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Article 6

Quality Improvement in Drilling Silicon by Using Micro Laser Assisted Drilling

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The micro-laser assisted drilling (μ-LAD) of monocrystalline silicon (100) using a diamond cutting tool coupled with a laser was tested in order to improve the cutting edge quality of drilled samples. The laser beam is transmitted through an optically transparent diamond drill bit and focused precisely at the tool-workpiece interface, where the material is under high pressure induced by the diamond tool. This essay presents the investigation of the influence of the laser power on the quality and inner surface finish of the drilled materials. Different laser powers were used to carry out the experiments. The experimental results indicated that the μ-LAD tests were successful in making precise holes in the silicon (100) samples with high edge quality, when comparing the holes made by a laser to the holes created through other methods.

Introduction

In machining, making high quality products is very important as it can affect their function. In drilling in particular, edge quality and circularity of the holes are important factors. Mechanical properties of the material can make drilling more challenging. Hard and brittle materials such as ceramics and semiconductors have many desirable properties that make them ideal for many applications, but for the same reason make them more challenging to cut, compared to metals for example. Due to the hardness of these materials, the cutting tool gets worn very fast; due to the brittleness of these materials, edges chip away and sometimes cracks appear on the holes' edges. Although drilling is an established process, it has many limitations. Current conventional methods such as mechanical drilling and non-conventional techniques such as laser drilling, micro-electrical discharge machining (micro-EDM), photo-etching, ultrasonic, and micro-electrical chemical machining (micro-ECM) have limitations (Egashira & Mizutani, 2002; Jahan, Wong, & Rahman, 2012; Moon et al., 2014; Rashed et al., 2013; Ziki & Wüthrich, 2015). Mechanical drilling is limited by the hardness of the tool that can be used. The thermal stability and wear resistance of the conventional drilling tools are significantly reduced above high temperatures because of material properties (Tönshoff, Spintig, König, & Neises, 1994). Even diamond, as the hardest material known, gets worn depending on the hardness of the workpiece material. Researchers have studied the errors in mechanical drilling for many years. V. Schulze et al. (2010) examined conventional mechanical drilling errors and surface damages of a glass fiber workpiece reinforced with composites. Non-conventional methods such as laser drilling suffer from inaccuracy and unwanted thermal effects. Other processes such as EDM or ultrasonic are limited to certain types of material that they can drill.

Micro Laser Assisted Drilling (μ-LAD) is a new technique to drill hard and brittle materials introduced and under study at Western Michigan University, Nano Manufacturing Laboratory. In μ-LAD, as shown schematically in Figure 1, the laser beam is transmitted through an optically transparent diamond drill bit and focused precisely at the tool-workpiece interface, where the material is under high pressure induced by the diamond tool. The laser softens the material under the tool, which leads to lower cutting forces and therefore lower tool wear and longer tool life.

It has always been a challenge to drill brittle and hard materials such as ceramics and semiconductors free of fractures, damage, cracks, and micro-cracks, with good edges and high surface quality, due to these mate-

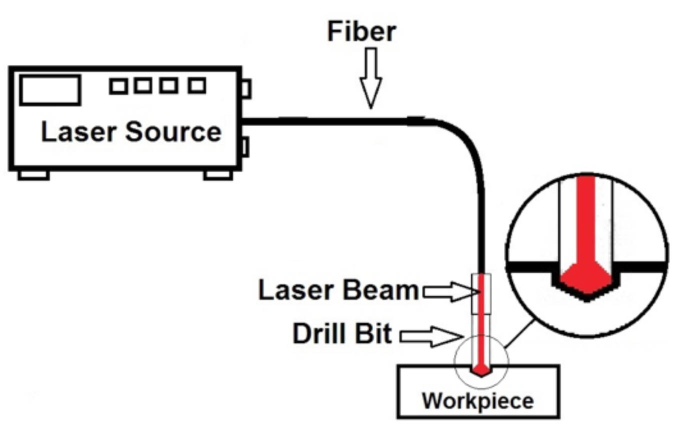


Figure 1. Schematic of μ-LAD process

rials' low fracture toughness. Often, severe fracture can result due to their low fracture toughness. The μ-LAD technique allows the drilling of brittle materials without fracture.

Using the laser assisted technique to machine hard and brittle materials is reported in literature. Mohammadi et al. (2015) used the micro laser assisted machining (μ-LAM) technique to machine and improve the surface finish of silicon. Ravindra et al. (2012) used the same technique for scratching the silicon with and without using lasers and studied the high pressure phase transformation (HPPT) on the material. In Mohammadi et al. (2013), they studied the effect of using a visible laser wavelength, green, on scratching the silicon.

The focus of this study is on micro drilling of single crystal silicon (100), which is a very brittle and hard to drill material by conventional methods. This article will discuss the effects of using a laser on process outputs such as edge quality and surface roughness of the wall of drilled holes. For this purpose, a number of tests with different setups have been carried out to find the best drilling condition. Since this process is in the early stages and under study, measuring the cutting forces is essential to control the amount of load on the diamond cutting tool. Even though diamond is a very hard material, it is a very fragile material, especially at the sharp cutting edge. Monitoring the forces during the testing helps to ensure that the tool is not damaged.

Experimental Setup

In the first setup, a load cell is mounted on the Universal Micro Tribometer (UMT) manufactured by CETR-Bruker Inc. The UMT was modified to perform the cutting and drilling test on it, as it has micrometer resolution, which makes it ideal for a high level of accuracy (Figure 2). The laser used in these tests was an IR, CW fiber laser with a wavelength of 1070 nm and maximum power of 100 W. The drilling bit was a single edge diamond bit with a 0.5 mm radius with -45° rake and 45° clearance angle. Negative rake angle is common for machining brittle materials to keep the compression on the material and avoid any tensile stress, which causes fracture. The diamond bit is mounted on a nozzle, as shown in Figure 3, which is attached to the optical part of the setup called Beam Delivery Optics (BDO). The sample was mounted on a circular disc as a replaceable stage that can be fastened to the spindle. The air bearing spindle, a product of Professional Instruments Co., has a runout error of less than 2μm. In this setup, the sample rotates instead of the tool, which is similar to the drilling operation in the turning process. As the sample is rotating, before each test the tool should be moved to the center of the spindle and the sample should be mounted at that position to avoid any inaccuracy. A fixture was designed for bringing the tip of the tool to the center of the spindle before starting the tests. By using a long focal length microscope, it was ensured that the tool was positioned at the center of the spindle.

In this process, many parameters can be adjusted such as the rotational speed (RPM), feed rate, laser power, and depth. The rotational speed selected for a safe range for the tool and setup was 1000 RPM. This value is

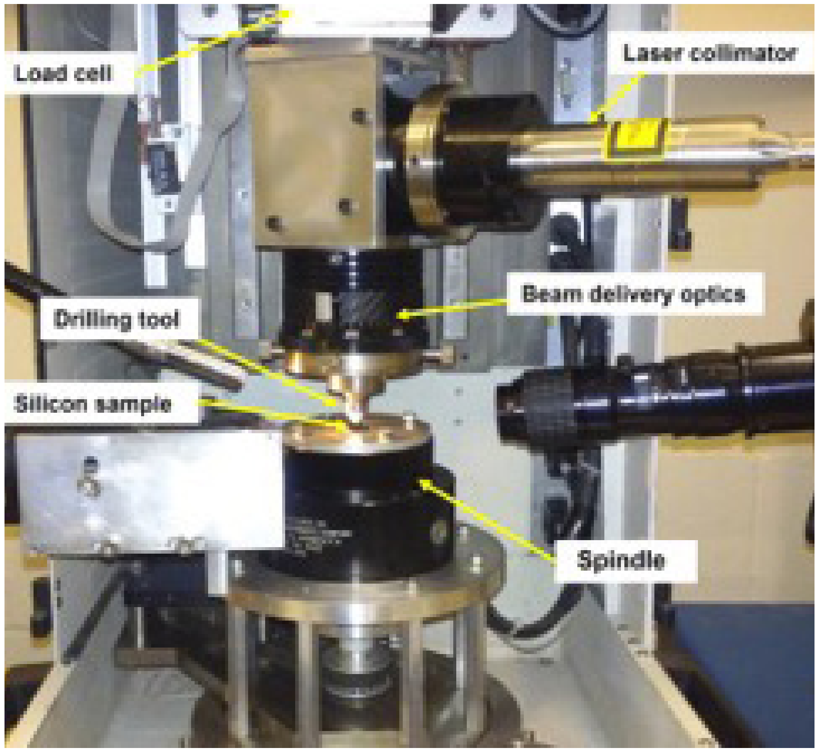


Figure 2. μ-LAD Setup used to perform the tests.

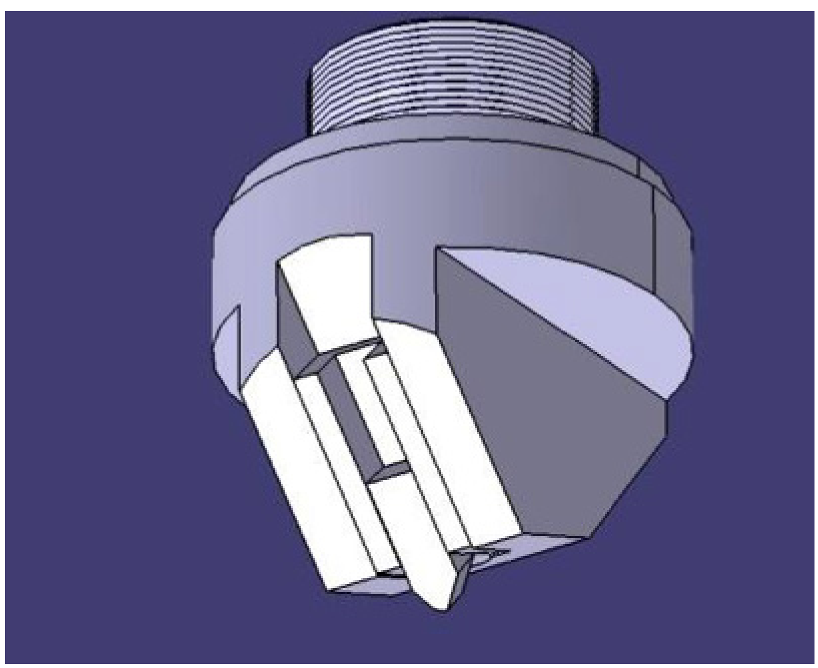


Figure 3. Nozzle that holds the diamond drill bit.

not the limitation of the process, but it was the limitation of the setup. Feed rate is the minimum value that can be adjusted on the equipment. Since the silicon is very hard and brittle, chip thickness plays an important role. For the selected rotational speed and feed rate, the chip thickness was 120 nm, which is a common chip thickness for this material (Kovalchenko, 2013). Holes are blind, and as the tool is single edge and round, a dimple shaped hole can be achieved. As the tool is curved, the diameter of the holes depends on the depth and for 40 μm depth, the diameter is ~460 μm. Crucial to the process is the selection of laser power, because the cutting process is happening at one spot of the workpiece and it could cause undesired thermal effects such as overheating. High laser power can cause thermal cracks and even burning, which would result in a rougher surface. Drilling parameters such as RPM, feed rate, laser power, and depth are shown in Table 1.

Results and Discussion

After performing the drilling with different laser power conditions, the sample was cleaned and imaged under a microscope. The first series of tests shows non-circularity and fractures on the entrance edge, as illustrated in Figures 4. In the no laser case, non-circularity is apparent when comparing the resulted edge to an ideal circle (i.e., the yellow dashed circle), as shown in Figure 4(a). By comparing the images, circularity was improved slightly by using the laser, although the edge chipping still occurred, as shown in Figures 4(b) and 4(c). This improvement in circularity was mainly due to thermal softening, which decreases the hardness and the strength of the

Parameter	Value
Rotational Speed	1000 RPM
Feed Rate	2 μ/s
Laser Power	0, 10, 20 W
Depth	40 μm

material. Figure 5 shows the circularity improvement of using a laser, which decreased the error by almost half. Despite this improvement, quality of drilled holes was not ideal due to the low rigidity of the setup.

In order to improve the quality of the entrance edges, the rigidity of the setup is essential. Even though it was important to monitor the forces to avoid any damage to the diamond drill bit in the first tests, using a load cell that is not rigid enough can weaken the stiffness of the setup. The type of load cell used for the first series of tests works based on how strain gauges movement. The load cell acted like a spring in the setup, which is suitable for low speed tests. Therefore, to increase the stiffness, the load cell was removed from the setup. Since the range of the load was obtained and was

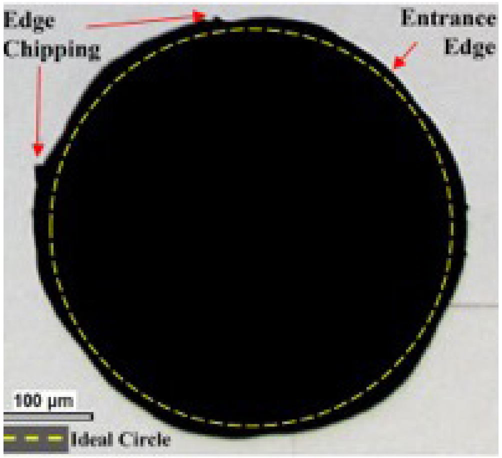


Figure 4 (a)

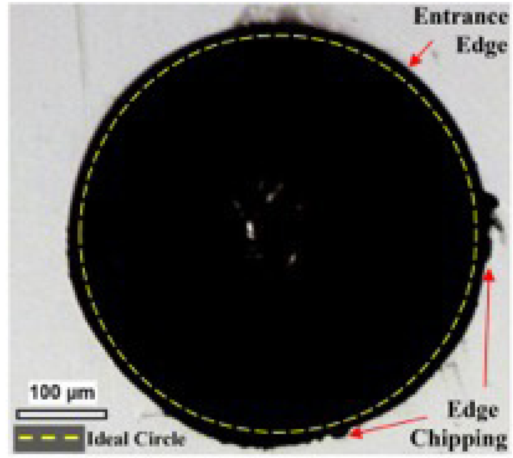


Figure 4 (b)

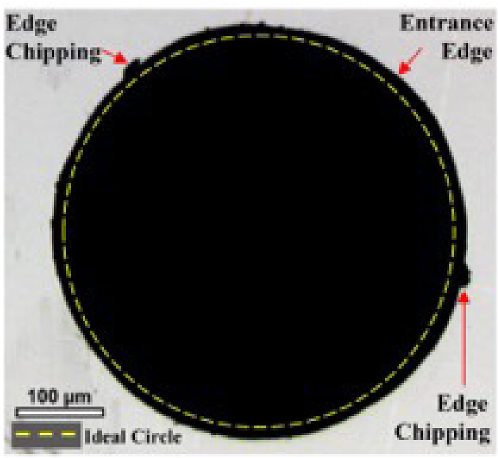


Figure 4 (c)

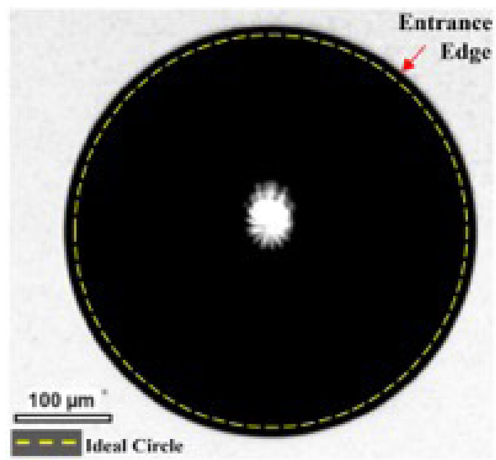


Figure 4 (d)

Figure 4. Edge entrances quality compared to an ideal circle (a: without laser, b: 10W, c: 20W, d: after increasing the rigidity of setup)

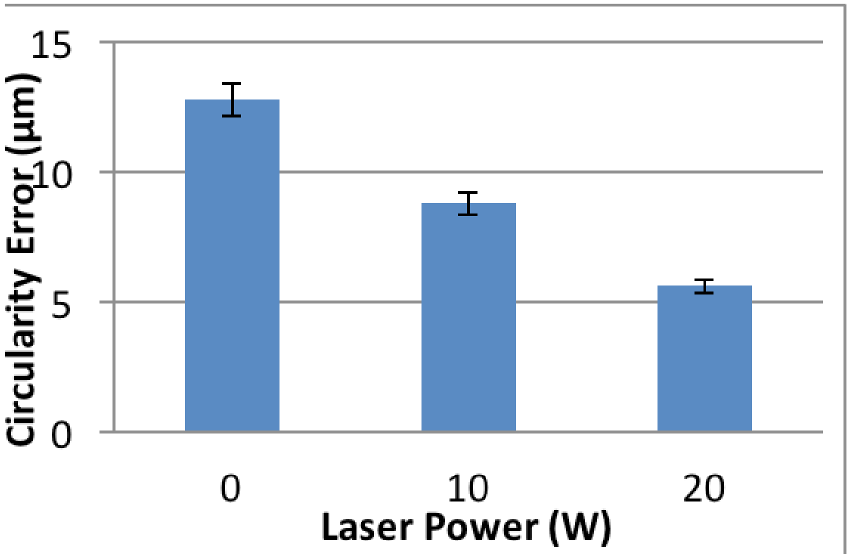


Figure 4. Edge entrances quality compared to an ideal circle (a: without laser, b: 10W, c: 20W, d: after increasing the rigidity of setup)

found to be low enough to not damage the tool, no other type of load cell was used.

By repeating the tests without the load cell in the force loop, a very clean entrance edge with an improved circularity was achieved. As shown in Figure 4(d), the edge of drilled holes shows no evidence of edge chipping with circularity error of << 1µm.

Surface Quality

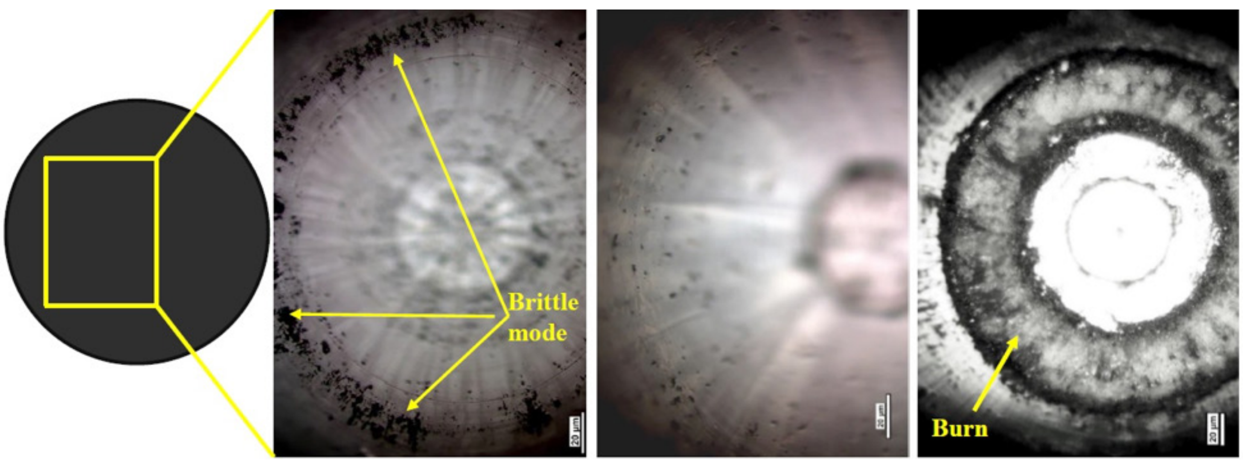
Since samples were single crystal silicon, it was possible to have fractures of the drilled surfaces, especially on the inner surface of the holes. The bottom of the drilled holes was imaged, and resultant surfaces are shown in Figure 6. As mentioned before, using the proper laser power level is very important in this process. Low laser power is not enough to soften and cut a ductile; on the other hand, a high intensity laser can cause overheating problems. Figure 6(a) shows the surface quality for low laser power, which still has some fractures left on the surface, while using a high laser power can burn the surface, as shown in Figure 6(c). For this particular set of tests, a 20 W laser power gave the best results, Figure 6(b), with no sign of fracture or burn on the inner surface of the hole.

Future Work

The technique presented is still in its early stages, and this study is based on the results achieved so far. For future work, the µ-LAD process will be used for drilling different materials such as ceramics, carbon fiber reinforced composites, and rocks. To better understand the effect of other parameters, more tests need to be performed. Studying the tool wear and the use of cutting fluid are other aspects of the process to be investigated.

Conclusion

This article introduced the μ-LAD process for drilling hard and brittle materials. It was shown that by increasing the rigidity of the setup, better quality results, including better edge entrance, were achieved in drilling silicon. Results showed that the μ-LAD tests were successful in making precise holes in the silicon samples with high edge quality, when comparing the silicon cut using a laser to the silicon cut with other methods. Inner surfaces were compared, and the best possible laser power to achieve the best surfaces was 20 W for this particular setup.



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