Since the middle of the beam has the highest intensity level, only this part of the beam can be caught. The beam has a diameter of approximately 100 µm when it is focused.

\[
\text{OD} = - \log_{10} T, \quad (3.1)
\]
\[ T = 10^{-OD}, \]  
\[ T = 10^{-3} = 0.001, \]  
Transmittance \( T \) = 0.1%

Figure 3.8 Diamond tool with no laser (left) with the guide beam (middle) and with IR beam tuned on (right)

The guide beam can be used for rough alignment, and by using a filter, actual laser beam can safely be turned on as shown in Figure 3.8. Since the actual beam is finer, the alignment would be much easier and more precise. To make sure that the beam is covering the contacting point, it is necessary to bring the beam to this spot in such a way that the cutting edge line is almost in the middle of the beam circle, Figure 3.9. In the case that the incident beam is perpendicular to the back surface of the diamond, as shown in Figure 3.10, the beam delivers from the flank face of the diamond. The other half of the beam will reflect internally due to Snell’s law as the internal beam angle with the inner surface, \( \beta \) angle in Figure 3.10, should be no more than the critical angle of 24.5°, which for rake angle of current tool is 45°. In Snell’s law equation, for the beam to be delivered out, the index number of the first medium, diamond, \( n_1 \) is 2.41 and \( n_2 \) would be 1 if the
tool is in the air. When the diamond is in touch with material, a different scenario can occur as the second medium is different now and its index number is more than 1, and critical angle for total internal reflection is different.

Figure 3.9 Aligned beam on cutting edge

Figure 3.10 Schematic of diamond tool and incident laser beam
3.3 Scratch Tests

Scratch test on samples is one of the first steps for performing the μ-LAM process on a material, especially crystalline type. By this method, the behavior of the material under an increasing load can be determined. It is usually used for quantifying the DBT depth in which mode of cut starts to change from ductile to brittle. A typical scratch test is shown in Figure 3.11. At small depths that correspond to small loads the mode of cut is ductile, and by increasing the load it starts to change, and small fractures appear. By the further increase of load, and consequently depths, the cut would be full of fractures. In Figure 3.11 black areas are the fractures. For better understanding the transition of a cut from ductile to brittle mode constant load cuts performed for a range of different loads and depicted in Figure 3.12. The nature of cut for 100 mN load (10 g) is purely ductile and for 200 mN (20 g) cut is in ductile to brittle transition. As it is evident for higher loads brittle mode cut is dominant. The width of the cuts also increases by applying higher loads due to deeper cuts. The diamond tool has a round nose, and higher loads cause deeper trenches in the material however, since it is exceeding the DBT depth, the regime of the cut changes from ductile to brittle.

![Figure 3.11 Typical load-increasing scratch test on the crystalline material](image)

Figure 3.11 Typical load-increasing scratch test on the crystalline material

33
Scratch tests were used in previous works to proof the concept µ-LAM and also measuring the DBT for several materials in different laser conditions. Scratch tests here utilized to examine the laser alignment and to evaluate the setup before performing the actual machining. It is important to mention that cutting speed for scratch tests were as small as 1 µm/sec and therefore results can be different for machining that usually occurs in high speeds. Yet the trend of the results should follow the scratch results which means by increasing laser power to an optimum level the quality of the cuts improves.

The cutting load was programmed to increase from 50 mN (~ 5 g) to 450 mN (~ 45 g) linearly shown in Figure 3.13. For each cutting condition, two tests were conducted in the purpose of increasing the reliability of the results. For the scratch with no laser, at the beginning the cutting tool seems is slipped before engaging. In literature, this part of the cut is referred to as elastic regime as is shown in the schematic of Figure 3.14 [84]. When the tool starts to cut, the mode is ductile, and after that, the mode of cut gradually changes and fractures occur. By using laser and increasing the power, less black areas as shown in Figure 3.10, which represent brittle mode cut, appeared. With 30 W laser power almost half of the cut is in ductile mode and for the 40 W all the cut is in ductile mode. Although using laser softening increased the DBT depth and cuts were
improved gradually, as shown in Figure 3.13, too much laser power can cause more damage. Figure 3.15 shows a 100 mN scratch with 50 W laser power. The excessive laser power burned the surface.

Figure 3.13 Scratch test with an increasing load of 50-450 mN for different laser power condition, first try (left), second try (right)
3.4 Machining in One Pass

3.4.1 Experimental Design

The main objectives of this section are to improve the surface quality and increase the MRR by using SPDT coupled to μ-LAM technique in one pass. A typical SPDT setup on the UMT for this purpose is shown in Figure 3.16. The UMT is reconfigured with some modifications to
perform SPDT operations. This equipment can be a load-controlled or position-controlled, depending on the testing procedure. For the experimental tests discussed in this section load-controlled mode is used, where the required thrust force (load) is applied for each test to achieve the desired DoC.

A diamond tool with 1 mm nose radius cutting tool \((-45^\circ \text{ rake and } 5^\circ \text{ clearance})\), is used for this set of experiments. The laser is a medium power, infra-red (IR), continuous wave (CW), diode laser \((\lambda = 1064 \text{ nm and } P_{\text{max}} = 100 \text{ W})\) with a Gaussian beam profile. The laser beam is guided through a single mode fiber optic cable to a collimator, which is attached to a Beam Delivery Optics (BDO) unit. The BDO then focuses the beam and delivers it through the transparent diamond tool to the cutting edge (Figure 3.16). Experiments were carried out on the unpolished side of a 2" diameter single crystal silicon wafer.

![Image](image.jpg)

**Figure 3.16 \(\mu\)-LAM – SPDT setup mounted on UMT to machine a 2" silicon wafer**
Many parameters can affect the process, however, the most crucial machining parameters used in this study, such as rotational speed (rev/min), load (mN), laser power (W) and cross feed rate (μm/rev), are summarized in Table 3.1. All tests were performed on one wafer sample in different regions, Figure 3.17, to be able to compare the results. As is clear from Table 3.1, after each test on one region, for the next region only one factor has been changed to avoid any hidden effect (changing more than one factor for each test) during interpretation of results. This study is concentrated on the effects of load and cross feed rate on the SPDT of silicon coupled with a laser beam. Rotational speed is maintained at 6 rpm because - based on preliminary tests - this is the most stable speed for machining of the sample. Machining with lower rotational speed is very time consuming.

As previously mentioned, the UMT in load-controlled mode is used. Maintaining the adjusted load with higher speed causes instability with high load deviation during the process. Laser power was adjusted on the laser equipment and was not the actual output. Actual output power is about 30% of adjusted power because of power loss which is due to scattering, reflection (side and back), and absorption by the diamond.

<table>
<thead>
<tr>
<th>Regions</th>
<th>RPM* (rev/min)</th>
<th>Load (mN)</th>
<th>Power (W)</th>
<th>Feed** (μm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>300±50</td>
<td>35±2</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>900±150</td>
<td>35±2</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>300±50</td>
<td>35±2</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>900±140</td>
<td>35±2</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>1500±250</td>
<td>35±2</td>
<td>30</td>
</tr>
</tbody>
</table>

*,** Uncertainty of RPM and feed rate are negligible
Figure 3.17 Machining regions on the silicon wafer specimen

The critical uncut chip thickness in this machining case is a function of cross feed rate, DoC and the ductile response of the material. For the roughing passes (as performed in these tests), a more aggressive approach can be taken. However, it will be needed to get the submicron level for the finishing passes. Also, the effect of the process has been proven to reduce brittleness and increase ductility in the material. Therefore, cross feed rate based on initial tests has been chosen: 30 μm/rev for the more aggressive passes.

3.4.2 Result and Discussion

The surface roughness, in term of Ra, of the unpolished side of the silicon wafer, was about 1.2 μm. Figure 3.18 shows a three-dimensional (3D) image of the as-received surface of the sample. The surface roughness and depth of cut for each region were measured after machining of all five regions. These outcomes were measured by using the Wyko white light interferometric
microscope. The surface roughness (in terms of Ra and Rz) and DoC for different regions after machining are shown in Figures 3.19, 3.20 and 3.21 respectively.

Surface roughness improved from 1.2 μm (as-received) down to approximately 1 μm in one machining pass in the first region. Rz or peak-to-valley value, decreased from 15 μm to 13.9
μm, which means only the top of the peaks have been machined. DoC in this region was 1.275 μm which is very close to Rz reduction.

![Figure 3.20 Surface roughness (Ra) corresponding to each region](image)

Figure 3.20 Surface roughness (Ra) corresponding to each region

The surface of the first machined region of the sample is smoother than before (Figure 3.22), mainly because of removal of the peaks during machining. There are still many valleys which the tool could not reach. For more clarification, Figure 3.23 illustrates an exaggerated schematic of machining of peaks during a low load material removal of an unpolished surface of silicon wafer. The thrust load (300 mN for this region) is distributed along the cutting edge and the tool cannot penetrate the material anymore.
To get a deeper cut, thus achieving a better surface finish, the second region load was increased to 900 mN. Results show that by increasing the load the surface roughness was decreased significantly from 1 μm to 0.274 μm. Achieving such a surface finish from 1.2 μm of an
unmachined surface to 0.274 μm in just one pass is a very promising result for this process. The microscopic image of the surface in Figure 3.24a shows that the surface finish improved significantly. Dark areas in this image represent the remained valleys of the surface. Feed marks on the surface are a sign of ductile mode machining. In brittle material like silicon, when the fracture occurs surface and features left behind are haphazard. The distance between two parallel feed marks shows the cross feed rate. It is more convenient to understand surface improvement by comparing Figure 3.24b and 3.18.

![Figure 3.23 Schematic of machining of peaks during a low load process](image)

The third region which was machined by 300 mN load and 10 μm/rev cross feed rate has Ra of 0.53 μm and depth of cut of 0.73 μm. Feed rate decreased in this region to see its effects on surface roughness. Effect of cross feed rate on surface roughness in SPDT has been discussed in research background in the previous chapter.
On the other hand, to avoid any brittle mode machining there is a limitation to increase the cross feed rate. It is mainly because in higher cross feed rate the chip thickness increases, which causes brittle mode machining [40]. Machining results did not show any significant surface finish improvement by decreasing cross feed rate, which is mainly because it is dominated by remained valleys on the machined surface. Decreasing the cross feed rate will influence the surface finish when almost all of those valleys have been removed, and the surface is almost smooth. By putting
the cross feed rate used for this region in equation 1, \( \delta \) for this region will be 0.125 \( \mu m \). This amount of roughness caused by feed marks is very low to affect the Rz and Ra of this region. In other word, feed marks should be higher than other imperfections on the surface to have significant effect on surface roughness. Therefore, at least for the first pass of machining of an unpolished Si wafer with such machining parameters and conditions, Ra would not change significantly. 3D image of region 3 (Figure 3.25) also is showing a major improvement in surface finish.

Region 4 is machined by increasing the load to 900 mN and without cross feed rate change from region 3 (10 \( \mu m/rev \)). Results show DoC increased compared with region 3, but it did not reach to region 2 depth. However, DoC was 1.9 \( \mu m \), and Ra was 0.53 \( \mu m \), which after region 2, are the highest DoC and lowest Ra. It was expected that because of 900 mN load, DoC in region 4 be at least the same as region 2, but it is almost less than half of that region. The main reason to not reach that DoC is tool wear which made the tool nose blunt.

![3D image of region 3](image)

**Figure 3.25 3D image of region 3**

Even though as long as a tool’s cutting edge is sharp it can be used for machining, a blunted tool (no nose) cannot penetrate into the material while it is mounted on a load controlled machine.
It is mainly because equipment maintains the load constant, and the load will distribute along a line on the blunted tool nose instead of a small region in a sharp tool. A distributed load means lower pressure which would not allow the tool to go deep enough into the workpiece material.

As can be seen from the Figure 3.26, it is obvious that the surface is not as smooth as region 2, but it is smoother than region 1 and 3. In a higher magnification microscopic image from Figure 3.27, it can be seen clearly that the surface roughness still is dominated by valleys (not feed marks). Therefore, it was soon to decrease the cross feed rate to get a better surface finish.

**Figure 3.26 3D image of region 4**

For region 5, the load was increased to 1500 mN, DoC is about 1.4 μm, slightly higher than region 1, and Ra is 0.95 μm. In this region, it was expected that with the higher load, the depth of cut would be more than region 2, and the surface finish would be better than other regions. But as mentioned earlier, a blunted tool cannot give the same results as a sharp tool. The resultant surface obtained after machining is depicted in Figure 3.28. It seems the tool rubbed the surface instead of machining it.
Figure 3.27 High magnification microscopic image of region 4

Since the surface roughness of the regions is dominated by the peaks and valleys, it will be very convenient to compare the surfaces by their Skewness. Surface Skewness ($R_{sk}$) is a measure of the average of the first derivative of the surface. A negative value of $R_{sk}$ indicates that the surface is made up of valleys, whereas a surface with a positive $R_{sk}$ is said to contain mainly peaks and asperities [85]. Table 3.2 presents the $R_{sk}$ of each region, as it expected the region 2 has the highest negative amount that shows is dominated mostly by valleys (not peaks). However other regions, as well as unmachined region, have the negative $R_{sk}$. After region 2, region 4 has the second highest amount and regions 3, 1 and 5 have the next values respectively. $R_{sk}$ of region 5 is same as the unmachined region which indicates that no noticeable machining happened on region 5.
Table 3.2 Surface skewness (Rsk) of different regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Unmachined</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rsk</td>
<td>-1.4</td>
<td>-1.58</td>
<td>-3.32</td>
<td>-1.79</td>
<td>-2.37</td>
<td>-1.4</td>
</tr>
</tbody>
</table>

3.4.3 Tool Wear Analysis

Figure 3.29 shows the images of the tool nose before and after machining of all regions. Tool wear can be observed easily by comparing the tool conditions before and after machining in Figure 3.29a and 3.29b respectively. It is clear that the cutting edge on the tool nose after machining is sharp enough, but it is flat (no nose). This means that when the tool touches the workpiece, the contact zone is along a 200 μm line. Also, since the wear is extended on the tool’s flank face for about 75 μm, the contact spot would be an area that has shown in Figure 3.16 as “tool wear”. Therefore this tool should be re-lapped to be used again to machine the material properly.
The tool is a synthetic diamond (CVD), and the transmission of this type of diamond at the 1 \( \mu \text{m} \) wavelength is about 70\% \cite{86}. The remaining 30\% is being reflected and absorbed (with the majority being reflected). Only a small portion of the laser energy is being absorbed by the diamond. With the CVD diamond having excellent thermal conductivity and diffusivity \cite{72}, \cite{87}, it has not observed any thermal softening effect of the diamond to date.

Depth of the cuts for region 2 and 3 compare with an unmachined region depicted in Figure 3.30. Feed marks in region 2 can be seen clearly in this figure. An unmachined region between region 2 and 3 is a good reference to compare the output surfaces.
3.5 Machining With Two Passes and Effect of Laser on Tool Wear

3.5.1 Machining parameters

In the previous section, improving the surface finish by using only one pass was experimentally studied. All tests were with laser, and no comparison with no laser case was made. The focus of this section is the machining of an unpolished single crystal silicon (100) wafer, using the µ-LAM process to improve the surface finish (as much as possible) in two passes. In this series of tests, a comparison was made between machining with SPDT (No laser) and when it is coupled with µ-LAM, with the same setup. To study the effect of using the µ-LAM technique on decreasing tool wear, two identical tools were used. One of these tools for the test with laser and a second one for without.

Machining parameters used in this study, such as rotational speed (rev/min), load (mN), laser power (W) and cross feed rate (μm/rev) for different regions are summarized in Table 3.3. As it is presented in Table 3.3, there are two main regions, and in each region, half of it was machined with a second pass. The first part of each region, for example region 1, is presented as 1-1 and the second part which is machined with two passes is presented as 1-2. Figure 3.31
schematically shows the cross section of a machined workpiece. Machining conditions were chosen based on initial tests that showed the best surface finish could be obtained when selecting such values for these parameters. To study the effect of the laser, two identical samples were used, one sample with no laser and the other sample with 35W adjusted laser power. Rotational speed is maintained at 6 rpm because - based on preliminary tests - this is the most stable speed for machining of the sample for UMT in load control mode. In load control mode, UMT tries to hold the load constant by moving the tool up and down, and in high RPM it can damage the tool or sample.

Table 3.3 Machining parameters

<table>
<thead>
<tr>
<th>Regions</th>
<th>Pass</th>
<th>Load (mN)</th>
<th>Power (W)</th>
<th>RPM* (rev/min)</th>
<th>Feed** (μm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>1</td>
<td>900±50</td>
<td>35±2</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>1-2</td>
<td>2</td>
<td>900±50</td>
<td>35±2</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>2-1</td>
<td>1</td>
<td>1500±150</td>
<td>35±2</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>2-2</td>
<td>2</td>
<td>900±50</td>
<td>35±2</td>
<td>6</td>
<td>30</td>
</tr>
</tbody>
</table>

*,** Uncertainty of Rpm and Feed rate are negligible

Figure 3.31 Exaggerated cross section of the machined workpiece
3.5.2 Results and Discussion

The Ra of the unpolished side of the silicon wafer used in this series of tests was about 0.85 μm. The surface roughness and DoC for each region measured after machining of all regions. The DoC and surface roughness (in terms of Ra and Rz) for different regions compared with no laser machining are shown in Figure 3.32, 3.33 and 3.34 respectively. Figure 3.33, for example, shows for no laser case Ra is not improved in second passes (1-2 and 2-2) compared to first passes (1-1 and 2-1). Even for the 2nd region, second pass (2-2) is slightly worse which is mainly because of the tool wear. In fact by starting the tool wear, the ability of the tool to penetrate the material and remove the peaks and valleys decreases. Therefore, no surface finish improvement was achieved.

![Graph showing DoC corresponding to each region with the laser and no laser](image)

**Figure 3.32** DoC corresponding to each region with the laser and no laser

At first glance it is obvious that using laser increased the DoCs and decreased the surface roughness significantly. For instance, DoC for region 1-1 increased 100% (doubled) and Ra and Rz decreased 45% and 70% respectively by using laser compared to the same region machined with no laser. Other regions also show the same trend which indicates the significant improvements
achieved by using a laser. Therefore, from now all discussions will be about machining with the laser which is the primary objective of the μ-LAM process.

Figure 3.33 Ra corresponding to each region with the laser and no laser

Figure 3.34 Rz corresponding to each region with the laser and no laser
Surface finish was improved from 0.85 μm (as-received) down to approximately 0.23 μm in one machining pass in the first region (1-1) machined with the laser. Achieving such a surface finish improvement from 0.85 μm of an unmachined surface to 0.23 μm in just one pass on a lab scale setup is a very promising result for this process. The Rz or peak-to-valley value of the same region decreased from 13.4 μm to 2.23 μm. The surface of the first machined region of the sample is much smoother than before (Figure 3.35a). This is mainly due to the removal of the peaks during machining. However, there are still many valleys which the tool could not reach. The thrust load (900 mN for the 1-1 region) was distributed along the cutting edge, and the tool could not penetrate material anymore. The DoC of this region was 2.95 μm.

To get a deeper cut to achieve a better surface finish, another pass with the same condition was carried out on region 1 (1-2). Results show that the surface roughness was decreased from 0.23 μm to 0.178 μm. Surface finish improvement for this region (1-2) was not as much as the first region (1-1). This is mainly because the unmachined surface was full of peaks, and it was possible to get a deep cut in the first pass. But after that, the surface was almost flat and harder for the tool to penetrate the material (more load and rigidity needed). A microscopic image of the surface in Figure 3.35b (region 1-2) shows that the surface finish was improved slightly in comparison to the region 1-1. The dark areas in this image represent the remaining valleys of the surface. Feed marks on the surface are a sign of ductile mode machining because in a brittle material like silicon only the metallic phase is ductile and can be plastically deformed without fracture. Three-dimensional (3D) images of the machined surfaces of different regions of the sample are illustrated in Figure 3.36. It is more convenient to understand the surface finish improvement of the regions 1-1 and 1-2 by comparing Figure 3.36a, 3.36b and 3.18.
In the second region, first pass (2-1), was machined by increasing the load to 1500 mN without changing any other parameters. Ra of 0.322 μm and depth of cut of 1.8 μm (from unmachined surface) was obtained. This region was machined with an even higher load than the first region, and a higher DoC was expected, but it was almost half of that region. The main reason that depth was not reached was tool wear, which made the tool nose blunt and will be discussed in “Tool Wear” section. As is mentioned in the experimental design section, cross feed was constant during all tests. The main reason for that was based on the initial results and the following discussion.

Figure 3.35 High magnification microscopic image of machined regions, a)1-1 b)1-2 c)2-1 d)2-2
3.5.3 Feed Rate Effect

To avoid any brittle mode machining, there is a limitation for increasing the cross feed rate. This is mainly because increasing the cross feed rate will increase the chip thickness which will cause brittle mode machining [40]. Initial machining results did not show any major surface finish improvement by decreasing cross feed rate, mainly because it was dominated by remaining valleys on the machined surface. Decreasing the cross feed rate can influence the surface finish when the surface is almost smooth, or the depth of cut is considerably high. By putting the cross feed rate used for this study (30 μm/rev) in Eq. 1, δ will be 0.112 μm. This amount of roughness caused by feed marks is not sufficiently high to affect the Rz and Ra. In other words, feed marks should be higher than other imperfections on the surface to have a major effect on surface roughness (in this case they were not).
Region 2-2 was machined with lower load (900 mN) to have a better surface finish. Results show the total DoC increased, but it did not reach the depth of region 1-2 or even 1-1 depth. The DoC for this region was 2.3 μm, and Ra was 0.257 μm. As long as a tool’s cutting edge is sharp it can be used for machining. A blunted tool (with a worn cutting edge) cannot penetrate material as deep while it is mounted on a load controlled machine. It is mainly because equipment maintains the load constant, and the load will be distributed along the blunted cutting edge of the tool. Therefore, lower pressure will be generated, which would not allow the tool to go deep enough into the workpiece. As seen from Figure 3.35d, it is evident that surface (2-2) is not as smooth as the region 1-2 (Figure 3.35b). From the microscopic images, it can be interpreted that the surface roughness is still dominated by valleys (not feed marks). Decreasing the cross feed rate would not improve the surface finish significantly. However, to make sure a ductile mode cutting is happening, the cross feed rate must be less than a critical value. After that brittle mode cutting will be dominant. A 3D image of regions 1-2 and 2-1 compared to an unmachined region is shown in Figure 3.37. An unmachined region is a good reference to compare the machined surfaces.

![3D image of machined regions of 1-2 and 2-1 compared to the unmachined region](image-url)

**Figure 3.37** 3D image of machined regions of 1-2 and 2-1 compared to the unmachined region
3.5.4 Tool Wear

Tool wear can be observed and analyzed by comparing the tool conditions before and after machining with and without the laser in Figure 3.38a, b and c. The machining track length that caused the tool wear for each case, with and with no laser, was 27.28 m. The cutting edge on the tool nose after machining with no laser is worn and extended to the rake face about 7 μm in Figure 3.38b. The contact zone is along a 150 μm line when the tool touches the workpiece. On the other hand, the identical tool used for machining with laser shows slight tool wear on the flank face and cutting edge is still sharp. As is shown in Figure 3.38c contact zone for this tool is along a 175 μm line, and no noticeable wear is on the rake face. More extended contact zone compared to the tool used for no laser condition is due to a deeper cut that occurred.

Figure 3.38 Microscopic image of tool nose a) before and b) after machining with no laser c) after machining with laser
Although no severe wear happened to the tool used with the laser, it seems its radius is slightly different from a new tool which means the tool’s nose is worn. That is why DoCs of regions 2-1 and 2-2 were lower than what was expected. The tool is a synthetic diamond (CVD), and the transmission of this type of diamond at the 1μm wavelength is about 70% [72]. The remaining 30% is being reflected and absorbed (with the majority being reflected). Only a small portion of the laser energy is being absorbed by the diamond. With the CVD diamond having excellent thermal conductivity and diffusivity [87], no thermal softening has been observed on the diamond.

3.6 Effect of Cutting Fluid

Previous tests on machining unpolished silicon were very promising, however, samples were dry machined, and tool wear was still considerable. This section focuses on improvement of surface finish and tool life by using cutting fluid in implementing the μ-LAM technology on a SPDT setup for machining unpolished silicon wafers.

3.6.1 Experimental Approach

As in previous sections, the UMT was used as the main platform and coupled to the μ-LAM system to perform all of the machining tests. The same laser unit, IR CW fiber laser, was used in this investigation. A single point diamond tool with a 1mm nose radius, - 45 degree rake angle and 5 degree clearance angle, was used for this cutting operation. Figure 3.39 shows the machining setup used for experiments. DI water and odorless mineral spirits (OMS), two common types of cutting fluid, were used for machining silicon wafers. Since laser was using, to avoide any
fire during the process, a nonflammable mineral spirits was used. A cutting fluid reservoir is added to the spindle and sample was submerged in the cutting fluid.

![Figure 3.39 Machining setup for the 2” silicon wafer equipped with a cutting fluid reservoir](image)

Different parameters such as using cutting fluid, laser power and cross feed rate, as Table 3.4, on process outputs like surface roughness (Ra) were investigated. These parameters were chosen based on previous results. To understand the effect of using laser and cutting fluid during the process, silicon samples were machined with/without laser with those two cutting fluids. It should be noted that in this series of tests, laser power output after going through diamond tool was approximately 40 % of adjusted power. This means that, for adjusted laser power of 20 W, the actual output was approximately 8 W. All tests were performed at constant spindle rotational speed of 100 RPM. All other conditions were kept constant to have the same conditions for all tests.
Table 3.4 Parameters used for machining

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power (W)</td>
<td>0, 20</td>
</tr>
<tr>
<td>Cutting fluid</td>
<td>Di water, Odorless Mineral Spirits</td>
</tr>
<tr>
<td>Cross feed(µm/rev)</td>
<td>30, 10, 2</td>
</tr>
</tbody>
</table>

Figure 3.40 shows a microscopic image of the unpolished surface of a silicon wafer used for this investigation, its three-dimensional image captured by using a white light interferometer. This work aims to reduce silicon wafer roughness as much as possible with the least number of machining passes with the lowest time of machining.

Figure 3.40 a) Microscopic and b) 3D image of the unpolished region of an unpolished/unmachined silicon sample
3.6.2 Results and Discussion

The surface roughness was measured and the tool wear observed with an optical microscope. Figure 3.41 shows microscopic images of the machined surface of the silicon without using a laser with 30, 10 and 2 µm/rev cross feed rates. OMS was used as cutting fluid for these tests. Dark areas in this figure represent either remaining valleys of the surface or brittle mode machining that should be removed in the final machining process. White areas represent ductile mode machined areas. By lowering the feed rate, better surface with less brittle mode cut was achieved. However, damage on such surfaces is extensive due to dominant brittle fracture which occurred during the process. Figures 3.42 and 3.43 show the machined regions with a laser using OMS and DI water as cutting fluids respectively. It is evident that surface qualities are much better than when no laser is used. Regions machined with 30, and 10 µm/rev cross feed still have dark areas, however, they are much smaller than no laser condition. Surfaces machined with 2 µm/rev cross feed are much smoother and the sample machined with DI water is almost in pure ductile mode (Figure 3.43c).

![Figure 3.41 Microscopic image of the machined surface of a Si wafer with no laser and mineral spirits as cutting fluid with a)30 b)10 c)2 µm/rev cross feed rate.](image-url)
The results from the analyses presented in Figure 3.44 suggest that the surfaces roughness for all regions with laser and cutting fluid are better than that of no laser power (room temperature). It was discovered previously that higher depth of cuts can be achieved by using a laser which
directly translates to increased material removal rates and higher productivity [88], [89]. The cutting forces for the machined regions with laser are lower suggesting extended tool life for large-scale production.

The surface roughness of samples machined with different cutting fluids is presented in a graph in Figure 3.45. Even though in rough pass (30 µm/rev), Ra of silicon sample machined with OMS is lower than that of with DI water, for low feed rate (2 µm/rev) it is vice versa. Ra for 10 µm/rev for both conditions is almost the same. In optimal condition, the surface roughness can be improved from 1.2 µm (as-received) down to approximately 83 nm. Achieving such a surface finish from an unpolished surface is a very promising result for the process.

Figure 3.44 Surface roughness (Ra) corresponding to sample machined with DI water with and without laser

![Graph showing surface roughness (Ra) for different cutting conditions](image.png)
Figure 3.45 Surface roughness (Ra) corresponding to different cutting fluids and feed rates

Figure 3.46 shows a 3D image of silicon sample machined with no laser with OMS as cutting fluid. This is the same surface as Figure 3.42c, which shows those black areas were pits. As mentioned before, these pits can be either the remained valleys of original surface or because of brittle fractures.

Figure 3.46 3D image of the unmachined region (right) and machined region with 2 μm/rev cross feed rate with no laser (left)

In Figure 3.47 an unmachined area is compared to a surface machined with 30 μm/rev cross feed rate with laser next to it. Even though cross feed rate for this region is much higher than the
region machined with 2 μm/rev in Figure 3.46, the surface is smoother. It is mainly due to using a laser which allows a higher chip thickness and therefore an adjusted higher feed rate. Comparing Figure 3.46 and 47 shows how thermal softening can improve surface quality. Figure 3.48 represents a surface machined with the same condition as the surface in Figure 3.46 (2 μm/rev cross feed rate) but with the aid of a laser. Figure 3.48 is the 3D image of the surface of Figure 3.43c. Almost no sign of brittle mode or transition can be seen in this image, and it is a pure ductile mode machining.

**Figure 3.47** 3D image of the machined region with 30 μm/rev cross feed rate with a laser (left) next to an unmachined region (right)

**Figure 3.48** 3D image of the machined region with 2 μm/rev cross feed rate with laser (left) next to an unmachined region (right)
3.6.3 Raman Spectroscopy

To analyze phase transformation, the Raman microscopy is used for the machined samples. The μ-Raman with the aid of a 514 nm beam of the sample machined with no laser, and 2 μm/rev feed rate and 100 RPM in Figure 3.49 is showing a graph that represents amorphous silicon (a-Si), and a sharp peak at 520 cm⁻¹ which represents the Si-I. The broadband peaks on this graph are the indications of the amorphous phase of the material. Detecting the amorphous phase is a good sign of the ductile mode machining. The sample machined with the aid of 20 W laser with same machining parameters, exhibits a single line at 520 cm⁻¹ in Figure 3.50 with no sign of a-Si. This can be interpreted as material experiencing a recovery due to laser heating and material recrystallization. Phase transformation benefits the machining silicon to avoid brittle fracture. On the other hand, it changes the mechanical, optical and electrical properties of the material by leaving a residual amorphous layer [90]. Recrystallization during the μ-LAM causes the material to maintain its important original properties.

![Raman spectroscopy of silicon sample machined with no laser](image)

Figure 3.49 Raman spectroscopy of silicon sample machined with no laser
3.6.4 Tool Wear Analysis

Tool edge radius plays a very important role in ductile mode machining of the brittle materials. The edge radius increases due to tool wear which even if the tool still be able to cut the material, it results in large stress field below the tool and a thick subsurface damage layer [90]. Maintaining the geometry of the tool by reducing the tool wear allows to machine continuously for a longer time and produce larger parts. Tool wear after machining all silicon samples (Figure 3.51) and track length of about 7 km was very minimal (compared to previous sections). Combination of laser to soften the material and cutting fluid to lubricate the cutting zone improved the tool life significantly. Results show that using cutting fluid, in this study DI water and OMS, not only improves the surface finish but also decreases the tool wear. The cutting tool is worn on the flank face and the cutting edge is sharp which means it can exert high pressure needed for phase transformation during the material removal.
3.7 Effect of Green Laser Wavelength

In this section, the effect of using different laser wavelengths on the μ-LAM process is studied. In previous studies, discussed in earlier sections of the current chapter and prior works, in the Manufacturing Research Center, different IR laser units have been used to perform the experiments on different materials [73], [74], [79], [91]. A search for a more efficient laser is essential to improve and optimize the process. As discussed in the research background chapter, brittle materials can be machined in ductile mode. Laser heating can enhance the ductility and reduce the brittleness of these materials. The amount of laser energy absorption during the machining process affects the thermal softening of the material. Ceramics and semiconductors in general have different absorptions to various laser wavelengths. Finding the most suitable laser wavelength based on the material’s optical properties can optimize the process and increase productivity. Also, the cost of laser equipment increases exponentially as the power increases. Thus, it is vital to choose the most appropriate wavelength based on the absorption of the material.
to maximize the thermal softening effect. If sufficient thermal softening of the workpiece can be successfully achieved, then a low power low-cost laser can be utilized to achieve higher MRR and significantly reduce the production cost.

Additionally, there is always laser energy loss at the tool during machining. Most of this energy causes the temperature of the tool and fixtures to rise which has negative effects and can even result in damage while using high power lasers. A lower power laser is always a better option to avoid these kinds of side effects. The results of current research will be very useful for ductile mode machining of silicon. These outcomes help to understand the effects (MRR, forces, productivity, etc.) of using a laser wavelength that is highly absorptive by the workpiece material.

![Reflectivity spectra (Rd) of silicon in diamond, β-tin, primitive hexagonal, and hcp phase at 4.5, 13.2, 30, and 44 GPa, respectively](image)

**Figure 3.52** Reflectivity spectra (Rd) of silicon in diamond, β-tin, primitive hexagonal, and hcp phase at 4.5, 13.2, 30, and 44 GPa, respectively [92]

### 3.7.1 Silicon Absorption Wavelength

Silicon has the minimum reflectance (highest absorption) at a wavelength of approximately 590 nm in the atmospheric phase of silicon (Si-I) [92]. Due to the high compressive and shear
stresses induced by the tool tip, HPPT occurs and metallic phase of silicon (Si-II) forms during machining which has very high absorption (lower but close to Si-I). This means that a laser with a close enough wavelength has the most efficiency and least energy loss. With the use of a 532 nm wavelength laser, termed “green laser”, the reflectivity (Rd) of silicon increases slightly from 0.41 to 0.43 (Figure 3.52).

3.7.2 Experimental Setup

In previous works, the IR (infrared) laser has been studied and clearly showed that coupling the diamond tool and laser improves the machining process outputs such as MRR and surface finish and even increases the tool life [73], [74], [79], [91]. This study is focused on the first investigation of integrating a green laser in the μ-LAM process and its effect on thermal softening of single crystal silicon during the material removal process. For this purpose, three sets of tests were carried out: with the green laser (532 nm wavelength), with IR laser (1480 nm wavelength) and without any laser radiation. The test results are analyzed and compared. The scratch tests were carried out to examine the effect of thermal softening of the high pressure phases via laser heating formed under the diamond tip. The effects are studied based on the measured depth of cut, cutting forces, and machining regime (ductile or brittle). Cutting forces were measured in-situ using a dual axis load cell and the regime of machining for each scratch was analyzed using a high magnification optical microscope. The microscope images were used primarily to identify the cut surface conditions and detect any possible scratches or chips. The μ-LAM system is coupled to the modified Universal Micro-Tribometer (UMT) to perform all of the scratch tests (refer to Figure 3.53). The UMT is a device where the required thrust force is applied for each test to achieve a desired depth of cut. The load-controlled mode of the machine is preferred in this case to study the
thermal softening effect. The cutting speed is set constant at 1 μm/sec for all scratches in order to heighten the thermal softening of silicon during the material removal process. Based on preliminary studies, in order to get ductile mode cut and show a transition from ductile to brittle mode, scratch tests at loads ranging from 10 mN to 70 mN are ideal. A 5 μm tip stylus, which is coupled to a 10 μm fiber to have a maximum density of laser energy, thus maximizing the thermal softening effect, was used. The maximum laser power achievable from the laser unit was 50 mW after going through the diamond styli. As shown in Figure 3.53 a considerable amount of laser was scattered.

![Figure 3.53 μ-LAM scratch test setup mounted on UMT](image)

In the setup, the beam is guided through a 10 μm fiber optic cable to the ferrule, which is coupled to the diamond stylus (refer to Figure 3.54). The laser beam passes through an optically transparent diamond tip (tool) and heats the workpiece material in the cutting zone.
Monitoring the cutting forces during the cutting process is an effective method to detect any occurrence of brittle mode machining. Brittle mode machining can generally be observed in the cutting force data by its unstable behavior, which is represented in higher peaks and valleys in the force plot. Another usage of these data is to know how much laser softening decreased cutting forces to achieve similar depths of cuts as that without laser heating. This is crucial as lower forces suggest longer tool life for large-scale production.

3.7.3 Results and Discussion
3.7.3.1 Green Laser Results
The results of two series of tests, such as nature of scratches (brittle or ductile) and visual amount of chips, which gives an idea of the amount of MRR, were analyzed by using a high magnification optical microscope. From the images in Figure 3.55, it is clear that more chips can
be observed on the sides of the scratches done with a laser. However, depth of cuts needs to be measured to evaluate the effect of green laser on the cuts.

![Image of scratches with and without laser, labeled a, b, c, and d.]

**Figure 3.55** Scratches with 10 mN (a & b) and 40 mN (c & d) thrust forces

Depths of cuts were measured using a Wyko white light interferometer. Figure 3.56 shows the cross-section of the scratches with and without laser for 10 mN thrust forces. Two identical cuts, with and without laser, were performed next to each other to be able to compare them visually.

The results in Figure 3.57 show that with the same amount of applied thrust force, the scratch performed with laser heating yielded a greater depth of cuts in ductile mode. Scratch nature for thrust forces more than 40 mN were changed to brittle mode. Ductile to brittle transition (DBT) and small cracks were observed at 40 mN. This condition caused the results of more than 30 mN to be different from 10 mN to 30 mN loads, and measured depth was not reliable. Therefore, only the depth of cuts of the range of 10 mN to 30 mN are presented.
Monitoring the cutting forces during the cutting process is an effective method to detect any occurrence of brittle mode machining. Brittle mode machining can generally be observed in the cutting force data by its unstable behavior which is represented in higher peaks and valleys in the force plot. Another usage of this data is to know how much laser softening decreased cutting
forces to achieve similar depths of cuts as that without laser heating. This is crucial as lower forces suggest longer tool life for large-scale production. Figure 3.58 shows how laser heating decreased the cutting force (Fx), even though it is a slight decrease, and fewer peaks due to micro cracks are observed when the laser is on. This means that less fracture or micro cracks occurred when the laser softening was occurring. It should be mentioned that thrust force (Fz) is maintained constant during the test.

![Graph showing cutting force (Fx) for 40mn thrust force, laser off and on](image)

**Figure 3.58 Cutting force (Fx) for 40mn thrust force, laser off and on**

### 3.7.3.2 IR Laser Results

Results of using IR laser, 1480 nm, with the same setup and same styli are depicted in Figure 3.59. It should be noted that the laser power used for this experiments was at the same level as the green laser, 50 mW, to be able to compare the results. Using higher laser powers (approximately 400 mW) with a same laser wavelength in previous works [74] has shown deeper cuts in scratching SiC. For current experiments, no significant effect of the laser can be seen in scratching silicon. Comparing the results for green laser and IR laser shows that cuts with a green laser were deeper though, Figure 3.60. Since the same level of laser power was used for both set
of tests, the only plausible explanation for this difference can be their laser absorption. It can be interpreted that single crystal silicon under cutting pressure absorbs the 532 nm wavelength more than 1480 nm wavelength.

**Figure 3.59 Depth of the cuts; with IR laser and without laser heating**

**Figure 3.60 Depth of the cuts; Comparing Green Vs. IR laser heating**
3.8 Summary and Conclusion

Combination of laser softening and SPDT on the machining of the single crystal silicon wafer, unpolished side, was successful in reducing the surface roughness. The Ra was brought down from 1 μm to 0.274 μm in only one pass and 850 nm to 178 nm in two passes. These results are very promising results for machining of silicon, based upon this initial experimental work. Tool wear by using laser decreased considerably, however, it should be minimized to have a more efficient process. It was shown that for the first pass the most important parameter was thrust load and for those machining conditions feed mark did not have a major effect on the surface roughness.

To further improvement of final surface roughness and decreasing the tool wear, for the first time cutting fluid was used. Results of this study showed that the technique with the aid of cutting fluid was successful in improving the surface finish of unpolished silicon wafers and less tool wear. Best surface roughness, Ra = 83 nm, obtained with laser and DI water as cutting fluid, while Ra for sample machined with no laser with cutting fluid was 376 nm. The effect of a combination of laser and cutting fluid on surface roughness is obvious and promising.

Green laser, 532 nm wavelength, was used for the first time for the µ-LAM process. To be able to compare the results an IR laser, 1480 nm wavelength, with the same level of laser power was used to scratch single crystal silicon (100) wafer. Results clearly show that by applying 50 mW laser power deeper cuts achieved when a green laser was utilized compared to IR laser. Cuts with the aid of IR laser power were not showing any significant change in depth of cuts. It can be understood that single crystal silicon, while is under pressure, absorbs the 532 nm wavelength more than 1480 nm wavelength. Therefore, using the green laser for machining silicon gives a better laser absorption, and less adjusted laser power can be used.
4.1 Introduction

Single crystal silicon (100) or semiconductor grade of silicon was the only types of silicon that was studied in previous works. Chemically they are the same material, but in the optics industry single crystal silicon (111), the optical grade of silicon, is in more demand. More complicated geometries such as concave and convex and even free-form surfaces for optical applications are made from this grade of silicon. In the silicon crystal, the top surface of silicon (111) oriented in the (111) plane. To understand the crystallographic planes and directions Miller indices are used. Three-integer of h, k, and l that simply are shown with (hkl) format, are widely used for this purpose. The reciprocals of the coordinates of the intercepts on the XYZ axes when is multiplied by the lowest common denominator, are used for the h, k and l values [93], see Figure 4.1. To show a plane (hkl) format is used, for direction [hkl], for a family of direction <hkl> and a family of planes {hkl}.

Silicon is an orientation-dependent material, which means in different orientations its shows different properties. As an example of the anisotropy in the mechanical properties of silicon and to have a viewpoint the Elastic modules anisotropy of the silicon and a cross section of it are shown in Figure 4.2. The value of the elastic modulus for different direction ranges from 130 to 170 GPa, respectively. Crystal orientation effect has been under study by other researchers [94]
and is not the focus of this study. However, it needs to be mentioned that the anisotropic behavior of the silicon is important while different planes are under study.

Figure 4.1 Miller indices in a cubic crystal; major planes for silicon [93]

Figure 4.2 Orientation dependence of Elastic modules (a), Variation of the elastic modulus around the (001) crystal plane of silicon (b) [95]
The only reliable process available for machining these shapes is SPDT, while for flat samples such as wafers, grinding and lapping are also widely used. It seems the μ-LAM process is more suited for the more challenging machining such as free from surfaces. The focus of this chapter is on the machining of the silicon (111). In the path to making the μ-LAM process more suitable for industrial usage, this series of tests was performed on an actual diamond turning machine. Previous feasibility tests have successfully demonstrated the use of IR fiber laser and green laser [79], [88] to preferentially heat and soften the high pressure metallic phase of silicon during scratching, which is the essence of the μ-LAM system. In the present chapter, the effect of μ-LAM on the surface roughness and material removal rate of single crystal silicon (111) has been studied.

4.2 Experimental Procedure

Single crystal optical grade silicon (111) supplied by Lattice Materials with a diameter of 28.1 mm was selected to the machine in this experimental study. The melting point of the material was 1412 °C. A 1 mm nose radius single crystal diamond cutting tool was used for this set of experiments. Same laser unit as the last study, previous chapter, which is an IR CW diode laser (λ= 1070 nm and P_{max}= 100 W) with a Gaussian beam profile is used. The laser beam is guided through a single mode fiber optic cable to a collimator, which is attached to a Beam Delivery Optics (BDO) unit. The BDO then converges the beam and delivers it through the diamond cutting tool.

The μ-LAM process does not have limitations that other processes and techniques utilizing thermally softening by preheating the material or shining the laser in front of the tool have. For those processes and specifically the Laser Assisted Machining (LAM), use of cutting fluid
interrupts the laser beam path and cools down the workpiece, however in µ-LAM, the laser is shining through the diamond tool and only softens a region of the material in contact with the tool. The schematic in Figure 4.3 shows the difference between LAM and µ-LAM. A combination of mechanical machining and laser softening while using the cutting fluid is one of the unique advantages of the µ-LAM process.

![LAM vs µ-LAM schematic](image)

**Figure 4.3 Difference between LAM and µ-LAM processes**

The µ-LAM system was mounted on a Moore Nanotech 350FG diamond turning machine as shown in Figure 4.4 for the experiments. A tool post compatible with the BDO was attached to the diamond turning machine to perform the laser-assisted machining experiments. Odorless mineral spirits (OMS) was used as the primary cutting fluid. As discussed in the previous chapter, cutting fluid minimizes the tool wear and assists with flushing the machined chips away. The experimental setup used for machining silicon sample is shown in Figure 4.4. There are many parameters to evaluate including machining parameters (speed, feed, depth, cutting fluid), optical parameters (laser power, wavelength, and beam size), cutting tool type (single crystal, polycrystals, nanocrystalline amorphous), etc. Machining parameters used in this test are summarized in Table 4.1.
Figure 4.4 Moore Nanotech 350FG diamond turning machine (left) Micro-LAM setup mounted on a diamond turning machine (right), (Courtesy of Micro-LAM Technologies, INC.)

Table 4.1 Machining parameters

<table>
<thead>
<tr>
<th>Machining Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle rotational speed</td>
<td>2000 RPM</td>
</tr>
<tr>
<td>Laser power*</td>
<td>0, 20W, 30W</td>
</tr>
<tr>
<td>Roughing feed rate</td>
<td>4 µm/rev</td>
</tr>
<tr>
<td>Roughing depth of cut</td>
<td>10 µm</td>
</tr>
<tr>
<td>Finishing feed rate</td>
<td>1 µm/rev</td>
</tr>
<tr>
<td>Finishing depth of cut</td>
<td>5 µm</td>
</tr>
</tbody>
</table>

* Actual output at the tool tip is about 40% due to scattering, reflection, etc.

4.3 Results and Experimental Data

Ductile mode machining was carried out on the unpolished side of the single crystal silicon (111) with a starting surface roughness of ~770 nm (Ra). The surface roughness of each region was measured after machining using a white light interferometric profilometer. The machined surfaces are also observed by an optical microscope to find any signs of brittle mode or imperfection. Achieving a high-quality surface finish is very challenging, and therefore machining
parameters should be selected carefully. Adding the laser as a new parameter increases the level of complexity in the optimization process.

A roughing pass is carried out to flatten the sample, primarily to avoid an interrupted cut for the finishing pass. The roughing pass was carried out with and without the laser to study the effects on improving surface roughness. The cuts were programmed at a 10 µm depth of cut, along with a 4 µm/rev cross feed. The roughing pass without the laser had a surface roughness of 80 nm Ra compared to a 16 nm Ra with optimal laser power (see Figure 4.5). At the 4 µm/rev feed rate, there is a possibility for ‘pull-outs’ in the sample, but due to the laser heating effect, pull outs have been significantly reduced resulting in better surface quality. Laser heating decreases the brittleness of the material and avoids brittle fracture of material in the machining region. An optical microscopic image of the unmachined silicon surface at 400x is shown in Figure 4.6a. Figure 4.6b also shows the surface machined conventionally with no laser. Although ductile mode machining with minimal surface damages was attempted, many imperfections can be observed due to partially brittle mode machining and pit/voids caused by the cutting process.
The laser power selection for the finishing pass is more critical than roughing pass because of its lower feed rate that could cause undesired thermal effects such as overheating. In this situation, since consecutive passes are very close to each other - and the beam diameter is much larger than the feed rate - the accumulated heat exceeds the optimal amount. Overheating in low range will cause the material to flow to the side of the tool nose and build up. Higher range (higher power) can cause other effects such as thermal cracks and even burning which would result in a rougher surface. Figure 4.7 shows the effect of excessive laser heating on the machined surface finish with a 160% increase in surface roughness compared to the optimum laser power (20W). It should be noted that no burn caused this increase in the roughness. The resulted surface finish with a laser power of 20 W, cross feed of 1 μm/rev and 5 μm depth of cut, was less than 10 nm Ra as shown in Figure 4.7 and actual surface in Figure 4.6c.

The tool rake angle plays another significant role in achieving good surface finishes. A high negative rake tool will exert higher compressive forces that are necessary for machining hard ceramics such as silicon to achieve HPPT. Ceramics, in general, can withstand high compressive forces but very little tensile forces due to their low fracture toughness. Selecting the appropriate rake angle is necessary to achieve the best surface finishes. A very high negative rake angle, on
the other hand, could result in rubbing of the surface which will result in low MRR, high tool wear, and even a poor surface finish.

Ductile machining of the brittle materials is a very complicated process. Many parameters can affect the ductile response of a material. Rake angle has a major effect on the critical depth of cut. To generate compressive stress, which is very vital in machining of brittle materials to avoid brittle fracture, tool rake angle needs to be negative as shown in Figure 4.8. In work by Patten and Jacob [96], effect of rake angles on cutting forces in machining single-crystal silicon carbide is investigated. Two different rake angles, 0° and -45°, were applied and cutting forces in -45° rake angle were higher than zero angle. Both the experimental and simulation results showed the almost the same trend. In other work by Patten et al. [48] the same trend of results in machining of silicon carbide is reported. The disadvantage of positive or even less-negative rake angle is that not enough compressive pressure to achieve maximum depth of cut can be achieved. The advantage is that cutting forces are less, resulting in less tool wear and requires less rigid machining setup. Blake
and Scattergood [40] investigated the effect of the rake angle on the critical depth of cut in Germanium and Silicon. Their results suggest more negative rake angle (-30° vs. 0°) increases the critical depth of cut significantly.

Figure 4.8 Cross section of the cutting tool used in SPDT, - \( \alpha \) is the rake angle, and \( \beta \) is clearance angle

Figure 4.9 Effect of rake angle on surface finish

In this part of the study, the effect of the tool rake angle on the surface roughness in the \( \mu \)-LAM process for the first time investigated. The results presented in Figure 4.9 obtained from a 2
µm depth of cut and a 1 µm/rev feed show that a -25° tool yields a better surface finish with Ra of 3.2 nm. One of the reasons that lower rake angle results in a better surface finish is the better chips flushing that can be achieved by using -25° rake angle tool.

One of the most common problems in machining single crystal silicon is the crystallographic orientation effect. In this situation, single point diamond turned silicon shows radial spokes of damages. One of the early papers that studied this problem was by Blackley and Scattergood [97] in which they explained it for (111) slip planes. The key point is to keep the depth of cut lower than the critical depth, which by exceeding it, material removal will be in brittle mode [98]. This phenomenon is observed in a test with no laser with a 4 µm/rev cross feed and 10 µm depth of cut as Figure 4.10. By using the laser it is possible to get rid of those radial spokes. Figure 4.11 shows three samples, an unmachined sample, machined with no laser, and a sample machined with optimum laser power. The sample machined with no laser has radial spokes while the one that machined with the laser has a mirror-like surface finish with no sign of surface damages.

Figure 4.10 Crystallographic orientation effect in machining single crystal silicon
4.5 Conclusion

A combination of laser heating and SPDT for machining of optical grade single crystal silicon (111) was successful in reducing the surface roughness significantly. The Ra was brought down from 770 nm to 3.2 nm. Radial spokes that occur during the machining of single crystal silicon due to crystallographic orientation effect can be “healed” and eliminated. It has been shown that using the optimum laser power is very crucial in this process and should be selected carefully so as not to overheat the sample. The effect of rake angle on the surface finish was also studied. For the cutting tool in diamond turning coupled with the μ-LAM process for optical grade silicon (111) a rake angle of -25 degree, rather than a -45 degree, resulted in a better surface finish.
CHAPTER 5

EFFECT OF THERMAL SOFTENING ON ANISOTROPY AND DUCTILE MODE CUTTING OF SAPPHIRE

5.1 Introduction

Monocrystal sapphire has many applications in optics and electronic industries such as blue LED, infrared detectors, substrates for semiconductors and superconductors, as it has high strength, good electric insulation and low dielectric loss [99], [100]. It is a very inert material to the majority of wet chemicals and dry etching and has many limitations for laser ablation due to the thermal effects of laser processing [101]. Different methods such as grinding [102], superfinishing [103], laser machining [104], plasma [105], etc. are the techniques for processing the sapphire, although mechanical finishing methods can cause surface and subsurface damages to the sapphire [106].

Sapphire is extremely hard and in the Mohs scale, in which diamond hardness is 10, sapphire hardness is 9. There is high demand for a method to efficiently machine it with no surface and subsurface damage, without the drawbacks of the current techniques. Sapphire shows a high anisotropic behavior, therefore, the effect of its crystal orientation on the machining is also another challenge for this material [107]–[109]. Machining sapphire in ductile mode has been reported by a few researchers. Liang et al. [99] investigated brittle to ductile transition during an ultrasonic assisted grinding process by performing scratch tests on the sapphire. They validated that this technique can be used for machining of sapphire in ductile mode. In another study by Smith et al.
[110] stress change during the grinding of sapphire optics was measured by the aid of the Twyman effect. They found out that the maximum stress is occurring during the brittle to ductile transition.

Tool wear is still an obstacle in the turning process, and researchers are trying to decrease or at least model the tool wear to be able to predict it [111], [112]. Although for brittle materials grinding and polishing are very common methods to achieve smooth surfaces [113], enhancing the machinability of these materials is still under study by researchers [114].

One of the main reasons, besides the importance of the material, for studying the effect of thermal softening on machining of the sapphire was the fact that it is reported that Young module of sapphire is decreasing in elevated temperatures [115], [116]. Therefore, it is expected that using a thermally assisted technique can help to enhance the machining of sapphire. In current experimental research, μ-LAM is utilized to carry out the scratch tests on a sapphire C-plane wafer in different directions. Scratches with different loads and laser powers are performed in [1̅1̅0̅2̅0], [1̅1̅0̅0̅], [1̅1̅2̅0̅] and [1̅1̅0̅0̅] directions of a C-plane monocrystal sapphire. The depth, as well as the nature of cuts, ductile or brittle, for each test, are examined and compared. The monocrystal sapphire sample used in this study was a C-plane polished wafer with a flat, which is representing the A-plane. Figure 5.1 shows the schematic of the sample and the directions in which scratch tests were performed. Table 5.1 presents the properties of the monocrystal sapphire sample used in this study.

5.2 Experimental Procedure

In order to perform the scratch tests, as shown in Figure 5.2, the μ-LAM setup was mounted on a tribometer which can be programmed for cutting speeds as low as 1 μm/sec. The utilized laser was a 1070 nm wavelength CW fiber laser with a power range of 10 to 100 W. A diamond with a
nose radius of 1 mm and negative rake angle of $-45^\circ$ and the relief angle of $5^\circ$ was used as a cutting tool. The negative rake angle provides compressive stress during the process which is necessary to avoid any fracture in the machining of brittle materials. The laser beam is then directed through the diamond to the tip of the tool and the cutting zone.

![Diagram of [1100], [1120], [11120], and A-plane (1120)](image)

**Figure 5.1 Monocrystal sapphire C-plane wafer and test directions**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Formula</td>
<td>$\text{Al}_2\text{O}_3$</td>
</tr>
<tr>
<td>Structure</td>
<td>hexagonal-rhombohedral</td>
</tr>
<tr>
<td>Hardness</td>
<td>2200 Knoop perpendicular to C-axis</td>
</tr>
<tr>
<td>Young Modulus (GPa)</td>
<td>345-386 ($30^\circ$-$75^\circ$ to C-axis)</td>
</tr>
<tr>
<td>Fracture Toughness (MPa$^{0.5}$)</td>
<td>$\sim4[110]$</td>
</tr>
<tr>
<td>Melting Point ($^\circ$C)</td>
<td>2040</td>
</tr>
<tr>
<td>Transmission</td>
<td>$&gt;85%$ for 1070 nm wavelength [110]</td>
</tr>
</tbody>
</table>

* Marketech Intl, Inc.
Experimental parameters such as length, the speed of cuts, loads, and laser powers and also their values are listed in Table 5.2. The actual laser output after going through the diamond was less than what was adjusted due to scattering, reflection, and absorption. For each laser power level, the actual output was measured and presented in Table 5.2. As the actual laser output and adjusted laser power were not showing the same gradients, the output power is addressed in this article. Two series of tests were performed in this study, first with the constant loads and second with the increasing load to find the depth that the ductile to brittle transition (DBT) occurs. In the first series, the thrust load was constant for each test and each laser power level, three different loads, 100, 200 and 300 milliNewtons (mN) were used. In the second series the increasing load of 50 to 500 mN (except for [1̅100] direction to 700 mN) were utilized. A white light interferometer was used to measure the depth of cuts, and the average of measurements is reported for each cut. Figure 5.3 shows the technique used to measure the depth of cuts. Any instability that usually took
place at the beginning and the end of the cut was excluded. Two modes of load and position control are available for the tribometer, and in this work, load control mode was used to carry out the tests.

Table 5.2 Experimental parameters and their value

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Length</td>
<td>100 μm</td>
</tr>
<tr>
<td>Speed of Cutting</td>
<td>1 μm/s</td>
</tr>
<tr>
<td>Adjusted/Actual Laser Output Power</td>
<td>0/0, 10/1.6, 20/6.75, 30/11.8, 40/16.8 Watt (W)</td>
</tr>
<tr>
<td>Cutting Directions</td>
<td>[1̅1̅2̅0], [1̅1̅0̅0], [1̅1̅2̅0], [̅1̅1̅0̅0]</td>
</tr>
<tr>
<td>Constant Thrust Forces</td>
<td>100, 200, 300 mN</td>
</tr>
<tr>
<td>Increasing Thrust Force</td>
<td>50 - 700 mN</td>
</tr>
</tbody>
</table>

Figure 5.3 Technique used to measure the depth of cut
5.3 Results and Discussion

5.3.1 Constant Loads

5.3.1.1 [1120] Direction

The first series of scratch tests were carried out in the [1120] direction of the sapphire sample. At first, three different thrust loads, 100, 200, and 300 mN, with no aid of laser were performed. Then the same cuts with 1.6, 6.75, 11.8, and 16.8 W laser powers were performed in the same direction. As Figure 5.4 shows for 200 mN and 300 mN, depth is significantly increased with 16.8 W, however, this is mainly due to fracture, or in other words, brittle mode cut.

![Figure 5.4 Depth of cut of [1120] direction](image)

Figure 5.4 Depth of cut of [1120] direction

Figure 5.5 shows the cutting nature, ductile or brittle mode, of the 200 mN scratches with 11.8 and 16.8 W laser powers after cleaning the sample. A 3D profile of each cut, which helps to visualize it, shows the depth of ductile cut and the pits caused by the fracture. Even though the
laser can enhance the ductility of the material, very high laser power can cause more fracture probably due to thermal stresses (Figure. 5.5b). That is the main reason that laser power is needed to be optimized for each machining condition and material. Based on previous works [67], [117], it is expected that the temperature at the cutting zone to be in the range of 300-1000 °C. The ability of the material to reach to this temperature depends on the laser power and materials absorption. As expected by increasing the thrust load, depth of cut also increases. Although depth increases slightly by applying 1.6 W laser power, by increasing the power to 6.75 W and then to 11.8 W, a deeper cut was not achieved. The significant increase was observed for 16.8 W laser power, which is mainly due to fracture enhancement because of the thermal stresses induced by the laser.

Figure 5.5 Microscopic image and 3D profile of cutting nature of [111 20] direction with 200 mN a: 11.8 W, b: 16.8 W
5.3.1.2 [1100] Direction

For the second direction, [1100], increasing laser power decreased the brittleness of the material and therefore decreased the depth of cuts. Comparing the depth achieved in this direction in Figure 5.6 to [1120] direction as shown in Figure 5.4, indicates that for the no laser case, depth of cut is almost doubled. The other noticeable difference between the results of [1100] direction is that by increasing the load, a deeper cut was achieved while for [1120] direction, increasing the load did not change the depth significantly, except when 16.8 W laser power was used, and the cut was in the brittle mode.

Ductile and plastically deformed chips in Figure 5.7 are good evidence of a ductile mode cut occurring in this direction. Although both cuts in Figure 5.7 look ductile, a close look at the cut with 11.8 W in Figure 5.7a indicates that in some points microscopic pits and fractures caused the depth to be higher than the cut with 16.8 W. Further evidence for this is the shape of the chips, which for the pure ductile cut, Figure 5.7b, are continuous while for Figure 5.7a, they are broken.
in half, (see Figure 5.7a). However, further investigation is needed to validate this claim. The lines perpendicular to cutting direction are tool nose marks on the surface as the tribometer in load control mode is trying to keep the programmed load constant during the process.

![Image of cutting nature with laser power and load conditions](image)

Figure 5.7 Cutting nature of [1̅1̅00] direction with 300 mN and laser power of a: 11.8 W b: 16.8 W

5.3.1.3 [11̅20] Direction

The depth of cuts of the direction [11̅20] for 100 and 200 mN loads, show a decreasing trend by increasing the laser power, as depicted in Figure 5.8, (except for the 200 mN and 6.75 W condition). On the other hand, for 300 mN thrust load, first depth of the cut decreased from no laser to 1.6 W and then increased for 6.75 W and beyond. With 1.6 W laser power, the nature of cut changed from brittle - or partially brittle - to ductile, and by increasing laser power, thermal stresses changed it back to brittle mode cut.

98
Figure 5.8 Depth of cut of [1120] direction

The 3D profile of the cut illustrated in Figure 5.9 clearly shows this transition. The cut is brittle for no laser, shown in Figure 5.9a, and a smooth cut was not achieved. However, by using 1.6 W laser, a ductile mode cut was obtained, as shown in Figure 5.9b. As mentioned previously, the beginning and end of a cut are usually unstable, which is why the end of the scratch is not smooth. Using the 6.75 W laser power caused a fracture, as seen in Figure 5.9c, and even though it is deeper than no laser case, it is not a smooth cut and is full of pits and voids. Figure 5.10 shows an example of the effect of the thrust load on the nature of cut for the same level of laser power. By increasing the thrust force from 200 to 300 mN, even when the 11.8 W laser was used, the cutting regime changed from ductile to brittle.
Figure 5.9 3D profile of 300 mN load cut a: No laser b: 1.6 W c: 6.75 W laser powers, [11\bar{2}0] direction

Figure 5.10 Cutting nature of [11\bar{2}0] direction with 11.8 W laser power and a: 200 mN b: 300 mN load
5.3.1.4 [$\bar{1}100]$ Direction

The deepest cuts were achieved in the last direction, [$\bar{1}100$], as shown in Figure 5.11, while laser power has no considerable effect on the results. Increasing the thrust loads from 100, to 200, and then 300 mN significantly changed the results, which is a sign of fracture that occurred due to higher thrust loads. Ductile mode cut in brittle materials occurs when the chip thickness is less than a critical size. By increasing the load and exceeding this critical thickness, the mode of the cut changes from ductile to brittle. Figure 5.12 shows the brittle mode cut of the scratch for the tests with 300 mN by using 1.6 and 6.75 W laser powers. However, it seems less fracture occurred using the higher laser power (6.75W), which is due to the decrease of brittleness and therefore less tendency of brittle mode cut of the material in elevated temperature.

![Figure 5.11 Depth of cut for [$\bar{1}100$] direction](image)
Figure 5.12 Cutting nature of [1100] direction with 300 mN a: 1.6 W b: 6.75 W with fractured chips

5.3.1.5 Anisotropy Effect

Comparing the depth of cuts for different directions in one graph can help to understand the anisotropy behavior of the monocrystal sapphire during the machining. In Figure 5.13 the results achieved for different directions with no aid of lasers are illustrated. The shallowest cuts were achieved for the [111020] direction and the deepest were achieved for the [11100] direction, although the nature of cuts in the latter case was brittle. [11100] and [1120] directions behave almost the same for 100 and 200 mN, and for 300 mN, a 32% deeper cut was achieved for the [1120] direction. For other laser power levels such as 1.6, 6.75, and 11.8 W, although the different depth of cuts was achieved, they showed the same trend as the cuts made with no laser case. For the highest laser power used in this study, 16.8 W, the results were different. As depicted in Figure
5.14, for the $\{11\bar{2}0\}$ and $\{1\bar{1}00\}$ directions with the 200 and 300 mN, as well as for 300 mN for $[11\bar{2}0]$ direction, the deepest cuts were achieved in the brittle mode cut. A pure ductile cut was achieved in the $[1\bar{1}00]$ direction and for 100 and 200 mN thrust loads for $[11\bar{2}0]$ direction.

![Figure 5.13 Depth of cuts for no laser for different directions](image1)

![Figure 5.14 Depth of cuts for 16.8 W for different directions](image2)
5.3.2 Increasing Load
5.3.2.1 Ductile Mode Machining

To achieve a smooth surface, machining of brittle materials should be in ductile mode. In diamond turning as shown in Figure 5.15a, chip thickness varies along the nose of the cutting tool, starting from theoretically zero at the tool tip. If the depth of the cut and feed rate are bigger than a certain amount, critical chip thickness, $t_c$, in which the mode of the cut changes from ductile to brittle, will be somewhere in the middle of the chip cross section. Damage depth, $y_c$, should not extend beyond the cut surface plane in order to avoid a brittle mode cut and a damaged surface left behind [52]. Since cutting passes overlap each other, to achieve a surface machined in ductile mode, feed rate, $f$, should be small enough to remove the brittle fractures from the previous pass by succeeding passes [53]. This feed rate, which is usually small, is a limitation for the machining of the brittle materials as it increases the machining time. Longer machining time increases the length of tool cutting track and leads to higher tool wear. Critical chip thickness for various materials is different as well as for different directions of materials with anisotropy effect. By enhancing the ductile response of material and pushing the boundaries, higher critical chip thickness can be achieved, and therefore higher feed rate can be used as shown in Figure 5.15b schematically.

Sapphire is known to generate dislocations and exhibit microscopic plastic deformation at elevated temperatures, 400-700 °C and 1.5 GPa pressure [118], which emphasizes the "very low dislocation density". Compared to the present work, where macroscopic plastic deformation (chips and surface) occurs under much higher contract pressures, >15 GPa, with higher temperatures. The underlying resultant plastic deformation mechanisms are presumable different, but no unifying
explanation currently exists to explain the latter macroscopic results (the authors suggest a high pressure phase transformation may be the origin but have no personal confirming evidence).

Figure 5.15 Diamond turning of brittle materials a: Cross section of the chip during the process, b: Laser heating is enhancing the ductile response

5.3.2.2 Ductile To Brittle Transition Tests

The ductile response of different brittle materials with various properties is not the same. Their response to laser heating is also different as they have diverse optical properties. In section 1, the achieved depths were reported, no matter of the nature of the cuts, ductile or brittle. It would be more beneficial to see the effect of the laser on increasing or decreasing the ductility of the material. The DBT tests with different laser power levels were performed in different directions. For this purpose, based on the initial tests, the load increased from 50 to 500 mN (for [1̅100] direction 50 to 700 mN was used) and different laser powers similar to the last section tests were used. Experiments were repeated to increase the reliability of the results. Using an interferometer and cross-section of the cuts, the deepest point right before the cutting mode transition from ductile to brittle (or the last point of the ductile region) of each cut was measured as shown in Figure 5.16.
5.3.2.3 [11̅20] Direction

For direction [11̅20] as depicted in Figure 5.17, the test with no laser resulted in a 103 nm DBT depth. Using the 1.6 W laser power barely increased the depth by 2%, and for the laser powers of 6.75 and 11.8 W, the depth increased by 17.5% and 24.3% (compared to the no laser depth), respectively. The laser power of 16.8 W resulted in a decrease of DBT depth by 25% which means the excessive laser power caused fracture, possibly due to thermal stresses. These results are compatible with the results of the constant load test and Figure 5.4.

Figure 5.16 a: DBT depth measurement of cross section of a cut b: 3D profile of a DBT test
5.3.2.4 [1100] Direction

Preliminary tests in the direction [1100] showed that the cut is not reaching to DBT if increasing load range of 50 to 500 mN is used and the entire cut would be in ductile mode. Therefore, since DBT should be achieved to be able to measure the depth associated with it, load
range of 50 to 700 mN was used. The laser increased the DBT depth for this direction significantly. While the DBT depth for the cut with no laser was 63 nm, using a 1.6 W laser power increased it to 83 nm (~ +32%). Increasing the laser power caused a linear depth increase as is shown in Figure 5.18. This linear DBT depth increasing behavior is similar to the ductility enhancement in Figure 5.6 for this direction. Unlike the [11̅20] direction, no premature fracture occurred when 16.8 W laser power was used in the [11̅00] direction.

5.3.2.5 [11̅20] Direction

For the direction [11̅20], DBT depth of 79 nm with no laser obtained and 1.6 W laser power increased depth by ~ 23% as shown in Figure 5.19. The depth increased by 76% and 128% (compared to no laser depth) by using 6.75 and 11.8 W laser powers, respectively. The same behavior of the first direction, [11̅10], was observed for this direction, [11̅20], and DBT depth dropped for the 16.8 W case, although a depth slightly bigger than the no laser cut was achieved.

![Figure 5.19 DBT depth of cut of [11̅20] direction](image)
5.3.2.6 [1100] Direction

For the last direction, [1100], as illustrated in Figure 5.20, DBT depth of 93 nm for the non-laser cut was achieved. Using 1.6 W laser power increased the DBT depth by 44% that is the highest depth increase for this laser power level among all directions. The DBT depth increase for 6.75 and 11.8 W laser power was almost similar, +102% and +103%. Similar to [1120] and [11120] directions, using 16.8 W laser power is not following the same trend as the lower laser powers, and a drop occurred, however, DBT depth is still higher than the no laser case for this direction too.

![Figure 5.20 DBT depth of cut of [1100] direction](image)

5.3.3 Conclusion

In this research, the anisotropy effect and ductile mode cutting of the monocrystal C-plane sapphire by using the μ-LAM technique were studied. Results showed that for [1120] direction using and increasing laser power slightly increased the depth of cut. However, excessive laser
power may cause more fracture (probably due to thermal stresses), which is usually an unwanted result where a smooth surface is a goal (the opposite may be true if a high material removal rate is desired). The DBT tests for this direction showed that the laser heating increased the ductile depth, compared to no laser case, about 24%. For [1̅100] direction, the laser was obviously increasing the ductility and quality of the resultant surfaces, and ductile chips were achieved. The DBT depth increased 144% by using 16.8 W laser power for this direction. Increasing the thrust load in [11̅20] direction can cause a brittle mode cut, however, for low thrust loads increasing the laser power enhanced the ductility of the cut. Using 11.8 W laser power increased the DBT depth by 128%. Even though the deepest cuts were achieved in the [1̅100] direction in constant load experiments, analyzing the images showed that it was mainly due to a fracture that occurred during the cutting operation. Also, it was observed that increasing both laser and thrust load caused more fracture. For a pure ductile cut, the laser power of 11.8 W increased the DBT depth by 103% for the [1̅100] direction. No noticeable tool wear was observed under a microscope (400X) as the total tool cutting track was minimal. The underlying resultant plastic deformation mechanisms reported in the literature on microscopic scale and this work in macroscopic scale are presumably different, but more investigation is needed to verify it.
PART B
CHAPTER 6

LASER AUGMENTED DIAMOND DRILLING: RESEARCH BACKGROUND

6.1 Introduction

Drilling is an established technology, but with many limitations. The current techniques and processes vary widely depending upon the material being drilled, precision and accuracy required, size (diameter, depth, etc.). Current applications require better quality materials that are mechanically harder, yet manufactured with high-level precision and accuracy. Materials with better mechanical properties which are usually hard, brittle, and difficult to cut such as ceramics, semiconductors, and composites have a variety of applications in various industries. Due to their superior properties, it is very challenging to drill holes free of fractures, damages, and cracks and micro-cracks. Achieving good entrance edges and high-quality surface finishes is difficult due to low fracture toughness, hardness and high strength of the mentioned materials. Their extreme hardness causes rapid tool wear that not only decreases the drilling efficiency but also increases the downtime of the process. Cutting tool replacement and new tool setting takes time that lower the productivity. Therefore, the cost of drilling these types of materials is usually high, and processes available for this purpose are expensive.
6.2 Drilling Methods

There are many drilling techniques available to generate precise micro/macro holes such as conventional methods and non-conventional processes. Conventional methods are such as mechanical drilling by the aid of a drill bit either made of a hard material [119], [120] or coated with hard particles [121]–[123]. In this type of drilling, the cutting mode is mainly governed by tensional stresses due to tool geometry. Therefore, edge chipping at the entrance and exit of the hole during drilling of brittle materials is inevitable [124]. Since brittle materials tend to fracture due to their low fracture toughness, the inner surface of the hole is also very rough. Drilling ceramics by using diamonds in abrasive particle form is reported in the literature [121]–[123]. Material removal mechanism in this process for crystalline materials is usually a mixture of brittle fracture and limited ductile mode cuts. The resultant surface typically looks full of pits and fractures with severe edge chipping at entrance or exit [121], [122].

Figure 6.1 Silicon sample drilled with a regular diamond coated twist drill bit; Entrance edge (a) bottom of the hole (b)
A preliminary drilling test by using a four-flute, 1/16 inch diameter diamond coated drill bit on a single crystal silicon sample with 300 RPM and 2 µm/sec feed rate, shows a similar result. Figure 6.1 shows the microscopic images of the bottom and edge of this drilled hole. Drilling hard materials such as ceramics also increases the tool wear which is a significant drawback of the mechanical techniques. Figure 6.2 shows the condition of the diamond coated twist drill bit used for machining silicon before and after the process. Not only the coating was removed in only one drilling operation, but also the chisel edge of the twist drill was completely worn away.

![Figure 6.2 Diamond particle coated twist drill bit before (a) and after (b) drilling a single crystal silicon sample](image)

On the other hand, in non-traditional drilling processes, there is not any direct contact between the tool and the workpiece, and therefore less damage is expected. Non-traditional methods use processes such as electrical discharge machining (EDM) [125], water jet [126], micro-electrical chemical machining (ECM) [127] and rotary ultrasonic [128], [129]. Some of these processes are limited in cost, machining efficiency, dependence on the material properties, and achievable aspect ratio. Processes such as EDM and electrochemical drilling (ECD) are limited to
electrically conductive materials and not suitable for ceramics [130]. Rotary Ultrasonic Machining (RUM), which is a hybrid process of grinding and ultrasonic, is a highly reported process for drilling brittle materials [131], [132]. However, edge chipping at the exit side of the hole in brittle materials in RUM is unavoidable [129], [131], [133].

Laser drilling is a very common process for making holes in the ceramics as it is a non-contact process and is suitable for almost any material. Pulsed laser methods such as nanosecond, picosecond, and femtosecond lasers are also reported for drilling [134], [135]. Nonetheless, laser drilling suffers from high power consumption, size inaccuracy and high non-circularity, tapered holes, re-deposited material, micro cracks due to thermal stresses, and heat affected zone [136], [137]. It is also not possible to make blind or very deep holes by the continuous laser drilling. In work focused particularly on drilling silicon by laser, Jiao et al. used a laser power range of 200 mW to 400 mW with the pulse of 200 fs [138]. Images provided in their work show that the quality of holes is still far from ideal. A comparison between the current conventional and nontraditional processes is summarized in Table 6.1. Parameters such as precision, production rate, cost, advantage, and disadvantage for each of these processes are listed and compared.

### 6.3 Laser Augmented Diamond Drilling

A process that combines the benefits of mechanical drilling and a non-contact process such as laser drilling to decrease the damage and tool wear can make a significant change in processing the challenging materials. The Laser Augmented Diamond Drilling (LADD) is a technology for drilling hard and brittle materials. The LADD process utilizes laser heating to thermally soften, thus reducing the hardness and brittleness of the workpiece material, and mechanical cutting by a diamond tip. In this hybrid process, a laser beam is focused through a transparent tip that is usually
a diamond. LADD can increase the MRR, decrease the tool wear, improve the edges and surface finish, and minimize or eliminate the sub-surface damages occurring during the drilling operation. An ideal schematic of the LADD technique is shown in Figure 6.3.

<table>
<thead>
<tr>
<th>Process for Micro Drilling</th>
<th>Drilling of Brittle Material</th>
<th>Drilling of Ductile Material</th>
<th>Precision</th>
<th>Production Rate</th>
<th>Capital Cost</th>
<th>Operation Cost</th>
<th>Notable Advantage</th>
<th>Notable Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional micro drilling</td>
<td>Fair</td>
<td>Good</td>
<td>Fair (0.001 mm)</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>- Drilling all materials</td>
<td>- Stress after machining - Size of tool</td>
</tr>
<tr>
<td>EDM</td>
<td>Doesn’t Matter</td>
<td>Doesn’t Matter</td>
<td>Excellent (0.001 mm)</td>
<td>Low</td>
<td>High</td>
<td>Fair</td>
<td>- Hardness does not matter</td>
<td>- Just for conductive materials</td>
</tr>
<tr>
<td>Laser drilling</td>
<td>Doesn’t Matter</td>
<td>Doesn’t Matter</td>
<td>Fair (0.01 mm)</td>
<td>High</td>
<td>Very high</td>
<td>High</td>
<td>- Drilling all materials</td>
<td>- Heat effects</td>
</tr>
<tr>
<td>Water jet</td>
<td>Good</td>
<td>Fair</td>
<td>Poor (0.1 mm)</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>- Drilling all materials</td>
<td>- Noise - Spacious</td>
</tr>
<tr>
<td>USM/VAM</td>
<td>Excellent</td>
<td>Poor</td>
<td>Good (0.01-0.001 mm)</td>
<td>Low</td>
<td>High</td>
<td>Fair</td>
<td>- Good for brittle materials</td>
<td>- Machining ductile material is difficult</td>
</tr>
<tr>
<td>ECM</td>
<td>Doesn’t Matter</td>
<td>Doesn’t Matter</td>
<td>Fair (0.01 mm)</td>
<td>Low</td>
<td>High</td>
<td>Fair</td>
<td>- Hardness does not matter</td>
<td>- Just for conductive materials</td>
</tr>
</tbody>
</table>

Researchers proposed hybrid laser assisted processes for the machining of hard and brittle materials which are different in concept with the LADD [139]–[142]. For example, Ito et al. proposed selective laser-assisted milling (SLAM) to cut the glass and reported that arithmetic average of the roughness profile is significantly (74%) reduced by SLAM beside the conventional cutting [142]. The main difference of these processes compared to the LADD is that they focus the laser ahead of the cutting tool to make the material soft and not through the cutting tool. These process (other than LADD) are using high power laser sources that are usually expensive. Also it is not possible to use cutting fluid - as it cools down the workpiece and interrupts the laser beam -
and therefore having a rough surface is another main drawback of these techniques. Furthermore, focusing the laser ahead of the tool, in drilling is difficult to envision geometrically.

![Figure 6.3 Schematic of the LADD process](image)

Since the laser is going through the diamond cutting tool in the LADD process, not only cutting fluid can be used but also the mechanism of the cutting can be different, depending on the types of materials. The laser is only focused on the cutting edge of the tool, and only used to make the material softer and not necessarily melt it. Therefore, the amount of laser power used in this process can be significantly lower compared to other laser assisted processes. A softer material means less hardness and less cutting force which results in less tool wear.
6.4 Detailed Technology Description

Using the LADD for crystalline materials is based upon the previous research of ductile regime/mode machining of nominally hard and brittle materials that studied in earlier chapters. One of the unique properties of these materials that discussed previously is the extremely high-pressure phase transformations (HPPT) that occur due to the material’s contact with the diamond cutting tool. At these extreme pressure and shear conditions many of the materials of interest transition from covalent/ionic bonding to a metallic structure (often referred to as β-tin). This high pressure phase is responsible for the “ductile/plastic” behavior of these nominally hard and brittle materials at the nano to micro scale (nm to μm) [75]. Generally, at the macro scale (mm), these materials behave as purely brittle materials, but at the microscale, due to the HPPT, a ductile response is possible. The underlying science behind the so-called “brittle to ductile or ductile to brittle transition” involves scale effects and energy considerations (kinetics). If the size scale is small enough to achieve HPPT without fracture, then a ductile/plastic response is possible. However, if the size scale is large, even if a portion of the material experiences a HPPT, at the contact interface with the diamond, cracks can be generated and propagated.

These fracture events generally dominate the material removal process mechanism (catastrophic fracture). The current research uses the discussed science to develop a system that effectively targets the HPPT (metallic) material (for the ceramics and semiconductors), to preferentially heat and thermally soften (with the laser) the zone involved in the process of material deformation and removal. It should be noted that to making this functional the HPPT must absorb the laser wavelength. Generally, non-transformed, or atmospheric conditions material state, may or may not absorb the laser energy. Therefore, this property can be used to preferential heating of the material being deformed and removed during the machining process, while the bulk material
is unaffected. For each material, a suitable laser wavelength can be selected and used to heat the material in the process zone encompassing material deformation, chip generation, and material removal.

The hybrid configuration of the laser coupled to the diamond cutting-tool is unique and enables simultaneous extreme pressure and temperature conditions to achieve heating of the HPPT ductile material. Heating and thermally softening these nominally hard and brittle materials leads to:

- Reduced tool wear, i.e., diamond tool life increases, requiring fewer replacements, less repair, less machine downtime, and thus more production;
- Higher precision as the diamond cutting edge maintains its geometry;
- Higher or greater material removal rates in the ductile regime;
- Superior surface finish. Ultimately, increased productivity, higher profitability, and improved quality result.

6.5 Cutting Forces Modeling

In order to calculate the pressure exerted to the material in the cutting zone, the schematic in Figure 4.4 can help to visualize the cutting process. Since the HPPT occurs at high compressed pressure and shear stresses, a diamond tool with -45° angle is used to apply compression stresses. The cutting tool is fed by the position control mode of the equipment, therefore, the force is the reaction of the workpiece to the cutting tool. Dynamometer shows the Fz as the thrust and Fx as the cutting forces and F would be the resultant force shown in Figure 4.4. Chip surface can be measured by knowing this fact that the width of it would be the feed rate, \( f \), and the length would
be the curve of the tool edge in touch with the material. Since the rake angle is \(-45^\circ\), angle between the resultant force and \(F_x\) and angle between the uncut chip surface and feed direction would be the same as \(-45^\circ\). \(F_x\) is measured by the dynamometer and projection of the uncut chip surface, shown as \(A'\) in Figure 4.4, can be calculated as below.

\[
A' = A \cos \theta \Rightarrow A = \frac{A'}{\cos \theta}, 
\]

(6.1)

\[
F_x = F \cos \theta \Rightarrow F = \frac{F_x}{\cos \theta},
\]

(6.2)

\[
P = \frac{F}{A} = \frac{F_x}{A' \cos \theta} = \frac{F_x}{A'},
\]

(6.3)

Figure 6.4 Forces at cutting zone in an orthogonal cutting condition

6.6 Phase Transformation Thickness

The thickness of phase transformed layer, \(t_{pt}\), suggested by Galanov model [143] for phase transformations under an indenter is as follow:

\[
t_{pt} = \left[\sqrt{c^2 - r^2} - (c - r) \cot \psi\right] \xi,
\]

(6.4)
where $\Psi$ is indenter include angle and $\xi$ is:

$$
\xi = \frac{HV - p_{pt}}{HV - p_m}
$$  

(6.5)

where HV is the Vickers hardness of the sample and $p_m$ is the radial pressure and $p_{pt}$ is phase transformation pressure in the core and the plastic zone, Figure 4.5 [143]. Include angle, $\Psi$, of the tool can vary because of the shape of the tool tip.

![Figure 6.5 Phase transformation in the core and the plastic zone [65], [143]](image)

For the LADD process, the tool was used is shown in Figure 4.6. To calculate the chip cross section this schematic is used. Solid lines in Figure 4.6 (left) show the tool and dashed lines shows the tool after is fed down in one revolution of the workpiece. As it is shown in Figure 4.7 the included angle, $\Psi$, varies because of the shape of the tool nose and the depth of penetration in the specimen.
Figure 6.6 The chip cross section (left) and tool nose of the tool used for the experiments (right)

Figure 6.7 Schematic of LADD tool front view with varying include angle due to nose radius and depth of penetration in the workpiece

If the rake angle of the drill bit to be at $-45^\circ$ angle and the projected area $S_c$ (to the vertical plane) in Figure 4.6 is the exaggerated chip thickness, the following equations can be written:

\[ S_1 + S_2 = S_2 + S_c \Rightarrow S_1 = S_c , \]  
\[ S_1 + \delta = f \times R , \]  

Then:
\[ S_c = (f \times R) - \delta, \quad (6.8) \]

Since \( f \ll R \), it can be assumed that \( S_c \approx f \times R \), therefore, the area \( S_c \) is almost equivalent to \( f \times R \).

\[ A' = S_c = f \times R, \quad (6.9) \]

By having the cutting forces and the feed rate and radius of the tool the pressure can be calculated. This pressure can be compared to the pressure that is required to achieve a ductile mode cut.
CHAPTER 7

LASER AUGMENTED DIAMOND DRILLING; PROOFING THE CONCEPT

7.1 Introduction

This chapter is focused on proofing the concept of the LADD process and evaluating the effect and benefits of using this technique on quality of the entrance edge and inner surface roughness of drilled materials. As discussed in the previous chapter, the LADD process utilizes high compressive and shear stresses induced by a diamond tool/tip and laser heating to thermally soften, thus reducing the hardness and brittleness of the workpiece material. Single crystal silicon (100) is the tested material as it has a wide range of applications and is considered a challenging material to drill. Silicon is a relatively hard and brittle material with a hardness of ~12 GPa and low fracture toughness of 0.83 to 0.95 MPa.m^{0.5} (depends on crystal orientation). These properties make it difficult to drill precise holes and free of fracture.

7.2 Experimental Procedure

The LADD system is coupled to a tribometer which is a load and position control device to perform the drilling tests as shown in Figure 7.1. An IR, CW fiber laser with a wavelength of 1070 nm and maximum power of 100 W was used in this study. A single edge diamond drilling bit with a 0.5 mm radius, a -30° rake and a 30° clearance angle was used for the drilling operation, as shown in Figure 7.2. The laser beam was guided through a fiber optic cable to a collimator,
which was attached to a Beam Delivery Optics (BDO) unit. The BDO then focused the beam and delivered it through the transparent diamond tool to the cutting edge. Silicon samples were mounted on a rotational air bearing spindle while the drilling bit and the BDO were stationary. This configuration is similar to the drilling process in the turning operation in which the sample is rotating instead of the drill bit. Due to tool geometry which has a round edge, the dimple shape hole is produced in the workpiece, as shown in Figure 7.3.

![Figure 7.1 LADD setup used for the tests](image1.png)

**Figure 7.1 LADD setup used for the tests**

![Figure 7.2 Diamond bit used for experiments a: front view b: bottom view](image2.png)

**Figure 7.2 Diamond bit used for experiments a: front view b: bottom view**
7.3 Load Controlled Drilling

First, a series of drilling tests were carried out by using a load cell (shown in Figure 7.1) for monitoring the load and cutting forces. Although the tribometer can be used in the load control mode, i.e., dynamically keeping a programmed load during the process, the position control mode was used in this research. Initial tests with the load control mode resulted in severely fractured cuts due to lack of rigidity as the equipment was not stiff enough to hold the programmed load at a relatively high RPM. Therefore, in this first series of tests, the load cell was only used to monitor the cutting forces (to avoid any possible damage to the tool), and not to control the load (by holding a constant force during the drilling operation). The programmed depth was 40 μm, and the other drilling conditions are summarized in Table 7.1. The actual laser output after going through the diamond bit is about 30–40% due to scattering, reflection, etc. The chip thickness in this cutting process, based on the machining conditions listed in Table 7.1, is 120 nm/rev.

![Figure 7.3 Cross-sectional illustration of a dimple shape hole (diameter depends on the depth)](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational speed</td>
<td>1000 RPM</td>
</tr>
<tr>
<td>Feed rate</td>
<td>2 μ/s</td>
</tr>
<tr>
<td>Laser power</td>
<td>0, 10, 20 W</td>
</tr>
<tr>
<td>Depth</td>
<td>40 μm</td>
</tr>
</tbody>
</table>

Table 7.1 Drilling parameters for the first series of tests
Imaging the drilled samples showed non-circularity and fractures on the entrance edge. For the no laser case as shown in Figure 7.4a, by comparing the resulted edge to an ideal circle (yellow dashed circle), non-circularity is apparent. Circularity was improved by using the laser, although the edge chipping still occurred as shown in Figure 7.4b, 7.4c. The circularity of the entrance of the holes was quantified by enclosing the profile with two concentric circles, in which all the points of the hole circle fall within. The difference between the radiuses of these two circles is used as the circularity error.

Figure 7.5 is the graph of the circularity error and the effect of using laser. For the no laser case, this error was 12.79 µm, while for the 10 W and 20 W laser power cases errors were 8.8 and 5.6 µm respectively. This circularity improvement was mainly due to thermal softening which decreases the hardness and the strength of the material. Despite this improvement, the quality of drilled holes was not ideal due to low rigidity of the setup. The load cell works based on strain gauges movement and acted similar to a spring in the force loop of the setup. Therefore, to increase the stiffness, the load cell was removed from the setup for further experiments.

![Figure 7.4 Edge entrances quality a: no laser b: 10 W laser c: 20 W laser compared to an ideal circle](image-url)
7.4 Position Controlled Drilling
7.4.1 Ductile and Brittle Mode Cut Evidences

By repeating the tests, without the load cell in the force loop, a very clean entrance edge with an improved circularity (error of <<1 µm) was achieved. As shown in Figure 7.6, the edge of the drilled holes shows no evidence of chipping. Compared to µ-LAM used for turning [81], [91], [144], [145], the laser for drilling shines at one spot, drill point/tip, and in one direction as the tool feeds through the workpiece. Too high of a laser power can cause thermal cracks and even burning, which results in a rougher surface. As shown in Figure 7.7a by using 10 W laser power, the machined surface shows that a ductile mode cut has been achieved in most of the machined area. However, there is a visible ring of brittle mode cut (black spots) in the inner surface. Increasing the laser power to 30 W improved the surface quality, and small amount of brittle mode was left on the surface (Figure 7.7b). An excessive laser power, 40 W, burned the surface as shown in Figure 7.7c. Burning can be due to the type of material that is drilled and its properties (absorption, heat capacity, etc.), laser power used, energy density (laser power divided by the beam spot size)
and machining condition, i.e. coolant (not used in this study), RPM, etc. Therefore, optimization of these parameters is necessary to achieve the acceptable and the best results.

Figure 7.6 Edge entrance quality after increasing the rigidity of setup compared to an ideal circle a: No laser b: 10 W c: 20 W

Figure 7.7 Resultant surfaces after removing the load cell with a: 10 W b: 30 W c: 40 W laser powers
To achieve the HPPT in silicon, a hydrostatic pressure in the range of 10-13 GPa is required [146]. Increasing the depth of cut can result in more fracture, as the tool has more contact with the workpiece along the cutting edge. In the second series of experiments, an 80 µm depth of cut with drilling conditions summarized in Table 7.2 was performed. Surface roughness was measured by using the Wyko interferometer. To be able to obtain the Ra, surfaces were flattened by the aid of software, and an average of the measured Ra is reported.

A sample was drilled without the laser, and the image is shown in Figure 7.8a. A rough surface with an average surface roughness of 127 nm was achieved for this experiment. The dark areas on the surface are the fractures, pit, and voids, caused during the cutting process. It can be interpreted that as the load is distributed along the cutting edge, the compressive stress needed to obtain the HPPT and therefore ductile mode cut may not have been achieved. With this cutting condition, the chip thickness was same as the first test series, 120 nm/rev. However, the critical depth of cut - a depth where a ductile to brittle transition occurs - was smaller than the previous test condition, with 40 µm drilling depth. It was mainly because of a longer length of tool’s cutting edge that was in contact with the material in this new condition. From previous works [81], [91], [144], [147] done on silicon, it was expected that by using a laser the critical depth of cut increases, i.e., the same drilling conditions, feed rate and RPM, less brittle mode occurs. The same experiment using 10 W laser showed partially brittle mode cut, illustrated in Figure 7.8b, and also a lower average of the roughness of 83 nm. Using 20 W and 30 W laser power improved the surface finish to Ra of 73 nm and 60 nm respectively by decreasing the brittle mode and fractures, shown Figures 7.8c and 7.8d. The diagonal pattern of the partially brittle mode in the sample drilled with 30 W laser power in Figure 7.8d is in agreement with the results reported by Randall, et al. [148] of machining of silicon (100). In the no and low laser power cases, there is a possibility for
‘pull-outs’ in the sample, but due to the laser heating effect, pull outs have been significantly reduced resulting in a better surface finish. Laser heating also decreased the brittleness of the material and reduced the brittle fracture.

Table 7.2 Drilling parameters for the second series of tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational speed</td>
<td>1000 RPM</td>
</tr>
<tr>
<td>Feed rate</td>
<td>2 µ/s</td>
</tr>
<tr>
<td>Laser power</td>
<td>0, 10, 20, 30 W</td>
</tr>
<tr>
<td>Depth</td>
<td>80 µm</td>
</tr>
</tbody>
</table>

Figure 7.8 Surface quality drilled with a: No laser b: 10 W c: 20 W and d: 30 W laser power
7.4.2 Surface Roughness Results

The diagram depicted in Figure 7.9 shows a reduction of 53% of the surface roughness for the sample drilled with 10 W laser power, compare to no laser case. Roughness reduction of 74% and 112% were achieved by using 20 W and 30 W laser powers respectively. The areas machined in a brittle mode in which pull-out occurred are mainly responsible for the rougher surface. Thus the improvement of the surface finish is because of the less brittle mode material removal. Therefore, applying the laser helped to decrease the brittle mode cut and perform the machining in the ductile mode.

![Figure 7.9 Effect of using the laser on the reduction of surface roughness](image)

To help to visualize the drilled surfaces, a 3D profile of the inner surface of the hole was generated by Wyko profiler for each test. The 3D profiles illustrated in Figure 7.10 are correlated with the surfaces of Figure 7.9. The blue areas in Figure 7.10a are the pits caused by brittle mode cut. Fewer pull-outs and smoother surfaces with much fewer imperfections are visible on the sample drilled with the aid of 10 W laser power, Figure 7.10b. In Figure 7.10c the surface is
smoother, but there is an uneven area in the middle of the profile which is correlated to the brittle mode cut ring in Figure 7.8c. A smoother surface can be seen in Figure 7.10d with small imperfection.

![Image](image_url)

Figure 7.10 3D profile of machined surface with a: No laser b: 10 W c: 20 W d: 30 W laser powers

### 7.4.3 Ductile Chips

Ductile chips are also an evidence of the ductile mode cutting occurring during machining of a brittle material. As single crystal silicon is extremely brittle with low fracture toughness, achieving continuous, plastically deformed and curly chips without the ductile mode cut is unattainable [41]. In the drilling process of the silicon, ductile chips were observed which generated by plastic deformation occurred during the drilling process. As shown in Figure 7.11, continuous chips, with ~50μm length, obtained in a case that 30 W laser power was used. Further investigation is needed to study these chips and to show their structural changes possibly due to the HPPT and laser heating.
7.5 Conclusion

In this chapter, it was demonstrated that making precise holes on single crystal silicon (100) in a ductile regime with higher edge quality is possible. Drilling with and without laser augmentation and the results were compared. Results indicated that laser power selection is crucial in this process. By choosing an optimized drilling condition it is possible to achieve high quality holes in silicon. It was also shown that by using the LADD technique, it is possible to drill brittle materials with minimal damages. Ductile chips observed after drilling is an indication of the ductile mode cut. The current study showed that using this technique can improve the quality of a drilled hole, entrance edge, and inner surface finish. The LADD system can achieve enhanced ductility, through reduced hardness (and reduced brittleness) resulting from laser heating and thermal softening, to promote more efficient, productive and less costly overall drilling process. It is expected that the exit side of the through holes achieves similarly beneficial results.
CHAPTER 8

CUTTING FORCE ANALYSIS IN LASER AUGMENTED DIAMOND DRILLING

8.1 Introduction

In the previous chapter, it was shown that using LADD improves the quality of hole entrance edge and inner surface finish. The focus of the current chapter is on cutting forces that were acquired by the aid of a dynamometer to evaluate the effect of using laser and thermal softening on the cutting condition. Comparing the cutting forces can give an estimate of the effect of laser softening on the process. The effect of utilizing different feed rates and cutting fluids on drilling single crystal silicon (100) was studied. Results such as microscopic and SEM images of the edge and inner surface of the holes and cutting forces for different test conditions were analyzed and discussed. The effect of critical parameters on the mode of the cut such as ductile or brittle also discussed and evaluated.

8.2 Experimental and Setup Preparation

8.2.1 Setup

In the LADD process, the laser beam is focused on the cutting edge of the tool to increase the temperature of the material in cutting zone that is in touch with the tip of the tool. Therefore, a medium power laser unit is adequate. Finding a proper laser power level that decreases the cutting forces sufficiently and also avoids thermal damage is one of the most important steps in this
process. The aim of using the laser is to make the material softer, but not necessarily to melt or burn it. Based on previous studies and as the rule of thumb, usually a temperature of about half of the material’s melting point is sufficient. In the case of brittle and crystalline materials, such as silicon, increased temperatures result in higher ductile to brittle transition (DBT) depth as discussed in Part A of this dissertation. In machining of these types of materials, the cross feed rate is limited to a critical chip thickness which, if exceeded, results in a severe fracture or brittle mode cut. Higher DBT makes using a higher feed rate possible, while the mode of the cut is still ductile. The melting point of silicon is \( \sim 1414 ^\circ C \), and its hardness decreases dramatically by increasing the temperature to more than 500 \( ^\circ C \) [149].

The cutting tool used for the drilling operation is a single edge diamond bit with a 0.5 mm radius and \( \sim 50 \text{ nm} \) edge radius, shown in Figure 8.1. Such a small edge radius helps to generate a very high pressure at the tip of the tool and eases the phase transformation needed to cut a brittle material in ductile mode [150], [151]. Enhancing the ductile response of silicon by shining the laser to the cutting zone and increasing the temperature has been shown in previous works [67], [152]. The laser used in this study is an IR continuous wave fiber laser with a wavelength of 1070 nm. The laser beam is in Gaussian profile and covers as much as possible of the cutting edge. The melting point of the diamond is more than 3000\( ^\circ C \), and the laser power absorbed by the diamond tool is less than the level that can damage it. The carbonization of the diamond due to exposure to high temperatures is minimal and does not affect the cutting tool significantly, and therefore, it does not change the geometry of the tool. Although the tip of the diamond tool might be affected by carbonization in high temperatures, it is surrounded by workpiece materials and is not exposed to the air. To ensure that all tests conducted in the same conditions, only one tool is used for the entire investigation because of 1. Changes in the tool necessarily result in changes to the laser
alignment and 2. Tools are not precisely identical. Although diamond tool remains functional for a considerable time, tool wear in machining hard materials is inevitable. Therefore, tests were conducted on a random basis to avoid any meaningful effect on results through the experiments. The LADD system is coupled to a programmable tribometer capable of micron range movements as low as 2 µm/s to perform the drilling tests. For this work the sample rotates instead of the tool. This configuration is similar to the drilling operation on a lathe. Samples were mounted on a precise air bearing spindle with a submicron run-out error.

Figure 8.1 Diamond bit used in LADD and laser alignment respect to the cutting edge

### 8.2.2 Cutting Force Measurement

Achieving high accuracy and minimizing the residual stresses, which occur due to cutting forces or clamping, are essential in precision manufacturing. Residual stresses can cause post process distortion to the workpiece. It is recommended that the workpiece to be cut with the lowest possible cutting forces. Lowering cutting forces is also beneficial to the tool life, which increases the repeatability of the process and decreases the deviation of the tolerances in sizes of the final product. Therefore, measuring the cutting forces can help to clarify the cutting mechanism during
the process and lead to improve the quality of the drilled holes. Since the cutting force has a major effect on the tool wear, monitoring it gives a better understanding of the process.

By comparing the forces obtained in different laser power conditions, the effect of thermal softening on the cutting and consequently the tool life can be evaluated. For this purpose, a Kistler dynamometer Type 9256A1, which is capable of measuring forces up to 250 N, is utilized in the experiments. The dynamometer is based on piezoelectric technology and is stiff enough in the setup. This piezoelectric measurement method provides very accurate results when there is a preload on the dynamometer. The LADD system was mounted on and measured the forces during the tests as shown in Figure 8.2.

![Figure 8.2 LADD setup while forces are being measured by a dynamometer (left) and a schematic layout of the process (right)](image)

A Kistler type 5010 dual-mode amplifier intensifies the signals from the sensor and converts the charge into a proportional voltage output signal. The output signals were collected by National Instrument Data Acquisition (DAQ) card and processed by the Matlab software.
8.2.3 Force Analysis

Single crystal silicon (100) is an anisotropic material which means it has different properties based on crystal orientation. Silicon shows crystallographic orientation dependence in cutting forces and critical chip thickness that has a pattern in every 90° [95], [153]. O’Connor et al. by using eq. 1, showed that on a cubic crystal plane of silicon elastic modulus, variation forms a 4-lobed pattern [95]. Their calculation was for (001) crystal face, but it is true for other faces such as (010) and (100). For the same reason, the fracture toughness of silicon also varies depending on crystal orientation. It was expected to see the same trend in drilling silicon by using a single edge diamond bit.

\[
E^{-1} = s_{11} - 2 \left( s_{11} - s_{12} - \frac{1}{2} s_{44} \right) \left( l_1^2 l_2^2 + l_2^2 l_3^2 + l_3^2 l_1^2 \right),
\]

(8.1)

where \(s_{11}, s_{12}, \) and \(s_{44}\) are the elastic compliance constants and \(l_1, l_2, \) and \(l_3\) are the direction cosines relative to the cubic crystal axes [95].

The raw data acquired by dynamometer is depicted in Figure 8.3. Wide force range is due to the force oscillates during the process. A close look at the force graph, by widening an arbitrary section of the graph, in Figure 8.4, shows that in addition to the peak points there are two other data points between. That means that there is sufficient data in that period of time and there are no major peaks in between.

The rotational speed of the spindle for the tests was 1000 RPM, and the data acquisition rate was 250 points per second. By a simple calculation, as indicated below, 15 data points per each revolution are acquired.
\[
1000 \frac{rev}{min} \times \frac{1 \text{ min}}{60 \text{ sec}} = \frac{50 \text{ rev}}{3 \text{ sec}} \Rightarrow \frac{50 \text{ rev}}{3 \text{ sec}} \times \frac{1 \text{ sec}}{250 \text{ data}} = \frac{1 \text{ rev}}{15 \text{ data}} \Rightarrow 15 \frac{\text{data}}{\text{rev}}, \quad (8.2)
\]

Figure 8.3 Raw cutting force graph obtained by dynamometer over a testing period of time (blue) and after filtered (red)

Figure 8.4 Close view of cutting force graph showing the force oscillation due to varying in crystal orientation respect to the cutting tool
By counting the number of peaks for each revolution (15 data points), approximately four peaks exist. A microscopic image of a drilled sample in Figure 8.5 shows that there are four spokes of fractures, 90° from each other, at the bottom of the holes. These spokes occur due to crystal orientation and an anisotropy effect that exists in the single crystal silicon. The valleys are attributed to the brittle spokes, dark and rough regions in Figure 8.5, since the fracture requires less energy and the tool experiences less force. Peaks belong to ductile regions, smooth and reflective regions, as plastic deformation requires more energy and higher force. This observation is correlated with the anisotropic behavior of the single crystal silicon.

![Spokes of fractures](image)

**Figure 8.5** Spokes of fractures a) at the bottom of a drilled sample and visible in b) SEM image and c) 3D profile

### 8.2.4 Data Processing

The measured Fz force before smoothing is shown in the color blue in Figure 8.3. New interpolated points are plotted in red on the raw force data points. These fitted new curves allow graphical comparison of the force data obtained from different experimental conditions. Thus, it is possible to obtain meaningful results from small force changes during the drilling process. As shown in Figure 8.3, the graph is filtered; therefore, the measured forces would not overlap. There
were 250 data points per second collected for drilling thrust force via National Instrument PCI-6025E DAQ card. The smoothing parameter is determined by the trial and error method and set to 0.01 where the filtered force values are distinguishable. To make a smoother fit this parameter (p) takes a value between 0 and 1 until the plot shows an acceptable smoothness. A parameter value of zero produces a linear polynomial fit, while 1 produces a piecewise cubic polynomial fit that passes through all the data points [154]. The smoothing spline is achieved by the equation below:

\[ p \sum w_i (y_i - s(x_i))^2 + (1 - p) \int \left( \frac{d^2 s}{dx^2} \right)^2 dx, \]  

(8.3)

where: p is smooth factor parameter, s is estimated function of the f (the smoothing spline estimates “s”), \((x_i, y_i)\) is a sequence of observations, modeled by the relation \(y_i = f(x_i)\). The weights \((w_i)\) are assumed to be 1 for all data points. The calculation of the new data points is based on the Matlab cubic smoothing spline function.

8.2.5 Experimental Procedure

In current study, tests with different conditions of the laser power, feed rate, and the type of cutting fluid were carried out and parameters are summarized in Table 8.1. The lower level of the feed rate, 2 \(\mu m/rev\), is based on a maximum reported chip thickness, as reflected in the literature [71] for the silicon (100) to achieve a ductile mode cut, 120 nm. Laser power is also the output power measured with the aid of a power meter before each test. Even though the focus of this study was on the benefit of using LADD to decrease the cutting force, the quality of the drilled samples, especially the entrance edge, was evaluated as well. Due to the size and shape of the drill bit, which has a negative rake angle (-45°), dimple shape blind holes were generated. Two types of cutting fluids were used in these tests: one water based and the other one oil based, DI water and odorless
mineral spirits (OMS). As the laser beam passes through the diamond bit and to the cutting edge, it will not be interrupted by the cutting fluid.

Drilled samples were imaged, and the quality of the entrance edges was analyzed. Initial results indicate that by using proper laser power and adjusting other parameters, under optimum conditions appropriate results can be achieved [152].

<table>
<thead>
<tr>
<th>Table 8.1 Drilling process parameters and their levels</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cutting parameters</strong></td>
</tr>
<tr>
<td>Feed rate (f)</td>
</tr>
<tr>
<td>Spindle rotation rate</td>
</tr>
<tr>
<td>Maximum depth of holes</td>
</tr>
<tr>
<td>Laser power</td>
</tr>
<tr>
<td>Cutting tool material</td>
</tr>
<tr>
<td>Nose radius</td>
</tr>
<tr>
<td>Rake angle</td>
</tr>
<tr>
<td>Relief angle</td>
</tr>
<tr>
<td>Cutting fluids</td>
</tr>
</tbody>
</table>

**8.3 HPPT and Force Modeling**

The ductile response of single crystal silicon as discussed in Part A of this dissertation is due to High Pressure Phase Transformation (HPPT). HPPT is a phenomenon that changes the diamond-like structure of silicon to β-Sn or a metallic structure. This change occurs due to compression and shear stress. For silicon to reach this condition, a pressure in room temperature of approximately 12 GPa [71] is required. For this purpose feed rate and the chip thickness should
be less than a critical value. The critical chip thickness to achieve a ductile mode cut is between 40 nm to 120 nm depending on the crystallographic orientation [95].

In order to measure the pressure that the material is experiencing in the cutting zone, the uncut chip area - the area to which the cutting force is applied - needs to be measured. Since the tool is stationary (workpiece is rotating) the cutting zone is also stationary with respect to the dynamometer, and therefore the cutting force, \( F_x \), can be used to measure the pressure. Equation 8.4, which is derived in research background chapter, shows that pressure is equivalent to cutting force, \( F_x \), divided by the projection of the chip surface, which is equal to the product of feed rate, \( f \), and hole radius, \( R \).

\[
P = \frac{F}{A} = \frac{F_x}{f \times R},
\] (8.4)

Comparing the cutting and thrust forces for the same experiment in Figure 8.6 shows that they are at almost the same magnitude as the rake angle is -45°. Therefore, even for a horizontal projection of the chip thickness and using thrust force, \( F_z \), the same result can be achieved.

Figure 8.6 shows that the cutting force is \(~1 \text{ N}\) at the bottom of the hole when the entire cutting edge is engaged. Therefore, pressure (P) for a feed rate of 2 \( \mu \text{m/s} \), which causes the chip thickness of 120 nm for 1000 RPM can be calculated as:

\[
P = \frac{F_x}{A} = \frac{F_x}{f \times R} = \frac{1 \text{N}}{120 \times 10^{-9} \text{ m} \times 0.5 \times 10^{-3} \text{ m}} = 16.67 \text{ GPa},
\] (8.5)
Such pressure is higher than ~12 GPa, as reported in the literature for HPPT of silicon [71]; therefore, it is expected that the mode of the cut to be ductile. Although such a pressure is high enough, other conditions can affect the regime of cut. It is assumed that the pressure is spread evenly on the entire chip cross section, while HPPT occurs in near hydrostatic pressure condition - material is confined properly - and shear stresses. For this cutting process, such a condition is more likely to occur near the tip of the tool and center of the hole, rather than at its outer edge. The pressure for 4 μ/s is 8.335 GPa, which is less than what is needed to ensure the ductile response.

8.4 Cutting Force Outputs

Thrust force was collected during the experiments, while the motion of the drill bit toward the workpiece was in position control mode (no control over the thrust force). The force, F, exerted to the drill bit has two main components, Fx and Fz, which are cutting and thrust forces, respectively as shown in Figure 8.9. These two forces are at almost the same magnitude since the

Figure 8.6 Thrust force (above) and cutting force (below) for 2 μ/s feed rate and 1000 RPM
rake angle of the tool is \(-45^\circ\). The negative rake angle of the tool is vital in order to have compressive stress.

![Diagram of cutting tool and forces](image)

**Figure 8.7** Cutting tool position while cutting (left) and cutting forces exerted to the drill bit in the side view (right)

Figure 8.8 shows the cutting force graph acquired during the test with 2 μm/s feed rate and DI water as the cutting fluid. Using 12 W laser power decreased the force by \(\sim 30\%\). The graph of the cutting force for the test with 4 μm/s feed rate and DI water, as shown in Figure 8.9, indicates lower force compared to the previous test condition (2 μm/s feed rate). This change is primarily due to transformation in the cutting mode from mainly ductile to brittle. It is well known that in the brittle mode condition, forces are lower as fracture occurs during the cut that needs less energy to remove the material.
Figures 8.8 and 8.11 show the microscopic and SEM images of the holes drilled with these two feed rates. Brittle mode cut was dominant when the feed rate was 4 μm/s which is apparent in black areas in Figure 8.11. The high deviation of the forces in the graph for both conditions in Figure 8.9 suggested that fracture occurred in almost the entire process (except for
the beginning). However, the entrance of the hole did not show any sign of severe fracture at the edge.

![Microscopic image](image1.png)  ![SEM images](image2.png)

**Figure 8.10** a) Microscopic image and b) SEM images of the hole drilled with 2 μm/s feed rate

Cutting force graphs for drilling with the aid of OMS cutting fluid also show a similar trend as with the DI water. Using 12 W laser power for the tests with 2 μm/s feed rate decreased the
force, as shown in Figure 8.12. In Figure 8.13, no apparent difference can be seen for different laser power conditions, as brittle mode cutting was dominant, and the laser was not absorbed to make any difference.

Figure 8.11 a) Microscopic image and b) SEM images of the hole drilled with 4 μm/s feed rate
For both cutting fluid conditions, the laser created a change in the cutting forces for 2 μm/s feed rate, but no apparent change for 4 μm/s feed rate condition can be seen. In 2 μm/s condition, for both of the cutting fluids, less fracture has occurred, and microscopic images exhibit that the ductile mode cut was dominant. Such a result means that the material is plastically deformed at the cutting zone, and it can be assumed that there was constant contact between the tool cutting
edge and the material. Such a steady condition and phase transformation are due to high pressure that changes the silicon diamond cubic crystal structure to metallic $\beta$-Sn structure and makes the laser absorption more feasible. Therefore, in 2 $\mu$m/s feed rate, cutting forces were changed as the laser is absorbed. In contrast for the brittle dominant condition, 4 $\mu$m/s feed rate, laser transmitted through the material, scattered or reflected from the cutting zone and not absorbed as shown in Figure 8.14.

Figure 8.14 Laser beam absorption depends on the occurrence of the HPPT a) unfavorable condition b) desired condition c) drilled with 4 $\mu$m/s d) drilled with 2 $\mu$m/s
Using the laser did not show any significant effect on the forces in 4 μm/s feed rate for both cutting fluid conditions. A close look at the edges shows that using laser results in better edge quality with less edge chipping, compared to no laser, as is shown in Figure 8.15. Laser increases the temperature at the cutting zone and thus decreases the brittleness of the material and its tendency to fracture. In the machining of brittle materials, achieving smooth surfaces with minimum fracture and cracks on the surface is in high priority. On the other hand, lower cutting force leads to decreased tool wear and, therefore, fewer tool replacements. Fewer tool replacement not only reduces the tool cost but also reduces the downtime of the process.

![Figure 8.15 Edge quality at 4 μm/s feed rate a) 12 W b) No laser with edge chipping](image)

**8.5 Effect of Cutting Fluids**

Evaluation of the cutting forces when different cutting fluids were used suggests that using DI water compared to OMS decreased the forces slightly more. This effect can be seen in both test results with and without a laser in Figures 8.16 and 8.17. It is apparently due to the embrittlement effect in which water makes the material more brittle and easier to cut. This is due to the fact that less energy is needed in a brittle mode cut. Comparing the graphs in Figures 8.16 (No laser) and
8.17 (12 W laser) also shows that using laser made the graphs smoother (less oscillation), at least from beginning to the middle of the graph. Less oscillation in forces means a more stable cutting condition which benefits both the tool and workpiece. It also can be interpreted from the force graphs for the 12 W (Figure 8.17) that the cutting was in a ductile mode during the first half part. However, at the end, the mode is changed to dominantly brittle and that is the main reason for achieving a rough surface in Figure 8.11. The reason for the change of mode of cut is the tool shape that is used. The angle of contact between the tool and material surface changes due to the tool nose by advancing through the workpiece material. For a shallower cut, the included angle of the tool, $\Psi$, at the contact point with respect to the surface of workpiece is high (close to 90°), and for a deeper cut, it is small, as shown in Figure 6.7 in research background chapter.

![Figure 8.16 Forces obtained in the test with 4 μm/s feed rate, No laser with force oscillation](image)

The analytical model for phase transformations under a rigid indenter proposed by Galanov et al. [143] also suggests that a smaller include angle decreases the thickness of the phase transformation layer. The model in the research background chapter also shows that by traveling from the center toward the edge of the indenter, the thickness of the phase transformation layer
shrinks to zero. The experimental study of Jang and Pharr [155] confirms that increasing the included angle of the indenter gradually decreases the length of cracks, which suggests a better condition for the ductile mode cut.

![Graph showing forces over time](image)

**Figure 8.17** Forces obtained in the test with 4 μm/s feed rate, 12 W, with low oscillation at first half

### 8.6 Raman Spectroscopy Analysis

Raman spectroscopy performed on the as-received (pristine) single crystal silicon (100) wafer and processed specimen. Different places on the inner surface of the drilled samples were examined as well. The Raman shift graph of the as-received sample shows a strong, sharp peak at 521 cm\(^{-1}\) (Si-I) and two weak peaks at \(~300\) (Si-I) [156] and \(~977\) cm\(^{-1}\) as shown in Figure 8.18a. Raman shift spectrum for drilled silicon samples with no laser and with the aid of 12 W laser also are depicted in Figure 8.18. A noticeable difference between Raman shift graph of the as-received sample to the sample drilled with no laser case is the lower intensity for 521 cm\(^{-1}\) peak for the drilled sample. Also since the spectroscopy performed on the surface of as received samples, a
weak indication of amorphous silicon (a-Si) can be seen. The graphs for drilled samples, however, show no sign of a-Si. It should be taken to consideration that wafers available in the market have gone through a grinding and polishing process and there might be a small layer of a-Si still on the surface. The depth of drilling was significantly higher (200 µm while the wafer thickness was 350 µm) than the thickness of this layer. No other peaks, even weak, can be seen in the Raman shift graph of the drilled samples. The graph for the sample drilled with the aid of 12 W laser shows a higher peak which can be interpreted as a re-crystallization that occurred due to high temperature.

Figure 8.18 Raman spectrum of the single silicon (100) sample a) as-received, b) drilled with no laser, c) drilled with 12 W laser power
8.7 Summary and Conclusion

LADD is a new hybrid process that combines mechanical drilling (using diamond tool bit) and laser softening (heating and thermal effects) for making holes in hard and brittle materials. Single crystal silicon, as a typical nominally brittle material, was tested by using two laser powers (0 and 12 W), two cutting fluids, DI water and OMS with two different feed rates: 2 and 4 µm/s. Results showed that by using this technique, cutting forces were lower due to laser heating and thermal softening. Less cutting force helped to preserve the drill’s cutting edge and therefore obtain a longer tool life. The cutting pressure calculation, based on the chip thickness and cutting force, implies that the pressure (16 >12 GPa) for achieving the ductile mode was reached for 2 µm/s feed rate. Evidence of the ductile regime/mode cut of silicon was observed in microscopic images. However, due to tool geometry and the fact that a compression and shear stress are needed to achieve a pure ductile mode cut, in some cases a mixed brittle and ductile mode cut was occurred.
CHAPTER 9

CUTTING FORCES ANALYSIS OF CARBON FIBER COMPOSITES

9.1 Introduction

In this chapter using Laser Augmented Diamond Drilling (LADD) to drill composites is investigated. Composites are materials with fast-growing applications in major industries such as automotive and aerospace [157]. As an example, in the Boeing 787 more than 50% of the structural weight [158] (80% by volume [159]) is made of composites. Their desirable properties such as high strength and light weight make them ideal materials for applications that need high strength to density ratios (specific modulus, E/\(\rho\)). Figure 9.1 shows that composites have a lower density than metals and the same or slightly higher than polymers and elastomers [160]. However, their strength is higher than the average of the metals and higher than polymers and elastomers. Carbon Fiber Reinforced Plastics/Polymers (CFRP) are very desirable materials with high damping capacity, fatigue resistance, and excellent damage tolerance which makes them widely used in various industries [161].

One of the desirable physical characteristics of CFRPs is that they can be manufactured in near net shape [161]. Therefore, processes such as cutting and machining would be minimal compared to the other types of materials such as metals. However, drilling is still one of the main processes applied to CFRPs since produced pieces usually need to be fastened to a main structure [161], [162]. Since the composite pieces need to be bolt-jointed, the quality of the drilled holes is very important [163]. As mentioned in the introduction, due to some characteristics of the
composites such as non-homogeneous, profoundly hard and abrasive fibers, and their anisotropic behavior make them very challenging to cut [163]–[165].

![Figure 9.1 Strength vs. density plot. Metals and polymers: Yield strength, Elastomers: tear strength, Ceramics: compressive strength, and Composites: tensile strength [160]](image)

**9.1.1 Drilling Composites Challenges**

Drilling CFRPs is challenging from different perspectives. Two main problems for drilling CFRPs are rapid tool wear and delamination [166]. Classification of delamination at the entrance and exit is illustrated in Figure 9.2. Typical delamination on CFRPs depicted in Figure 9.3 shows the low quality of drilled holes and edges. This type of damage is irreparable and accounts for about 60% of the part rejection in the aerospace industry [167].
Many researchers paid attention to delamination and tool wear in machining CFRPs [170]–[177]. In work by Davim [174], by using design experiment different parameters that can affect the delamination were studied. They used high-speed steel (HSS) and Cemented Carbide (K10) drill bits to find a relation between feed rate and cutting velocity with delamination of the CFRPs [174]. Feito, N., et al. [178] presented a numerical model for drilling carbon/epoxy laminates to predict the process. The model predicted the delamination damage and the thrust force during the process in a high-level accuracy. They validated the results with experiments to a high level of confidence. Faraz et al. [168] introduced cutting-edge rounding to measure the tool sharpness for
carbide bits to drill CFRP. They investigated the flank wear and its correlation with the delamination occurring as a result. Researchers also studied the other aspects such as drilling parameters [174], [179], [180], the effect of tool geometry [181], and the drill bit diameter [171] for different tool materials.

One of the main reasons for delamination, especially at the exit, is the thrust force, Figure 9.4. Researchers have studied the effect of it on delamination and suggested that there is a threshold force that causes delamination. By an equation proposed by Hocheng [182] thrust force at the beginning of crack propagation at the exit side of the hole can be calculated as:

\[
F = \pi \left[ \frac{8 G_{IC} E h^3}{3(1-v^2)} \right]^{\frac{1}{2}} = \pi \sqrt{\frac{32 G_{IC}}{M}},
\]  

(9.1)

\[
M = \frac{E h^3}{12(1-v^2)},
\]  

(9.2)

In which E is the modulus of elasticity, GIC is the critical crack propagation energy per unit area, and \(v\) is Poisson’s ratio. In this work, it is proposed that to avoid delamination at the exit side, the applied thrust force should be less than this value. The equation is a function of the material properties and the uncut thickness [182], [183]. Cutting forces are also the main reason for the tool wear. In another word, less force leads to less tool wear and fewer tool replacements. Lachaud et al. [184] derived an equation very similar to equation 1. Monitoring the forces in the drilling process of composites is vital to minimize the damage [185].
9.2 Experimental Procedure

9.2.1 Carbon Fiber Composite

Composites drilled with the different type of bits (other than twist bit) such as straight flute, step drill bit, slot drill bit, etc. and the delamination problem needs to be overcomed [163]. Twist drill bits make the delamination worst due to their geometry. LADD has the advantage to decrease the thrust force which is, as discussed, one of the main reasons for delamination. Also, its drill bit is a non-twist type that makes the delamination less likely to occur.

This study is the first attempt of using LADD for drilling composites. Different laser powers are utilized to perform the drilling process on the carbon fiber composites, and the forces are gathered by the aid of a dynamometer. At least 92% of carbon fiber total weight is made of carbon in crystalline, amorphous, or partly crystalline structure [157]. Carbon fibers possess a high modulus (as well as thermal and electrical conductivity) due to the tendency of carbon layers to be parallel to the fiber axis [157]. Properties of the two common types of carbon fibers used in industry are listed in Table 9.1. Figure 9.5 shows a typical 6-ply carbon fiber composite used in this study provided by Plasan Carbon Composites Company. Fibers are woven together and are in
zero degree and 90° respect to each other. To create the parts, fibers are impregnated with an epoxy resin matrix and are finalized by the aid of high pressure and heat. According to Plasan, the melting point of the epoxy is less than 200 °C.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm$^3$)</th>
<th>Tensile strength (GPa)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Ductility (%)</th>
<th>Melting point (°C)</th>
<th>Specific Modulus (10$^6$ m)</th>
<th>Specific strength (10$^4$ m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon High-strength</td>
<td>1.5</td>
<td>5.7</td>
<td>280</td>
<td>2.0</td>
<td>3700</td>
<td>18.8</td>
<td>19</td>
</tr>
<tr>
<td>Carbon High-Modulus</td>
<td>1.5</td>
<td>1.9</td>
<td>530</td>
<td>0.36</td>
<td>3700</td>
<td>36.3</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 9.5 Typical 6-ply carbon fiber composite cross section, 50x (a) layers and directions seen in cross section (b) actual photo (c) typical weave style (d)

Similar drilling setup used in previous chapters is also used for this study. To acquire the forces, a Kistler dynamometer is also added to the setup and cutting fluids employed to see the effects on the results. Parameters used in this experimental work are listed in Table 9.2. DI water is supplied by the aid of a mist system. The same setup and nozzle are used for supplying pressured air (the line for adding liquid to mist system was closed).
Table 9.2 Experimental parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>Carbon Fiber Composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational speed</td>
<td>1000 (RPM)</td>
</tr>
<tr>
<td>Cutting tool</td>
<td>Single Crystal Diamond</td>
</tr>
<tr>
<td>Laser</td>
<td>Fiber, IR, 1070 nm wavelength</td>
</tr>
<tr>
<td>Coolant</td>
<td>Air, DI water</td>
</tr>
<tr>
<td>Feed rate</td>
<td>16 (µm/s)</td>
</tr>
<tr>
<td>Drilling depth</td>
<td>200 µm</td>
</tr>
</tbody>
</table>

9.3 Results and Discussion

9.3.1 Air Coolant

The first series of tests were performed by using air to blow away the debris. Cutting forces achieved for the 8 µm/s feed rate are shown in Figure 9.6. As expected, by increasing the laser power cutting forces decreased. From no laser to 10 W and then 15 W forces reduced significantly. Forces for the 20 W and 25 W are almost zero, and that is the main reason that they are overlapped. Results for 16 µm/s feed rate with the same experimental condition are depicted in Figure 9.7. Forces for 16 µm/s feed rate are higher compared to lower feed rate 8 µm/s as expected (less laser power delivered per unit of time).

Figure 9.6 Thrust forces acquired for tests with 8 µm/s feed rate and air as a coolant
Microscopic images of the drilled samples in Figure 9.8 show that although forces for no laser test are the highest, the quality of the edges is satisfactory. Samples drilled with laser showed the low quality due to melted epoxy and burned carbon fibers, Figure 9.9 and 9.10. Since the carbon fibers are excellent heat conductors, melting occurred along the fibers direction. It seems there is a tradeoff between decreasing the cutting forces and unwanted heat effects due to using a laser. For carbon fiber composites in particular laser heat should be controlled and kept in the cutting zone. Fortunately, in the LADD process cutting fluid, or coolant, can be used. The aim is to control the heat and also flush away the debris, and therefore, DI water is used for this purpose.
9.3.2 DI Water Coolant

The same set of experiments with DI water as coolant was carried out on a carbon fiber composite specimen. Cutting forces for both 8 µm/s and 16 µm/s feed rates are depicted in Figure 9.11 and 9.12. The noticeable difference between these results and results of drilling with air as coolant is that the forces are higher here. For instance, while for the air as coolant forces for 20 W and 25 W tests were almost negligible, for DI water coolant condition forces are not insignificant.
The main reason for that is obviously cooling effect of the water that caused the temperature of cutting zone goes lower than the previous condition.

Figure 9.11 Thrust forces acquired for tests with 8 µm/s feed rate and DI water as a coolant

Figure 9.12 Thrust forces acquired for tests with 16 µm/s feed rate and DI water as a coolant

On the other hand, microscopic images show that for the sample drilled with the aid of DI water as coolant a much better edge quality was achieved. Even the sample drilled with no aid of laser shows better edge quality compare to the one drilled with air as a coolant, Figure 9.13. It needs to be mentioned that the tool used for this experiments was a diamond tool with a very sharp cutting edge and achieving such results without the aid of laser was not unusual.
Figures 9.14 and 9.15 show that DI water controlled the heat and the sample drilled with no heat effect that occurred previously. Forces, as mentioned before, were not as low as the cutting with the aid of air though. Figure 9.16 shows that even by using DI water as a coolant for high laser power, unwanted heat effects are not 100 percent avoidable. Coolant was supplied from one side of the cutting tool, and therefore the stream was blocked by the shank of the tool and that is why on one side of the drilled sample the epoxy was melted in Figure 9.16.

![Figure 9.13](image1.png) **Figure 9.13** Quality of drilled samples with no aid of laser and feed rate of 16 µm/s by a diamond bit with DI water as the coolant

![Figure 9.14](image2.png) **Figure 9.14** Quality of drilled samples with the aid of 15 W laser and feed rate of 8 µm/s by a diamond bit with DI water as the coolant
Figure 9.15 Quality of drilled samples with the aid of 15 W laser and feed rate of 16 μm/s by a diamond bit with DI water as the coolant

Figure 9.16 Quality of drilled samples with the aid of 25 W laser and feed rate of 16 μm/s by a diamond bit with DI water as the coolant
9.4 Conclusion and Future Work

Carbon fiber composites have widely emerged into industries such as automotive and aerospace since they display many desirable properties. Cutting the pieces made from these types of materials are challenging. Drilling hole as a necessary process is commonly applied to products made out of carbon fiber composites. Delamination and rapid tool wear are two significant drawbacks of drilling carbon fiber composites reported in the literature by many researchers. Thrust force is responsible for delamination, at least for the exit side of drilled holes. In this chapter, it was shown that the LADD process can decrease the thrust forces that not only decrease the delamination but also increase the tool life. It was also discussed and supported with the microscopic images that in LADD the quality of the final product can be deteriorated by melting the epoxy that holds the fibers together. However, since in this technique cutting fluid can be used, DI water is used as a coolant to control the heat during the process. Results showed that the specimen drilled with the aid of laser while DI water was used as coolant represents high-quality edges with no sign of delamination or heat effects. For laser power more than 20 W, the heat was too high and caused the epoxy to melt. Therefore, although using higher laser power decreases the forces significantly, it can melt the epoxy and needs to be controllable with the aid of a coolant. For future studies, other types of composites should be drilled by using the LADD technique. Materials such as Ceramic Matrix Composites with fast growing applications are among the most interested materials to be drilled with alternative techniques. Studying different parameters of the process by using the design of experiments techniques would be beneficial for optimization of the technique.
CHAPTER 10

LASER AUGMENTED DIAMOND DRILLING OPERATION USING A ROTATING TOOL DESIGN

10.1 Introduction

During a regular drilling process typically the drill bit rotates and the workpiece is stationary. Due to the complexity of the LADD process, the tests and studies were carried out by a stationary tool and rotary specimen setup. As the relative motion of the workpiece respect to the cutting tool was achieved, the obtained results were reliable enough to prove the concept. The results achieved by that configuration successfully showed that using laser heating can decrease the cutting forces which helps to preserve the drill bit’s cutting edge and obtain a longer tool life. Edge qualities achieved for two different materials, silicon and carbon fiber composite, were also very promising.

In the industry, a rotational tool setup has more applications and makes the process more versatile. For example, large parts can be processed, multiple holes can be drilled, and even a handheld (or robotic) tool is possible. In the configuration shown in Figure 10.1, a precise spindle is coupled to an integral motor with a hollow shaft. Then, the laser beam passes through the entire setup and then directly to a transparent drilling tool bit. An alternative design is a hollow shaft motor with an acceptable run-out.

In this chapter, the design for a rotating tool configuration of the LADD system and possible options to improve the process are presented. Different components that are designed and
manufactured and their issues, obstacles, possible solutions for future design, and optical and vibration evaluations are discussed.

![Figure 10.1 Schematic of the LADD rotating tool configuration](image)

10.2 Setup Design
10.2.1 Mechanical Design and Spindle

The first component to design for the LADD process is a motor that rotates the cutting tool and has a hollow shaft to pass the laser through. Several motor types and models were investigated that either had a hollow shaft or could be modified to shine the laser through their shaft. One of the major obstacles was their high run-out that could cause wobbling while for drilling the brittle materials, the rigidity of the setup is vital. The second thought was to find a proper air bearing
spindle with small run-out and couple it with a motor. Using the air bearing spindle secures the required accuracy and keep the run-out minimal. A custom-made air bearing spindle was selected and was coupled to a motor with a hollow shaft. A T-Series Air Spindle SS-55 of New Way spindles with the specifications listed in Table 10.1 was selected. A frameless motor made by the Parker Hannifin Corporation was coupled to the spindle.

| **Table 10.1 Specifications of New Way air spindle SS-55** |
|----------------|----------------|
| **Title**      | **Specifications** |
| Size           | 55 mm           |
| Axial load     | 91 (N)          |
| Radial load    | 41 (N)          |
| Axial and radial error motion | 0.1 µm |

| **Table 10.2 Specifications of Optosigma focusing lens used in the setup** |
|----------------|----------------|
| **Parameter**          | **Values**                           |
| Acceptance angle       | ± 1°                |
| Focal length (f)       | 150 mm               |
| Working Distance (WD)  | 131 mm               |
| Laser Damage Threshold | 7 J/cm²              |
| Transmittance          | > 98.5% (1060 - 1080 nm) |
|                        | > 97% (1040 - 1150 nm) |
|                        | > 53% (600 - 700 nm)  |
| Material               | Synthetic fused silica |
| Coating                | Broadband Multilayer Antireflection Coating |
| Design Wavelength      | 1064 nm             |

**10.2.2 Optical Design**

A laser collimator attached to the system provides the laser beam. A lens inside the setup focuses the laser beam to the tip of a diamond drill bit. The selected lens is an Optosigma focusing lens for the fiber laser model HFDLSQ-30-150PF1 with specifications listed in Table 10.2. This type of lens is designed for high performance and is suitable for focusing and collimating solid-
state lasers like Yb fiber laser, YAG laser, and YVO₄ laser. The 150 mm focal distance was chosen based on the distance needed to have the motor, spindle, and then the tool holder. This distance varies with the height of the motor shaft, the spindle, and the adaptors that connect the components in the setup.

To adjust the laser focal point, the lens should be able to move up and down. This feature is necessary as the tools are not identical and also setup might need further modification and also adjustment would be necessary. Finding a proper mechanism for a precise movement, easy to use, and compact was a challenge because this mechanism is not available for general purposes. Therefore, it was designed by the idea of the thread drive mechanism concept. The lens in this mechanism is attached to a disk shaped piece that is threaded on its circumference and works like a screw and large nut with an inner thread holds them. By rotating the nut, the inner disk shape screw moves up and down when it rotates. Making such a mechanism with the traditional method is time-consuming and not precise enough. By using 3D printing, this mechanism was produced to achieve the motion as seen in Figure 10.2. The exploded view drawing of the assembly is shown in Figure 10.3. The whole setup can be mounted to any equipment with controllable vertical motion as shown in Figure 10.4 to perform drilling.

![Custom made 3D printed large screw and nut](image)

**Figure 10.2** Custom made 3D printed large screw (left) and nut (right) to adjust the lens

Since the laser beam is fixed with respect to the setup, the tip of the tool needs to be at the center of rotation. In the current version of the system, alignment achieved by using a fixture and a handled camera. After replacing each drill bit, the new tool should be aligned to make sure that laser will be delivered at the cutting zone. A lack of proper alignment can result in a rapid tool wear, damage to the setup due to laser misalignment, and damage to the workpiece.
10.3 Setup Vibration Analysis

During the initial tests using a rotational tool system, polygon pattern was noticed as shown in Figure 10.5. The first thought was that anisotropy property of the material, single crystal silicon as the pilot material, was the main reason. However, repeating the tests on other types of materials such as carbon fiber composites and soda lime glass showed the same result for that particular rotational speed.
To find the source of this effect a series of tests were performed while the spindle was running to find any vibration or resonance. A four-channel (NI-9234) data acquisition card and M+P International Smart Office Analyzer Software used for performing the tests and analyzing the collected data [186]. An accelerometer was attached to the spindle and data were acquired in order to process. Vibration data for a linear increment of rotational speed from zero to 3000 RPM for one minute gathered is shown in Figure 10.6. Resonance around the 1600 RPM was noticeable that resulted in a polygon pattern during drilling. The second peak in the graph was at around 2500 RPM. No noticeable vibration was detected for higher rotational speeds.
Drilling on carbon fiber composites for different fixed RPMs was performed for 250, 750, 1600, and 2500 RPM as shown in Figure 10.7. As it is expected the noticeable polygon pattern occurred for 1600 RPM and for 2500 RPM a slight pattern was visible as well. For other rotational speeds, no pattern was detected. For the next version of the spindle vibration test should be performed before finalizing the design and air bearing selection.

Figure 10.7 Quality of the holes drilled on carbon fiber composites for a-250, b-750, c-1600, and d-2500 RPM
10.4 Optical Analysis

To evaluate how the designed system optically performs, the optical modeling software Zemax Optic Studio 16.5 was used to model the laser beam propagating through the focusing optics to the image plane. The diamond cutting tool (for this case 1.2 mm thickness) was added into the model, and the beam was focused at the cutting edge of the diamond. For this purpose, the diamond input surface was perpendicular to the beam propagation in order to see how the material impacts the beam shape. Other optic components are neglected in this model as they can be eliminated, but the cutting tool is essential. The detail optical analysis of the system is presented in Appendix A.

10.5 Fiber Laser Delivery

A laser beam is traveling through the air in a straight line. As discussed before the area that laser should cover on the cutting edge is a small range (sub-millimeter) area. Also, the drill bit deflection in the drilling process is unavoidable. In this situation laser delivery through the air (i.e., a hollow tool shank) can be very unproductive. The current design limits the depth of penetration as well, such as the thickness of material and depth of the hole, based upon the geometry of the diamond drill material. The diamond is a component within the optical system, i.e., the last optical element. In different alternative designs for the drill bit, the geometry of the shank and diamond can make it impossible to send the laser efficiently to the cutting zone. A different medium is required to bend the beam to optimize the laser delivery and to transmit through the diamond. The

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2 This section is based on a project in collaboration with LumenFlow Corp. on 2017.
optical fiber is an ideal medium to guide the laser beam. Therefore, the next iteration of the LADD drill bit can be to implement a fiber optic coupler within the drill tool shank. A concept design for using fiber to guide and deliver the beam through the shank is shown in Figure 10.8. As shown in Figure 10.8, the beam can be bent to make sure the laser is entering the diamond. A lens to focus the beam to the fiber is also required, mainly because the shank is rotating, the laser source is stationary (collimator), and the optical fibers diameter is typically small. The total run-out of the shank must be less than the errors in the setup. Therefore, the focal point of the laser beam will remain in the optical fiber cross section area. Otherwise, it will not go through the predetermined path.

Figure 10.8 Fiber laser delivery through the tool shank
Rotary joints or slip rings for single fibers are widely available in the market. These types of joints are usually limited in the RPM that they can handle. For multi-edge drilling tools, different types of rotary joints are needed. A multi-channel rotary joint can be used to send a multi-laser beam for a multi-drill bit design. There are designs available in the market mainly used for communications networks and optical fiber [187].

10.6 Conclusion

The LADD is an under-development technology for drilling of hard, brittle, and challenging materials. It is a hybrid process that combines the mechanical cutting (i.e., a diamond drill) and laser heating to soften the material which reduces the hardness and brittleness of the workpiece. For the first time a rotating tool configuration of the LADD system is presented in this chapter. Optical analysis of the system shows that the laser power reduction is not significant, i.e., the optical transmission is adequate (but not yet optimized). For an ideal double edge tool design, an optical evaluation has been performed (in Appendix A). Also, the problems and possible solutions were identified.

Splitting a single laser beam into two beams and beam shaping the focused spot to have a line shape is undoubtedly possible. This can be achieved via optics by using a pair of cylindrical lenses with a flat backing plate and a doublet. The other possible option is using fiber to guide and deliver the laser beam through the tool shank. This method has the advantages of ability to guide and deliver the beam precisely at the tip of the tool and the variety of the tool design that can be used for the LADD technique. The next generation LADD system with a rotational double-edge bit and the stationary workpiece can also be achieved. However, this would require a carefully designed diamond cutting tool surfaces and optimized optical components. Although the power
density can be reduced for different types of materials, a laser source with higher output power or a smaller beam spot size is required if it cannot.
CHAPTER 11

SUMMARY, CONCLUSION AND FUTURE WORK

Advanced materials have superior properties that make them an ideal choice for high tech technologies. Materials such as ceramics and composites are challenging to cut. They are designed and produced to endure the severe conditions such as high temperature, wear, a corrosive environment, and/or high applied stresses. Traditional material processes such as turning, milling and drilling and even nontraditional such as EDM, water jet, ultrasound machining, and laser ablation are not able to process these materials. In this work two processes were studied and results were presented in separate chapters. Part A of this dissertation was focused on the Micro Laser Assisted Machining (μ-LAM) technique. A new process to drill hard, brittle, and difficult to cut materials using the Laser Augmented Diamond Drilling (LADD) was introduced in part B.

In part A, a combination of laser softening and SPDT on the machining of different materials was discussed, and experimental results were analyzed and discussed. In chapter 3, the unpolished side of the single crystal silicon wafer was successfully machined with the aid of μ-LAM combined with the SPDT and the results showed that the surface finishes improved significantly. The tool wear decreased considerably due to using the laser and thermally softening the materials but wear should be minimized to have a more efficient process, as was discussed. Different laser wavelengths were utilized to cut a silicon sample, and the results showed that using a laser wavelength that material absorb better, can enhance the process. It should be noted that material under pressure has different optical properties and that phase of the material determines the suitable wavelength.
For the first time cutting fluid was used to enhance the process and the results showed that the technique with the aid of the cutting fluid was successful in improving the surface finish of unpolished silicon wafers. Significantly less tool wear was noticed when the cutting fluid was used. Surface roughness of Ra = 83 nm was obtained with the aid of DI water as the cutting fluid. The Ra for the sample machined with no laser but still used the cutting fluid was 376 nm. The effect of a combination of laser and cutting fluid on surface roughness was obvious and promising.

Chapter 4 was focused on the SPDT of the optical grade single crystal silicon (111) as a different grade material than the previous chapter. The Ra was brought down from 770 nm to 3.2 nm in an optimal parameters condition. Radial spokes that occur during the machining of single crystal silicon because of the crystallographic orientation effect were “healed” and eliminated. The effect of the rake angle on the surface finish was also studied. A rake angle of -25 degrees, rather than -45 degrees, for the cutting tool in the diamond turning assisted with a laser for optical grade silicon (111) resulted in a better surface finish.

In chapter 5, the anisotropy effect and ductile mode cutting of the monocrystal C-plane sapphire (by using the µ-LAM technique) were studied. Results showed that for specific directions using and increasing the laser power increases the depth of cut. However, excessive laser power may cause more fracture (probably due to thermal stresses), which is usually an unwanted result where a smooth surface is the goal. The opposite may be true if a high material removal rate is desired.

The DBT tests were also performed for different directions, and it showed that the laser heating also increases the ductile depth. However, for different directions the depth increase was varied. Even though the deepest cuts were achieved in the [itics100] direction in constant load experiments, analyzing the images showed that it was mainly due to the fracture that occurred
during the cutting operation. Also, it was observed that increasing both laser and thrust load can cause more fracture. No noticeable tool wear was observed under the microscope (400X) as the total tool cutting track was minimal. The underlying resultant plastic deformation mechanisms reported in the literature of microscopic and macroscopic scale are presumably different, but more investigation is needed to verify it.

In chapter 7, part B, it was demonstrated that drilling the single crystal silicon (100) in a ductile regime with higher edge quality is possible. Results indicated that laser power selection is crucial in this process and by choosing an optimized drilling condition it is possible to achieve high-quality holes in a brittle and crystalline materials. It was also shown that by using this system, it is possible to drill brittle materials with minimal damage. Ductile chips observed after drilling is an indication of the ductile mode cut.

The main benefit of using a hybrid process that uses the laser softening is lower cutting forces associated with the process. To show how cutting forces can be decreased by using laser, chapter 8 was mainly focused on monitoring cutting forces during the LADD process. Single crystal silicon, as a typical nominally brittle material, was tested by using different laser powers, cutting fluids, and feed rates. Results showed that by using the LADD technique, the cutting forces are lower due to laser heating and thermal softening. Less cutting force helps to preserve the drill’s cutting edge and therefore obtain a longer tool life. Evidence of the ductile regime/mode cut of silicon is observed in microscopic images. However, due to tool geometry and the fact that a compression and shear stress are needed to achieve a pure ductile mode cut, in some cases a mixed brittle and ductile mode cut occurred. The Raman spectroscopy was performed on the samples, and it showed that material healed due to using laser heating, and no amorphous material was left on the cutting area.
In the next chapter, chapter 9, cutting forces were also monitored for the carbon fiber composite. Delamination and rapid tool wear are two significant drawbacks of drilling carbon fiber composites reported in the literature by many researchers. Cutting forces, and more specifically thrust force, are responsible for delamination on the exit side of the drilled holes. In this study, it was shown that the LADD process can decrease the cutting forces that not only decrease the delamination but also increase the tool life. It was also discussed and supported with the microscopic images that, in the LADD, the quality of the final product can be deteriorated by melting the epoxy that holds the fibers together. However, since in the LADD process cutting fluid can be used, DI water is used as a coolant to control the heat during the process. Results showed that the specimen drilled with the aid of a laser while DI water was used as coolant represents high-quality holes with no sign of delamination or heat effects.

In chapter 10, a rotating tool configuration of the LADD system was presented and discussed. For an ideal double edge tool design, an optical evaluation has been performed and problems and possible solutions identified. The other possible option was to deliver the laser beam to the cutting zone that discussed in this chapter was using the optical fiber. The advantages of this method for the LADD technique were discussed as well. For the future study of the LADD process following topics are proposed. By making a few changes, these topics are applicable for further investigation of the μ-LAM process as well.

**Parameters**

Different parameters play a role in the LADD process and not yet been studied. Varying the laser power and feed/RPM relative to the depth of the hole (including entry and exit considerations) is a potential area of interest. Laser power, along with drill feed rate and RPM, are
maintained constant during the hole making process. Studies discussed in this dissertation indicated that varying laser power and cutting RPM and feed rate can affect the overall process and subsequent results. By using methods such as the design of experiment (DOE), various combinations of these input parameters can be investigated. It is possible that changing the laser power and feed rate during the drilling process may be advantageous. For example, the testing of ceramic materials has indicated that using the laser to preheat the material before drilling may be beneficial in pre-softening the material. Similarly, a reduced entry and exit force resulting from a lighter/lower feed rate may decrease the delamination. The ability of LADD to adjust two process parameters, drill feed/RPM, and laser power, to achieve best results is the basis of the proposed future experimental work.

**Materials**

Many other materials can be investigated to show the benefits of the LADD process. Ceramics such as zirconium dioxide, silicon nitride, silicon carbide, aluminum oxide, etc. are the materials with many applications, but are very difficult to drill by conventional methods. Composite materials also can be the other target materials that benefit from the LADD process. Carbon fiber composites with different layer formation and also difficult to cut ceramic matrix composite are among the materials that can be investigated. For the composites used to evaluate material responses, samples of each layer can be drilled independently to evaluate the response of individual layers in the composite structure to the LADD process. The layer results will inform the eventual work with respect to varying the drilling/laser parameters (speed, feed, and laser power) relative to the depth of penetration into each layer in the composite structure.
Laser Sources

A laser is the heat source of the process and the only laser types used so far were IR and green laser with 1070 nm and 532 nm wavelength respectively. However, different wavelength lasers can be used to optimize material interaction and study the beneficial heating effect. The power range also can be different, and for example, higher laser powers can be used for faster material processing (i.e., increased speeds and throughput) and potentially can lead to a larger diameter and deeper holes. The laser beam profile used for the current work was in the Gaussian form. The cutting edge is straight, and the beam should be shaped. Laser beam shaping to a top hat and/or oval can optimize and enhance the drill – hole making process. The type of laser that is studied so far was the CW, a pulsed laser to enhance material interaction can also be used.

Cutting Fluid

In any mechanical cutting process, the cutting fluids play a significant role. Lubricating properties of them can reduce the torque but not the thrust forces associated with drilling and may chemically interact with the surface. Oil based and water based cutting fluids used in the studies were discussed in this dissertation. However, many other fluids can benefit the processes studied in this dissertation. Chemically active cutting fluids such as CMP slurries can modify material properties and make the cutting process easier.

Acoustic Emissions

Acoustic Emissions (AE) sensing technology can also be utilized to detect brittle fracture events (i.e. crack initiation and propagation) and delamination in drilling brittle materials. Previous research [79] has shown that AE is sensitive to fracture damage events, and that through appropriate filtering the signals can be correlated to the location and extent of the cracks. This
technique can be useful for evaluating entry/exit hole fracture events and occurrences of
delamination in-situ.

**Simulation and Modeling**

Using an advanced modeling software to explore the precision drilling of different
materials such as ceramics and composite structures is also a potential research topic. One possible
approach can be a collaboration with simulation companies to investigate the process further.
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APPENDIX A

A.1 Optical Analysis of Rotational Tool Design

In this appendix performance of the LADD rotational tool designed system optically is evaluated. The optical modeling software Zemax Optic Studio 16.5 is used to model the laser beam propagating through the focusing optics to the image plane. This is shown in Figure A.1, where the layout of the focusing optic and beam is shown as well as a 3D surface plot of the irradiance. The irradiance shows a Gaussian-like profile, as expected.

The diamond cutting tool (for this case 1.2 mm thickness) is then added into the model, and the beam is focused at the cutting edge of the diamond. For this purpose, the diamond input surface was perpendicular to the beam propagation, in order to see how the material impacts the beam shape. Figure A.2 shows the 2D cross-sectional view of the irradiance at the output plane. The beam is symmetrical and circular, and there is 30% reduction of the laser power due to absorption, reflection, and scattering. Other optic components are neglected in this model as they can be eliminated while the cutting tool is essential.

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3 This section is based on a collaboration project with LumenFlow Corp. on 2017
Finally, the diamond is rotated by the angle given in the CAD data to see how the beam performs when in use. The relatively high index of the diamond refracts the beam strongly before exiting the output surface near the tip of the diamond as shown in Figure A.3. The irradiance of this configuration is shown in Figure A.4 for both the 2D and 3D representations. It is observed that the beam profile becomes elliptical, which is caused by the asymmetry in the beam path. This means that the power delivered to the target material is slightly uneven, although the deviation from the symmetrical circular profile is not significant.
The layout of the diamond, as tilted to the angle specified in the CAD.

3D (left) and 2D (right) beam profiles at the focus when the diamond is tilted, the profile exhibits an elliptical shape due to the asymmetry of the beam path.

A.2 Polarization Dependence of Laser Delivery

A key point in the analysis of the current LADD system is the polarization-dependent delivered power. Since the laser beam is incident on the diamond at an angle much larger than 0°, the reflection coefficients are different for different polarizations. In Figure A.5, two linear polarizations labeled $x$ and $y$ are shown. For $x$-polarization, the delivered power is 51.1W, while for $y$-polarization the power increases to 83.5W. This significant difference in delivered power.
highlights the importance of laser polarization and how it can impact drilling performance. One solution to this problem is to design diamond with a flat back side.

Figure A.5 A perspective view of the diamond cutting tool showing the linear polarizations along the short axis (x-polarization) and along the long axis (y-polarization)

A.3 Splitting Laser Beam for a Double Edge Tool Configuration

Specifications to be met in the next design:

1. Two diamond edges are to be irradiated by the laser.
2. The irradiated area has a length of 0.25 mm to 5 mm and a diameter (width) of 50 µm to 100 µm.
3. The desired irradiance ranges from 5-100 GW/m².
4. The diamond cutting tool is rotating.
5. The laser type and diamond material remain the same.

To meet the design criteria, it was recommended the general configuration seen in Figure A.6, where two cylindrical lenses are used to split the beam in one axis while a doublet focuses the beam in the other. This configuration allows for the “line” beam shape that is desired along the
diamond edge. The specifics of this configuration (such as lens radii, thickness, tilt, positioning) are dependent on the distance to the diamond edge, the surface angles of the diamond tool and the shank dimensions, etc.

Figure A.6 The recommended general configuration for splitting a single laser beam into two "line" profile beams. This configuration consists of two cylindrical lenses (leftmost), a flat backing plate (middle), and a doublet (right)

The impact of the different focusing on the two axes is shown in Figure A.7. Along the cylindrical lenses axes, it has been seen that the incident beam is split into two beams that have an intermediate focal point that occurs before the final focus at the diamond tip (Figure A.7, left). On the other hand, a view of the other axis indicates that only one focal point occurs at the tip of the diamond cutting tool (Figure A.7, right). This optical configuration allows for two distinct line beam profiles to form, as will be seen in the following section.
Figure A.7 The recommended general configuration with propagating rays. On the left, a "top" view is shown where the beams can be seen splitting, and on the right a "side" view is shown which shows the rays focusing down to the diamond tip.

A.4 Evaluation of Double Edge Diamond/Shank Configuration

An ideal configuration for a double edge drilling tool was designed and then evaluated to find the problems and possible solutions. The shank is approximately 100 mm in length and is shown in Figure A.8. For the diamond cutting tool, a V-shaped notch is formed by the centers of the diamond. Each diamond cutting tool is approximately 5.3 mm in length and 0.86 mm in depth.

One issue with implementing this with the optical design recommendation is that opening in the shank that allows the laser to focus on the diamond is insufficient. The first issue was that the opening was not large enough; it should be around 12 mm in diameter to enclose the cone of light fully. In Figure A.8, it was observed that the light that does not enter the opening was reflected a focal point behind the optical system. The second issue was that the opening does not taper to accommodate the light rays. This results in rays that reflect off the shank at various angles and leads to much less delivered power to the diamond edges.
Then the shank was removed from the model to see how the recommended optical configuration performs. In Figure A.9, the system is shown where a detector has been placed at the focal point, and the diamond has been ignored so the base system performance can be seen. The detector allows viewing the irradiance of the focused laser beam, as seen in Figure A.10. Here it can be seen that two very narrow line profiles were formed by the optical configuration. These narrow beam profiles were about 4.5 mm in length and 25 µm in diameter.

The peak irradiance for the model was 1.04 GW/m². In general, it can be approximated the amount of irradiance $E$ in a beam spot by:

$$E = \frac{P}{A},$$  \hspace{1cm} (A.1)
where $P$ is the delivered power, and $A$ is the beam spot area. By using the specified beam spots along with the best and worst-case scenario of delivered power, the irradiance has been calculated and notated in Table A.1. From this table, it can be seen that none of the combinations of delivered power and beam spot area provide the minimum specifications of $5 \text{ GW/m}^2$, except for the smallest beam spot size with most considerable delivered power.

![Figure A.9 A view of the optical system with propagating rays when the diamonds are shown but not considered. The rays focus to a line profile where a detector is placed.](image)

Figure A.9 A view of the optical system with propagating rays when the diamonds are shown but not considered. The rays focus to a line profile where a detector is placed.

![Figure A.10 The detector view of the laser beam at the focus. On the left, the whole detector area is shown, and on the right, a zoomed-in area is shown. The diameter of this beam is about 25 µm.](image)

Figure A.10 The detector view of the laser beam at the focus. On the left, the whole detector area is shown, and on the right, a zoomed-in area is shown. The diameter of this beam is about 25 µm.
The diamond cutting tools were then considered in the model, and it was observed the behavior of the rays as seen in Figure A.11. The rays appear to undergo total internal reflection (TIR) on the inside surfaces and exit at the input surface with some angle. In this configuration, every ray was TIR out of the diamond, meaning that no power was delivered to the target material.

Table A.1 Calculation of the beam irradiance at the focus. The only configuration that meets the 5 GW/m² minimum irradiance is the 0.25 mm × 50 µm spot size with 90W delivered power.

<table>
<thead>
<tr>
<th>Beam length</th>
<th>Beam width (diameter)</th>
<th>Irradiance with 50W delivered power (W/m²)</th>
<th>Irradiance with 90W delivered power (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm</td>
<td>100 µm</td>
<td>1.0 × 10⁸</td>
<td>1.8 × 10⁸</td>
</tr>
<tr>
<td>5 mm</td>
<td>50 µm</td>
<td>2.0 × 10⁸</td>
<td>3.6 × 10⁸</td>
</tr>
<tr>
<td>0.25 mm</td>
<td>100 µm</td>
<td>2.0 × 10⁹</td>
<td>3.6 × 10⁹</td>
</tr>
<tr>
<td>0.25 mm</td>
<td>50 µm</td>
<td>4.0 × 10⁹</td>
<td>7.2 × 10⁹</td>
</tr>
</tbody>
</table>

Figure A.11 The diamond cutting tool and the light ray propagation is shown. The light rays appear to reflect on the inside surfaces of the diamonds, which causes them to exit the diamond at the input surface. Note that OpticStudio terminates rays that do not intersect any object, and therefore the rays seem to end in free space.
Upon further investigation, these rays TIR reflect at the steep (~65°) angled surface and the shallow (~25°) angled surface and then exit at the input surface. It is important to note that the rays were converging in both the X and Y axes; this means that both the “V” angle (Figure A.12, left) and the input surface angle (Figure A.12, right) are factors in the TIR that is occurring. It is imperative to eliminate this TIR to deliver laser power to the target material. Therefore the design of the diamond tool surfaces, as well as the optical components, are critical in this system performing correctly. With the current diamond cutting tool CAD and the recommended optical configuration, there was no power being delivered because all the rays reflect out of the diamond input surface.

Figure A.12 A "top" view (left) and "side" view (right) of the TIR of one ray that enters and exits the diamond cutting tool

To elaborate on how crucial the input surface is, it should be referred to Figure A.13. Here it can be seen a laser ray enter the diamond and TIR from the steep and shallow angled surfaces and exit the input surface. This situation is similar to the current design seen in Figures A.11 and A.12 but only considers one axis. To alleviate this issue, the surface could be angled differently such that the ray refracts away from the steeply angled surface and strikes the shallow surface. Because this ray now strikes the shallow surface at an angle that is below the TIR critical angle, the ray is not reflected and is delivered to the target material.
Figure A.13 Two different diamond shapes that result in TIR (left) and refraction (right). Refraction is desirable at the output surfaces so that optical power is delivered to the material target. Note that this figure is only an illustration and is not to scale, nor necessarily the correct solution to eliminating TIR.
APPENDIX B

List of publications related to this dissertation:

1- Mohammadi, H. and Patten, J. A. (Nov. 2017). Laser Augmented Drilling Operation Using A Rotating Tool Design, 32nd Annual Meeting of the American Society for Precision Engineering (ASPE), Charlotte, NC, USA (Relates to Chapter 9)


7- Mohammadi, H., & Patten, J. A. (2015), Micro-Laser Assisted Drilling Of Single Crystal Silicon in Ductile Regime, 30th Annual Meeting of the American Society for Precision Engineering (ASPE), Austin, Texas, USA. (Relates to Chapters 6 and 7)


