MICRO-LASER ASSISTED DRILLING OF SINGLE CRYSTAL SILICON IN DUCTILE REGIME

Hossein Mohammadi and John A. Patten

Manufacturing Research Center
Western Michigan University
Kalamazoo, MI, USA

INTRODUCTION

Micro drilling is an established technology, but with many limitations. The techniques and processes vary widely depending upon the material being drilled, precision and accuracy required, size (diameter, depth, etc.). Current applications demand better quality materials that are mechanically harder, yet manufactured with high level precision and accuracy. Drilling free of fractures, surface and subsurface damage and cracks and micro-cracks with good edges and high surface quality of the brittle and hard materials such as ceramics and semiconductors is always a challenge due to their low fracture toughness. Often, severe fracture can result due to their low fracture toughness. For silicon, as an example, fracture toughness is 0.83 to 0.95 MPa.m$^{0.5}$ (depends on crystal orientation).

There are many micro drilling techniques available to generate micro-holes such as micro-electrical discharge machining (micro-EDM), laser, photo-etching, ultrasonic and micro-electrical chemical machining (micro-ECM). However, each process has its limitations in cost, machining efficiency, properties of the workpiece and aspect ratio of a micro-hole [1,2]. In this current work a method of drilling by using laser which is focused through a diamond to the tip of the tool to drill hard and brittle materials is presented.

In the previous research works [3-6], it has been demonstrated that the ductile mode machining of semiconductors and ceramics is possible due to the high pressure phase transformation (HPPT) occurring in the material. 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. In µ-LAM the laser and cutting tool are integrated into a single package, i.e. the laser energy is delivered by a fiber laser to and through a diamond cutting tool. This hybrid method can potentially increase the critical depth of cut (DoC), i.e., a larger ductile-to-brittle transition (DBT) depth, in ductile regime machining, resulting in a larger material removal rate.

In micro laser assisted drilling (µ-LAD), as is 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. Laser softens the material under the tool which also leads to lower cutting forces and therefore lower tool wear (higher tool life). The focus of this study is on micro drilling of single crystal silicon (100) which is very brittle and hard to drill material by conventional methods. Effects of using laser on process outputs such as edge quality, surface roughness of the wall (of drilled holes) and brittle or ductile mode of the achieved surfaces have been investigated and discussed.

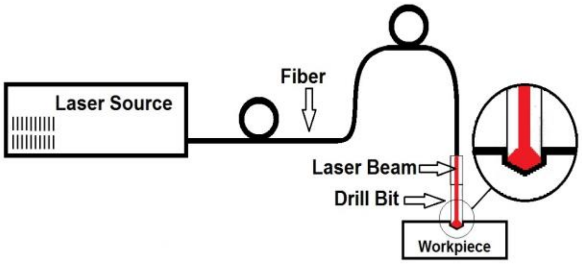

FIGURE 1. Schematic of µ-LAD process

EXPERIMENTAL SETUP

An IR CW fiber laser with wavelength of 1070 nm and max. power of 100 W is used in this investigation. A single edge diamond drilling bit with a 1 mm radius with -45° rake and 5° clearance angle was used for this drilling operation. The Universal Micro-Tribometer (UMT) manufactured by CETR-Bruker Inc. was modified and coupled to the µ-LAD system to perform all of the drilling tests. Figure 2 shows the experimental setup used for performing the tests. In this setup sample is rotating instead of the tool which is similar to drilling operation in turning process. For this purpose samples are mounted on a precise air bearing spindle. As the sample is rotating, before each test, the tool should be moved to the center of the spindle and sample should be mounted at that position to avoid any inaccuracy. However in this study, which is the first feasibility test of the µ-LAD process, the size of the drilled hole is not the main concern.

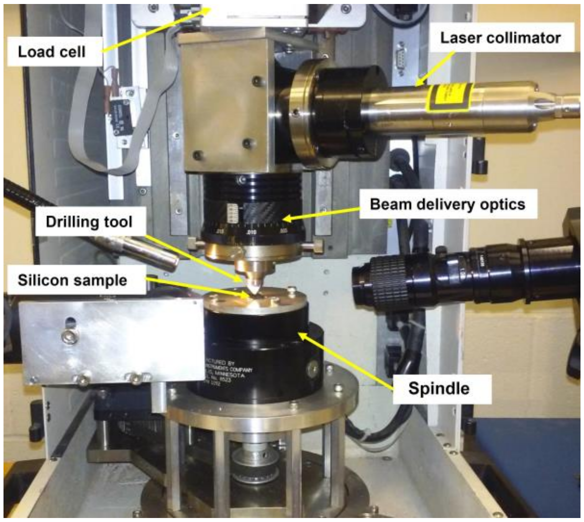

FIGURE 2. µ-LAD setup

Initial results of micro drilling the silicon by a diamond coated drill bit showed that ductile mode cut can be achieved, as it is shown in figure 3, if the feed rate be less than a critical value. This critical value can be determined by increasing infeed rate and check the hole under microscope, after each test, until ductile to brittle mode transition starts. After this value which is mainly depend on unmachined chip thickness and many other parameters such as thrust load or pressure, brittle mode cut starts. The white areas on the surface (wall) of the hole in figure 3 are machined in ductile mode while the dark areas are in brittle mode cut. These dark areas are pits and fractures that occurred during the drilling process which can initiate more cracks and even fail the final part. That is why an ideal hole in a brittle material should have minimum amount of brittle mode cut and depend on application even should be without any imperfection. Despite the face machining (turning) of the brittle materials which is possible to remove any unwanted surface and subsurface damages by post process techniques such as polishing, drilling is a final process and usually no further process is being used to increase the quality of the product. Therefore using a process with minimal unwanted effects on the material is highly demanded.

EXPERIMENTAL AND RESULTS

Due to low fracture toughness of the brittle materials, fracture happens when they are under tensile stress. Therefore entrance and specially exit of a through hole are very important as tensile stress is much higher than compress stresses in these zones. This experimental study is the first try of using this process for drilling and is focused on benefit of using laser on wall surface roughness and the edge quality of the hole entrance. Therefore a dimple shape hole is drilled in the silicon sample for each test as shown in figure 4 schematically.

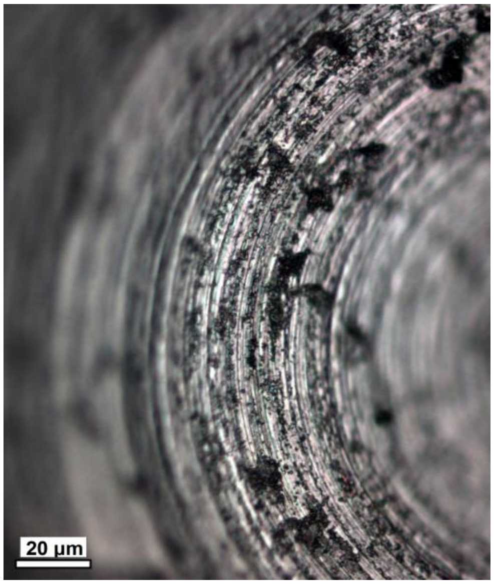

FIGURE 3. Hole wall surface under microscope

Spindle RPM used was 350 as lab scale equipment is used and not rigid as an industrial machine. For each cut, both with laser and with no laser, load was kept about 80 g and tool was fed continuously to reach a 150 micron depth. For the first test, sample drilled with no laser to be able to compare the results later. Figure 5 shows the edge and wall of the hole drilled with no aid of laser. Edge chipping, cracks and brittle mode (in some areas ductile mode) cutting are clearly can be observed. It was possible to infeed the tool more gently, with lower feed rate, to get a better surface finish, however to show

how laser possibly can help to increase the ductility of the material and decrease the damages, sample is drilled in an aggressive manner intentionally.

FIGURE 4. Schematic of a dimple shape hole

Surface roughness parameters of the hole inner surface, Ra and Rz, were measured with a white light interferometer (WYKO). Due to brittle mode cut and the fractures happened during the process, shown in figure 5, obtained surface was rough with Ra of 602 nm and Rz of 5.58 µm. Many cracks at the entrance of the hole, that can propagate later, are due to tensile stresses during the process. For next test a new silicon sample was drilled with aid of laser. It should be mentioned that to keep the condition similar, for both with and no laser tests, same setup used and the only difference was the laser.

TABLE 1. Parameters used for experiments

Parameter	**Value**
RPM	350
Load	~ 80 g
Laser power	0, 10 W
Depth	150 µ

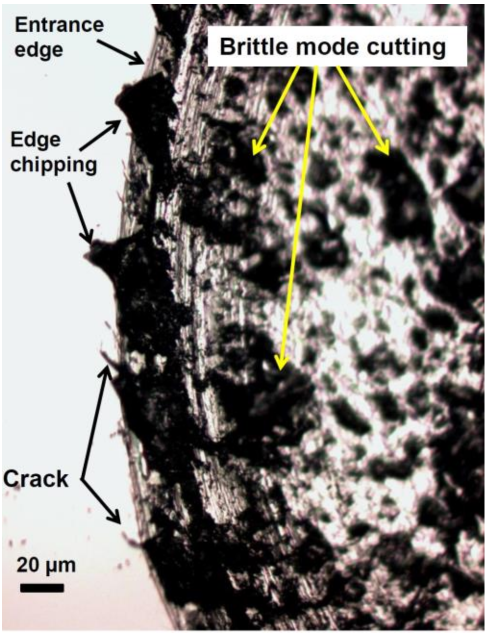

FIGURE 5. Entrance and wall of a hole drilled with no laser

10 W laser power is used for the test with laser, however due to reflection, absorption, error of the laser and scattering the actual laser output was less than 4 W. Low laser power, compare to the power level used in previous works [3-5] on machining, is used as in drilling process the tool respect to the sample is rotating at one spot (in this experiment workpiece is rotating). Test carried out with same condition, same load feed rate and other parameters, as with no laser test except laser. Figure 6 shows the resulting entrance edge and the wall of the hole. Quality of the edge is clearly much better than the hole drilled with no laser (figure 5). Drilling was in ductile mode with almost no sign of fracture. Feed marks also can be seen and surface is obviously smoother than the case with no laser. The Ra and Rz obtained for this surface were 44 nm and 445 nm respectively. No sign of chipping, crack or fracture can be seen on the edge and the wall. In fact laser helped to decrease the brittleness of the material especially at the entrance edge which tensile stress is high.

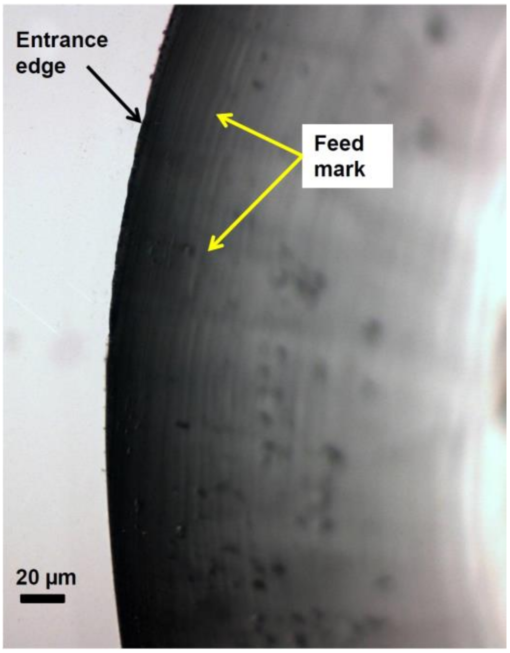

FIGURE 6. Entrance and wall of a hole drilled with laser

To help to visualize the obtained surfaces, a three dimensional (3D) profile of the inner surface of the hole is generated by WYKO profiler for each test. Drilled hole wall with no laser is shown in figure 7. The 3D profile is flattened by software on purpose to be able to see the features on the surface. Blue areas in figure 7 are the pits caused by brittle mode cut. The 3D profile of the silicon sample drilled with aid of laser, figure 8, shows the feed marks and very minimal imperfections on the surface as well.

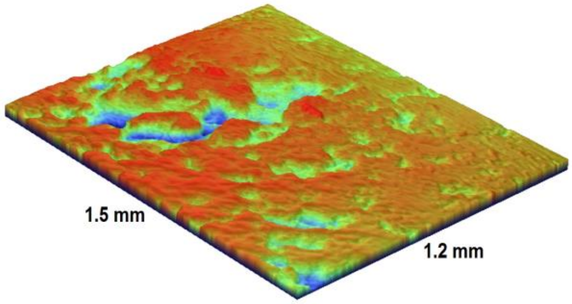

FIGURE 7. 3D image of the inner wall of the hole drilled with no laser

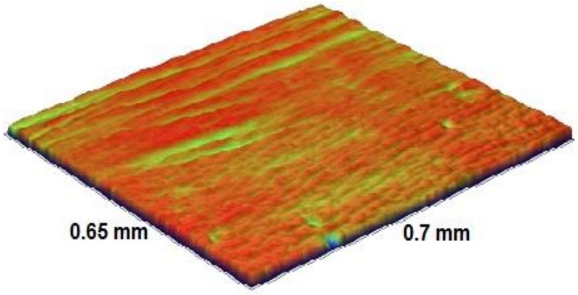

FIGURE 8. 3D image of the inner wall of the hole drilled with μ-LAD process

FUTURE WORK

For future work, μ-LAD process will be used for drilling different materials such as ceramics, carbon fiber reinforced composites, and rocks. Also to understand the effect of other parameters such as RPM, laser power and feed rate more tests are needed to be performed. Studying the tool wear and use of cutting fluid are other possible aspects of the process to be investigated.

CONCLUSION

Results show that the μ-LAD tests were successful in making precise holes on the silicon samples in ductile regime with higher edge quality due to using laser compared to the case drilled with no laser. The μ-LAD 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.

ACKNOWLEDGEMENT

The authors would like to thank the National Science Foundation (PFI: AIR – TT, Award #: 1445017) for funding this study.

REFERENCES

[1] Moon, J. S., Yoon, H. S., Lee, G. B., & Ahn, S. H. (2014). Effect of backstitch tool path on micro-drilling of printed circuit board. Precision Engineering, 38(3), 691-696.

[2] Ahn, S. H., Ryu, S. H., Choi, D. K., & Chu, C. N. (2004). Electro-chemical micro drilling using ultra short pulses. Precision Engineering, 28(2), 129-134.

[3] Ravindra, D., Ghantasala, M. K., & Patten, J. (2012). Ductile mode material removal and high-pressure phase transformation in silicon during micro-laser assisted machining. Precision engineering, 36(2), 364-367.

[4] Mohammadi, H., Poyraz, H. B., Ravindra, D., & Patten, J. A. , Nov. 2014, Micro-Laser Assisted Single Point Diamond Turning On Unpolished Single Crystal Silicon. 29th Annual Meeting of the American Society for Precision Engineering (ASPE), Boston, Massachusetts USA.

[5] Mohammadi, H., Ravindra, D., Kode, S. K., & Patten, J. A. (2015). Experimental work on micro laser-assisted diamond turning of silicon (111). Journal of Manufacturing Processes, 19, 125-128.

[6] Mohammadi, H., Ravindra, D., & Patten, J. (2013) ‘A first investigation of green lasers in micro-laser assisted scratch tests on silicon’, In American Society for Precision Engineers (ASPE) 28th Annual Meeting. St. Paul, Minnesota, USA.