Laser Augmented Diamond Drilling: A New Technique to Drill Hard andBrittle Materials

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Abstract
Laser Augmented Diamond Drilling (LADD) is a new technique to drill hard and brittle materials. It utilizes a laser that is focused through an optically transparent diamond bit to drill the workpiece. The laser decreases the hardness and brittleness of the material by heating and thermally softening, and also increases the tool life. Single crystal silicon (100) has been used as the working material in this research. It has been demonstrated that using the LADD process can improve the quality of entrance edge of the drilled holes as well as their inner surface finish. Resulting surfaces and chips (machining debris) show evidences of ductile mode cut.

Keywords: Drilling, Laser, Diamond, Laser Augmented Diamond Drilling, LADD, Silicon, Ductile Mode, Brittle Mode, Surface Finish, Edge Quality

1 Introduction

Drilling hard, brittle and difficult to machine materials is often a challenge. Materials such as ceramics, semiconductors and composites have a variety of applications and often they need to be drilled to a high level of precision and accuracy. Due to these materials’ low fracture toughness and high strength, it is very challenging to drill holes free of fractures, surface and subsurface damages, cracks and micro-cracks, with good edges and high surface quality. Their high hardness and strength causes rapid tool wear that not only decreases the drilling efficiency, but also increases the downtime of the process. Drilling materials such as composites and carbon fiber reinforced plastics/polymers (CFRP) is also very challenging due to their material properties and rapid tool wear (Che, et al., 2014) and (Wang, et al., 2013). Therefore the cost of drilling of mentioned materials is usually high and processes available for this purpose are expensive. There are many drilling techniques available to

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generate micro/macro holes in brittle materials such as conventional and mechanical methods (Egashira & Mizutani, 2002) and (Moon, et al., 2014), nonconventional methods such as electrical discharge machining, laser machining, waterjet, and ultrasonic machining (Jahan, et al., 2012), (Tan, 2005), (Rashed, et al., 2013), (Gill, et al., 2009), and (Ziki & Wüthrich, 2015). However, some of these processes are limited in cost, machining efficiency, dependence on the material properties, and achievable aspect ratio. Laser drilling is another process for making holes in the hard and brittle materials as it is a non-contact process and able to drill almost any material. However this process suffers from hole inaccuracy, tapered holes, redeposited material, micro cracks due to thermal stresses and heat effected zone (Samant & Dahotre, 2009), (Wu, et al., 2014), and (Meunier, et al., 2003). For silicon in particular, mechanical drilling causes edge chipping due to low fracture toughness of the material (Egashira & Mizutani, 2002). A process that is able to drill these hard and difficult to machine nominally brittle materials with no, or minimal fracture and with minimal tool wear is in high demand by industry.

The Laser Augmented Diamond Drilling (LADD) technique is a new technology for drilling of hard and brittle materials. A laser beam is focused through a diamond tool/tip to drill the workpiece. 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. The LADD can increase the material removal rate (MRR), decrease the tool wear, improve the edges and surface finish, and minimize or eliminate sub-surface damages occurring during the drilling process. A schematic of this technique is shown in Figure 1.

Machining hard and brittle materials such as semiconductors and ceramics is considered a high cost process, which is mainly due to many parameters such as expensive tools, high tool wear, long machining time, low production rate, etc. The low production rate is primarily due to the occurrence of surface/subsurface damages, i.e., cracks and brittle fracture. However, ductile mode machining is considered to be one of the acceptable machining techniques to shape this type of material. Ductile mode machining of semiconductors and ceramics is possible due to the High Pressure Phase Transformation (HPPT) occurring in the material (Blackley & Scattergood, 1994), (Morris, et al., 1995), (Leung, et al., 1998), (Arif, et al., 2012), (Yan, et al., 2004), (Patten, et al., 2003), (Patten, et al., 2005), and (Dong & Patten, 2007). To further augment the ductile response of these materials, in our previous works (Ravindra & Patten, 2011), (Mohammadi, et al., 2014a), (Ravindra, et al., 2012), (Mohammadi, et al., 2014b), (Mohammadi, et al., 2015a), and (Mohammadi, et al., 2015b), the Micro Laser Assisted Machining (µ-LAM) system was used to preferentially heat and thermally soften the workpiece material in contact with a diamond cutting tool. This hybrid method can potentially
increase the critical depth of cut, i.e., a larger ductile-to-brittle transition (DBT) depth, in ductile regime machining, resulting in a higher MRR.

This current experimental study is focused on proofing the concept and evaluating the benefit of using the LADD on the entrance edge quality and inner surface roughness of drilled holes. Therefore a dimple shape hole is produced in the workpiece for each test, as shown in Figure 2. 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), which makes it difficult to drill precise holes, free of fracture.

![Figure 2: Cross sectional illustration of a dimple shape hole (diameter depends on the depth)](image)

### 2 Experimental Procedure

The LADD system is coupled to a reconfigurable Universal Micro-Tribometer (UMT) which is a load and position controlled device to perform the drilling tests as shown in Figure 3. An IR CW fiber laser with 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 +45° clearance angle was used for the drilling operation, as shown in Figure 4. The laser beam was guided through a single mode 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 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 tool.

![Figure 3: LADD setup used for the tests](image)
First a series of drilling tests were carried out by using a load cell (shown in Figure 3) for monitoring the load and cutting forces. Although the UMT 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 it did not control the process (by holding a constant force during the drilling operation). The programmed depth was 40 μm and the other drilling conditions are summarized in Table 1. The actual laser output after going through the diamond bit is about 40-50% due to scattering, reflection, etc. The chip thickness in this cutting process, based on the machining condition in Table 1, is 120 nm/rev.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Rotational Speed</td>
<td>1000 RPM</td>
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<tr>
<td>Feed rate</td>
<td>2 μ/s</td>
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<tr>
<td>Laser power</td>
<td>0, 10, 20 W</td>
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<tr>
<td>Depth</td>
<td>40 μm</td>
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Table 1: Drilling parameters for the first series of tests

3 Results and Discussion

Imaging the drilled holes in the first series of tests showed non-circularity and fractures on the entrance edge. For the no laser case as shown in Figure 5a, by comparing the resulting edge to an ideal circle (yellow dashed circle), non-circularity is apparent. By comparing the images, circularity was improved by using the laser, although the edge chipping still occurred as shown in Figure 5b,c.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 radii of these two circles is used as the circularity error. Figure 6 is the graph of the circularity error and the effect of using the laser. For the no laser case, this error was 12.79 μm, while for the 10W and 20W laser cases 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 like a spring in the force loop of the setup. Therefore to increase the stiffness, the load cell was removed from the setup.

![Figure 5: Edge entrances quality a: without laser b: 10W laser c: 20W laser compared to an ideal circle](image)

By repeating the tests, without the load cell in the force loop, a very clean entrance edge with an improved circularity (error of $\ll 1$ µm) was achieved. As shown in Figure 7, the edge of the drilled holes shows no evidence of chipping. Compared to $\mu$-LAM used for turning (Ravindra, et al., 2012), (Mohammadi, et al., 2014b), (Mohammadi, et al., 2015a), and (Mohammadi, et al., 2015b), the laser power for drilling, occurs at one spot, drill point/tip, in one direction (feed) through the workpiece. Too high of a laser powers could cause thermal cracks and even burning, which would result in a rougher surface. As shown in Figure 8a by using 10W laser power, the machined surface shows that ductile 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 30W improved the surface and little sign of brittle mode was visible (Figure 8b), however an excessive laser power, 40W, burned the surface (Figure 8c). Burning of the surface is dependent on the type of material (absorption, heat capacity, etc.) that is drilled, laser power used, energy density (laser power over the beam spot size) and machining condition i.e. coolant (not used in this study), RPM, etc. Therefore an optimization of theses parameters is needed to achieve acceptable and the best results.
Figure 7: Edge entrance quality after increasing the rigidity of setup compared to an ideal circle. a: No laser, b: 10W, c: 20W.

It is known that to achieve HPPT in silicon a hydrostatic pressures in the range of 10-13 GPa is needed (Needs & Mujica, 1995). Increasing the depth of cut can result in more fracture, as the tool has more contact with the workpiece along the cutting edge. In a second series of experiments an 80 µm depth of cut with drilling conditions summarized in Table 2 was performed on the silicon sample. Surface roughness was measured by using a WYKO white light interferometer. To be able to obtain the Ra, surfaces were flattened by the software and an average of the measured Ra is reported.

Figure 8: Resultant surface after removing the load cell with a: 10W, b: 30W, c: 40W laser power.

A sample was drilled without aid of the laser (0W) and the image is shown in Figure 9a. A rough surface with an average surface roughness of 127 nm was achieved for this sample. The dark areas on the surface are fractures, pit and voids, caused by the cutting process. It can be interpreted that as 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, although the chip
thickness was same as first test series, 120 nm/rev, the critical depth of cut - a depth where a ductile to brittle transition happens - was smaller than previous test condition (the test series with 40 µm drilling depth) as a longer length of tool’s cutting edge is in contact with the material. From previous works (Mohammadi, et al., 2014a), (Ravindra, et al., 2012), (Mohammadi, et al., 2014b), (Mohammadi, et al., 2015a), and (Mohammadi, et al., 2015b) done on silicon it was expected that by using a laser the critical depth of cut would increase, i.e., the same drilling conditions, feed rate and RPM, less brittle mode happens. The same experiment using 10W laser showed partially brittle mode cut, Figure 9b, and lower average of roughness of 83 nm. Using 20 and 30W laser power improved the surface finish to Ra to 73 and 60 nm respectively by decreasing the brittle mode and fractures, refer to Figures 9c and 9d. The diagonal pattern of partially brittle mode in the sample drilled with 30W laser power, Figure 9d, is in agreement with the results reported by Randall, et al. (2009) 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 decreases the brittleness of the material and reduces brittle fracture.

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<td>Depth</td>
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Table 2: Drilling parameters for second series of tests

![Figure 9](image_url): Surface quality drilled with a: No laser b: 10W c: 20W and d: 30W laser power
The diagram depicted in Figure 10 shows a reduction of 53% of the surface roughness for the sample drilled with 10W laser power, compare to no laser case. Roughness reduction of 74% and 112% were achieved by using 20 and 30W laser powers respectively. The areas machined in brittle mode in which pull-out happened are mainly responsible for the rougher surface, thus the improvement of the surface finish is because of less brittle mode material removal. Therefore applying the laser helped to decrease the brittle mode cut and helped to perform the machining in the ductile mode.

![Figure 10: Effect of using the laser on reduction of surface roughness](image)

To help to visualize the cut 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 11 are correlated with the surfaces of Figure 9. The blue areas in Figure 11a 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 aid of 10W laser power, Figure 11b. In Figure 11c the surface is smoother but there is an uneven area in middle of profile which is correlated to the brittle mode cut ring in Figure 9c. A smoother surface can be seen in Figure 11d with small imperfection.

![Figure 11: 3D profile of machined surface with a: No laser b: 10W c: 20W d: 30W laser power](image)
Ductile chips are also an evidence of the ductile mode cutting 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 HPPT is unattainable (Morris, et al., 1995). In the drilling process of the silicon, ductile chips were observed which were generated by plastic deformation happening during the drilling process. As shown in Figure 12, continuous chips, with ~50μm length, obtained in a case where 30W laser power was used. However, further investigation is needed to study these chips and to show their structural changes due to the HPPT and laser heating.

Figure 12: Ductile chips achieved in ductile drilling of the silicon

4 Future Work

The LADD process will be investigated further and for this purpose it will be used for drilling different types of materials such as ceramics, composites, and rocks. The effect of other parameters such as rotational speed, laser power and feed rate will be investigated as well to have a better understanding of the process. Studying the tool wear and use of cutting fluid to possibly further improving the surface finish and decreasing the tool wear are other possible aspects of the process to be investigated. Through holes and exit side analysis is currently ongoing.

5 Conclusion

The LADD process is a new technique to drill hard and brittle materials. In this paper it was demonstrated that making precise holes on single crystal silicon (100) in ductile regime with higher edge quality is possible due to using laser, compared to the case drilled with no laser. 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 silicon. It was also shown that by using this system, 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 process 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 assisted 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 will achieve similarly beneficial results.
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References


