Lasers in Manufacturing Conference 2017

New picosecond laser technology for micromachining of metal and brittle materials

Jim Bovatsek[a,*] , Rajesh Patel[a]

[a]*Spectra-Physics, MKS Instruments, 3635 Peterson Wy., Santa Clara, CA. 95054, USA*

Abstract

The benefits of micromachining with shorter pulse durations ("ultrashort" pulses) have led to their increased use in a diverse range of advanced manufacturing industries, including microelectronics, photovoltaics, light-emitting diodes, flat/touch panel display, and medical devices. Picosecond lasers, in particular, are becoming increasingly well known throughout various industries because of their ability to ablate material with reduced heat affected zones (HAZ) as well as their ability to generate nonlinear absorption and thereby cleanly machine transparent materials both at and below the surface. Unfortunately, picosecond laser sources have historically been relatively inflexible, large, costly and unreliable, significantly limiting industrial adoption.
In this work, we present micromachining results using Spectra-Physics' IceFyre™ industrial picosecond laser. This laser generates high pulse energies along with TimeShift™ ps—a versatile programmable burst mode capability—and has a wide adjustability of repetition rates in a compact package with industry-leading cost-performance. The benefits of burst mode machining of stainless steel has been studied. Also, the high energy pulses available with IceFyre are shown to effectively ablate hard brittle materials—such as glasses and ceramics–with excellent quality.

Keywords: picosecond laser; ablation; burst; efficiency

1. Introduction

Ultrashort pulse laser technology has been utilized for manufacturing in various industries for some years now. Lasers with both femtosecond and picosecond pulse durations have demonstrated excellent micromachining quality in a wide range of materials. For medical device manufacturing, ultrafast lasers are

* Corresponding author. Tel.: +14089988785 .
E-mail address: Jim.Bovatsek@Spectra-Physics.com .

used for machining metals such as stainless steel and nitinol, used in implantable vascular stents. Very challenging materials, from a thermal damage standpoint, such as PLLA (poly-l-lactic acid)) has also been successfully processed [1] for manufacturing biodegradable vascular stents.

Ultrashort pulses can create sufficiently high intensities that various nonlinear processes occur in transparent materials which can allow surface sub-surface processing of transparent or semi-transparent

and/or brittle materials such as glasses, crystals, and ceramics. With surface ablation, compared to longer pulse widths such as nanosecond-scale which produce edge chipping typically of several 10's of µm, picosecond pulse widths can form very fine edges with little or no chipping.

Relatively new laser technology has been developed which allows for material processing with a compact burst of pulses rather than just a single pulse. This so-called "burst machining" has been shown to improve processing throughput because the energy is used more efficiently when spread out amongst several pulses [2]. That is, for the same total energy, the sum of the volume ablated by a group of lower energy pulses is greater than that ablated by a single high energy pulse. Today's high power laser sources have so much pulse energy that small focus spots used for micromachining create fluences well above that which is optimal for best efficiency and quality. One solution would be to increase the laser pulse repetition frequency (PRF) which correspondingly decreases the pulse energy, but often-times the MHz level PRFs that are required to enter an optimal fluence regime for processing are too high for the beam scanning equipment used. In such cases, it can be beneficial to operate at a lower PRF and use burst machining.

Here, we report micromachining results using a novel, high power yet compact picosecond laser source. Using burst mode, volume ablation efficiency and machining quality of stainless steel plate material is characterized with respect to variation of (a) number of pulses within the burst and (b) temporal separation of pulses within the burst. In addition, using traditional single pulse mode, the high energy that is available from the laser is used to process features in difficult-to-machine thin materials such as glass, sapphire, and ceramic plate.

2. Volume ablation of stainless steel

Stainless steel is a widely used material in a variety of industries and laser processing of it has garnered much interest over the years. In this work, Spectra-Physics' compact IceFyre 1064-50 picosecond laser has been used for volume ablation studies aimed at discerning what benefits, if any, can be gained by using a burst machining approach—particularly when there is great flexibility in defining both the number and separation of pulses within the burst.

2.1. Experiment

The experiment consisted of pocket milling volumetric regions in 3 mm thick stainless steel plate material (type 304, polished) using various experimental conditions, measuring the depth of the milled pockets, and determining volume ablation rates and efficiencies. In addition, a quality assessment such as optical microscope inspection and roughness characterization of the milled surfaces was performed.

2.2. Laser system

The laser used for all processing was a Spectra-Physics IceFyre 1064-50. The laser outputs sub-20 ps laser pulses with >50 W average power and >200 µJ maximum pulse energy from a single pulse. Figure 1 below shows the laser system as well as key specifications of the laser.

Parameter	Value
Wavelength	1064 nm
Power	>50 W
Max. pulse energy	>200 µJ
Pulse width, FWHM	<20 ps
TimeShift™ ps?	Yes
Pulse repetition frequency	Single shot to 10 MHz
Pulse energy stability	<1.5% rms
Beam quality (M^2 factor)	<1.3

Fig. 1. Spectra-Physics IceFyre 1064-50 laser system.

Besides the high average power and high pulse energy available with IceFyre, it has TimeShift™ ps, a proprietary pulse burst mode capability. TimeShift ps is a highly flexible capability, allowing for an arbitrary number of pulses in a burst, a programmable burst envelope shape, and widely adjustable separation of adjacent pulses, all along with widely adjustable repetition rates. Lastly, this highly configurable pulse tailoring capability does not come with any cost of reduced average power; full power output is maintained regardless of the number of pulses, separation of pulses, or the variation of the separation of the pulses within the envelop.

2.3. Equipment and process parameters

High speed, multi-pass pocket milling was performed using a 2-axis scanning galvanometer (ScanLAB HurrySCAN 20 1064) with an aperture diameter of 20 mm. The laser beam was focused onto the work-piece with a non-telecentric F-theta objective (focal length of 163 mm). The focused beam diameter was approximately ~28 µm ($1/e^2$). Proximate to the processing area, a fume extraction duct and low flow air nozzle were arranged to evacuate the ablation byproducts out of the work area. The fume extraction set-up did not impact the quality or efficiency of the ablation processes.

For all tests, the laser power at the workpiece was set at 40 W. For the burst machining tests, the laser PRF was fixed at 400 kHz; for single pulse ablation tests, the laser PRF was varied from 400 kHz to 10 MHz. The pulse width for all operating conditions of the laser was approximately 16 ps. For burst mode milling experiments there were up to 30 pulses included in a single burst and the separation times between burst sub-pulses was varied from 10 to 100 ns.

Pockets were milled by scanning a set of 100 parallel lines, each 10 mm in length and offset from one another by 10 µm, thus forming a 20 mm × 1 mm rectangle. The scanning speed was 4 m/s in most cases; however for PRFs of several MHz used in some single pulse tests the scan speed was increased to 8 or even 12 m/s. Relative to the 28 µm beam focal diameter, the 10 µm offset perpendicular to the scanning direction equates to an overlap of ~64%. A majority of the tests were executed with 4 m/s scan speed and 400 kHz PRF which equates to pulse-to-pulse spacing in the scanning direction that is also 10 µm, with therefore the same ~64% overlap in the scanning direction. Multiple repeat iterations (10 – 75) of the pattern were used to generate measureable depths, which were then measured via scanning white light interferometry over the rectangles' central 1 mm × 0.75 mm area. The range of depths measured in the subsequent analysis was approximately 10 – 65 µm. A schematic representation of the scan pattern, laser pulse layout, and resulting feature can be seen in Figure 2.

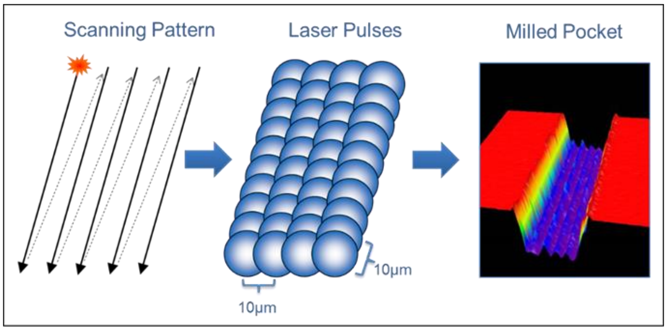

Fig. 2. Multiple parallel lines scanned with 10 µm pulse spacing in both axis were used to fabricate milled pockets.

2.4. Results – single pulse ablation

Initially, single pulse volume ablation studies were conducted to set a baseline for all experiments to follow. Before pocket milling features were machined, the single pulse ablation threshold fluence Fth was determined for the stainless steel material using the Liu method [3]. The threshold is important in that it is known from both theory and experiment [4] that the most efficient ablation occurs when operating at a particular multiple of this threshold (the multiplier is e^2, with e being the natural number 2.71828). In accordance with the technique, single pulse ablation craters were created and their diameters were measured for a range of pulse energies. The ensuing log-linear regression analysis based on a Gaussian energy (fluence) distribution yielded an ablation threshold fluence of ~0.6 J/cm^2. In other work [5] using the same methodology, a threshold of 0.5 J/cm^2 using 10 ps pulse widths was determined, which agrees well especially when considering the slight pulse width difference. The optimal fluence for ablation then calculates as $e^2 \times F_{opt}$ = 4.4 J/cm^2. It is expected that operating at fluences significantly above or below this number will result in relatively poor ablation efficiency.

Pocket milling experiments were conducted with single pulse output operation of the IceFyre laser. Features were machined at operating PRFs from 400 kHz to 10 MHz. For PRFs below 5 MHz, 4 m/s scanning speed was used; for PRFs above 5 MHz, scanning speeds of 8 m/s (5 MHz) and 12 m/s (6.67 and 10 MHz) were required in order to avoid severe thermal effects associated with high pulse overlap, high PRF, etc. While the overlap conditions at the higher PRFs did increase the ablation rate, the quality was excessively poor. The volume ablation rate as it varies with laser pulse frequency is plotted in Figure 3 below.

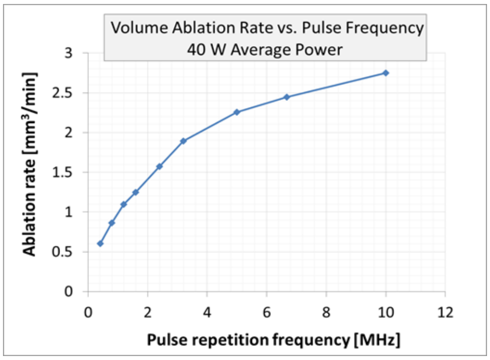

Fig. 3. Single pulse volume ablation efficiency improves with higher PRF, lower pulse energy operation.

Considering the relatively low threshold of the material, it was expected that volume ablation at 40 W and 400 kHz would be inefficient, given that the fluence level (at center of beam) is ~32 J/cm^2, which is ~7× what would be considered optimal. The data in Figure 3 clearly show the benefits of high PRF, low fluence processing of stainless steel with picosecond laser pulses. At 10 MHz, the ablation rate is approaching an apparent maximum near about 2.75 mm^3/min. Dividing this by the average power (40 W), the per-Watt volume ablation efficiency rate is ~0.07 mm^3/min/W. The fluence level (1.3 J/cm^2) at 10 MHz PRF is less than a third of the single-pulse optimal fluence F_{opt}, and it may be that the relatively high rate of material removal at the lower fluence is a result of some beneficial heat accumulation at the high PRF as well as a lowering of the damage threshold (and hence F_{opt}) with the multi- vs. single-pulse irradiation of the material.

At such high PRFs in the range of several MHz, there is a concern that heat accumulation between incident pulses may lead to reduced quality. Figure 4 shows a comparison of the milled surfaces at lower (400 kHz) and higher (10 MHz) PRFs alongside the native, unprocessed surface of the steel.

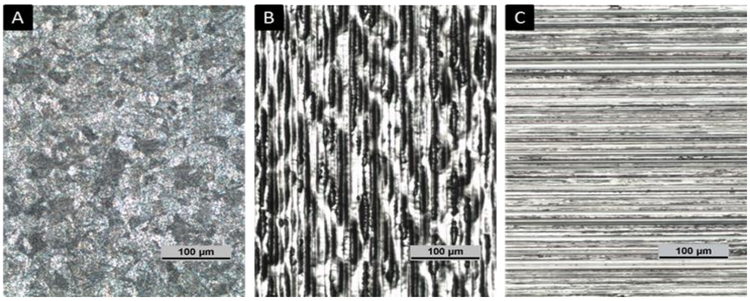

Fig. 4. Optical microscope photos of low fluence result at 400 kHz (A) and 10 MHz (B); the unprocessed surface is also shown (C).

With reduced average power to generate a lower fluence (2.30 J/cm^2) at 400 kHz, Figure 4(a) shows that the processing is gentle enough to reveal the boundaries of the individual steel crystal grains. With low fluence (1.3 J/cm^2) at 10 MHz, however, there appears to have been melting and re-solidifying of the steel, resulting in a surface that is slightly smoothed but at the same time somewhat bumpy/textured. Further considering the laser milled surface at 400 kHz, the 2D and 3D topographic data from scanning white light interferometry can be seen in Figure 5 below, along with a close up optical microscope photo showing the laser induced periodic surface structures (LIPSS) that are present on the laser-processed surface.

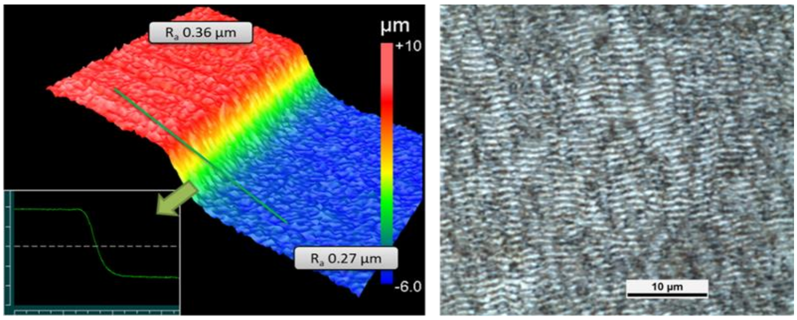

Fig. 5. 2D and 3D topographical surface mapping of a low fluence, low PRF milled pocket (A) and close-up optical microscope image showing laser induced periodic surface structures (LIPSS) (B).

The 3D profile data shows a very flat surface with a fine texturing. Roughness R_a was measured at several locations at the bottom of the pocket and on the surrounding surface, and the data indicates that the roughness of the processed area is 25% lower than the native unprocessed surface. The 2D profile shows very clearly that there is no burr present at the edge of the ablated area. Figure 5(b) shows the fine laser induced periodic surface structures (LIPSS) on the processed area that are known [6] to be generated at low fluence conditions with ultrafast lasers. Low fluences applied at low pulse frequencies clearly offer super quality, but with the penalty of reduced throughput compared to low fluence at high PRFs.

2.5. Results – multi-pulse burst ablation

The single pulse studies showed that material removal is most efficient with lower fluences, which can be generated at both higher and lower PRFs. At higher PRFs, the full average power is being utilized with maximal ablation rates, but quality seems to suffer, likely due to heat accumulation. At lower PRFs, the average power has to be reduced to achieve lower fluence which provides better quality but with very low throughput and overall is a very inefficient use of the laser's capability. With this context in mind, multi-pulse volume ablation experiments were executed to determine: (a) if high throughput and high quality could be achieved at lower overall PRFs, and (b) if any additional throughput advantage could be gained via burst machining.

In Figure 6, volume ablation rates using 40 W average power with pulse bursts number 4—30 pulses and intra-burst separation times of 10—100 ns are plotted. Also included is the data point for single pulse output at 10 MHz PRF (which effectively has a pulse separation time of 100 ns).

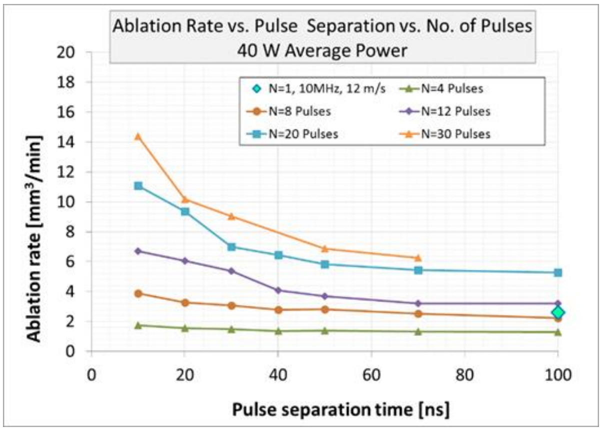

Fig. 6. Volume ablation rate with 4—30 burst pulses and intra-burst pulse separation times from 10-100 ns; for reference, data for single pulse output at 10 MHz PRF (i.e. 100 ns separation time) is also included.

The data presents us with three clear outcomes: (1) for a given pulse separation time ablation efficiency increases with increasing number of pulses in the bursts, (2) ablation efficiency increases with decreasing separation time of pulses within the bursts, and (3) the relative advantage of shorter burst separation times increases with increasing number of pulses in the bursts. Compared to the highest ablation rate with a single pulse, which approaches 3 mm^3/min, using a 30-pulse burst results in a ~5× improvement over this. Besides the ablation rate decreasing with increasing pulse separation, quality also degrades. In all cases, the best quality in terms of machined surface roughness was obtained with the shortest pulse separation of 10 ns.

With burst machining showing such a large ablation rate advantage compared to single pulse, quality should also be considered. Ultrashort pulse machining of metals has shown to be very sensitive to fluence and overall dose. With excessive fluence and high numbers of scan repetitions, surfaces of machined steel have exhibited extremely poor quality with, for example, large molten nodules of material protruding upward from the floor of the ablated areas when machining with both 10 and 50 ps pulse widths [7]. In this work, similar phenomena were also observed. Figures 7 contains a sequence of optical photomicrographs of machined surfaces using 4, 8, and 30 pulse bursts (all with 10 ns sub-pulse separation times) as well as for single pulse output at 400 kHz and 10 MHz PRFs; fluence and roughness R_a values are also noted.

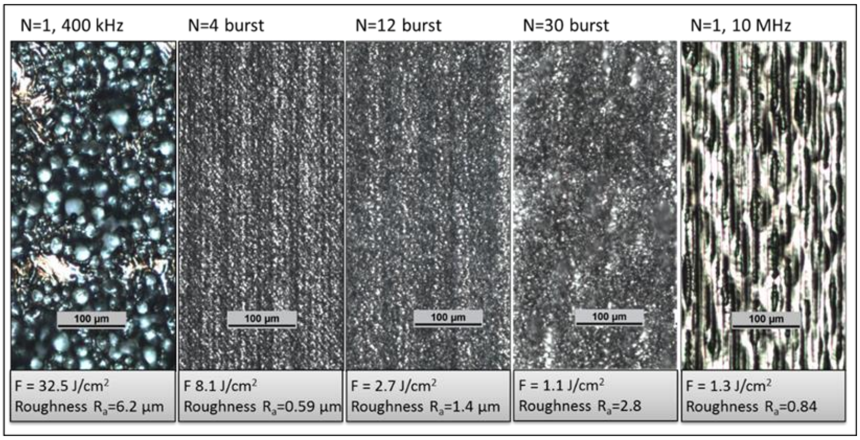

Fig. 7. Optical microscope photos showing improvement of milled surface with increased number of burst pulses; best quality and throughput single pulse result is also shown at far right for reference.

For single pulse output at 400 kHz, the fluence is excessive and the quality is extremely poor with large regions of molten metal. Splitting to bursts of 4 and then 12 pulses, the quality shows marked improvement. In appearance they are very similar, however the roughness R_a is somewhat higher for 12 vs. 4 pulses. For 30 pulses in the burst—which had the highest removal rate of all conditions tested—the R_a value is higher still; however, the surface quality is visibly far superior to that of the single pulse, 400 kHz case. Further improvement of surface roughness could likely be achieved by optimization of the scanning pattern, such as by using cross-hatch fill instead of parallel lines, optimizing line spacing, etc.

Based on the results of this test, throughput and quality are affected by both the number of burst pulses and the pulse separation time when machining stainless steel. With the flexibility inherent in IceFyre's TimeShift ps capability, these parameters can be easily adjusted to provide the optimal balance of throughput and quality, depending on the requirements of a particular application.

3. Processing of brittle materials

Hard and brittle materials such as glass, ceramics, and crystals are historically difficult to machine with good quality and high throughput. Traditional mechanical processes are often too harsh and, in particular for thinner materials, must be slowed down to prevent severe cracking and chipping of the material. In addition, tool wear is problematic because the cutting edges are continually degrading throughout its lifecycle and the quality, yield, etc. of the processed parts are likely to also degrade—this on top of the consumable replacement cost that can be quite high over time. Hence, manufacturers have increasingly looked towards laser technology as a solution.

3.1. Experiment

The tests conducted on transparent and/or brittle materials were aimed at developing optimized processes for real and specific industrial applications common to microelectronics industries. Materials tested include 200 µm thick Corning® Willow® glass, 150 µm thick sapphire wafer, and 200 µm thick aluminum oxide (Al2O3) ceramic plate. In these materials, processes were developed for trepan cutting of holes with diameters in the 5—10 mm range.

In these tests, the same equipment set-up was used as for stainless steel, however the beam was further expanded so as to create a focus spot size of ~18 µm, 1/e2 diameter. The smaller spot size is beneficial in that higher intensities are generated which help to trigger nonlinear absorption mechanisms. Tests were conducted at the laser's nominal PRF of 400 kHz and 40 W average power was incident on the workpiece.

3.2. Results – hole cutting in 200 µm thick glass

In thin glass used for manufacturing of current and future personal mobile devices, picosecond pulse laser have proved to be valuable. Closed shape cutting is important for integration of features such as buttons, audio speakers, camera lens cover windows, etc. Using the IceFyre laser combined with a high speed, multi pass trepan cutting process, 10 mm diameter holes were cut in 200 µm thick Willow glass. Figure 8 below shows a digital camera macro photo as well as an optical microscope image of the processed feature.

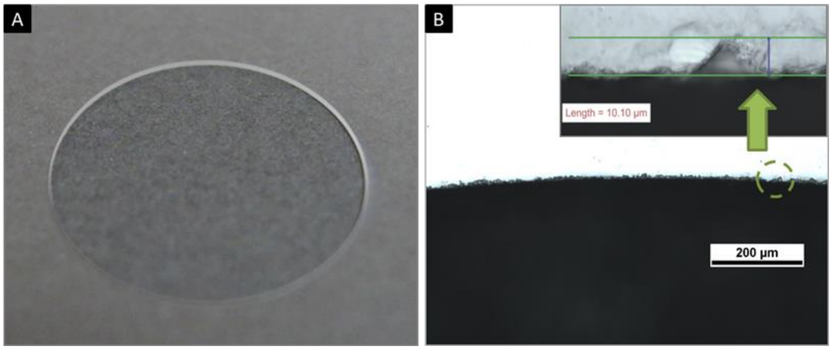

Fig. 8. Macro camera photo (A) and optical microscope photo (B) of 10-mm diameter hole cut in 200 µm thick Corning Willow Glass; the inset microscope photo in (B) shows the very small edge chipping along the cut of approximately 10 µm or lower.

The hole cutting time was ~2.5 seconds and the ablated edges appear very smooth. Edge chipping was typically 0-10 µm as determined by optical microscope inspection and surface profile data indicated roughness R_a of <1 µm.

3.3. Results – disk cutting in 150 µm thick sapphire wafer

Sapphire is increasingly being implemented in mobile devices as a tough, scratch resistant material for components such as cover plates for watches, fingerprint sensors, and camera windows. For some time now, there has also been industry speculation of entire device cover plates being made out of sapphire. Some drawbacks of the material include significantly higher density and cost compared to, for example, chemically strengthened glass. For both of these reasons, there is constant downward pressure on the thickness of the sapphire that is used for such components.

In these tests, small disks or "planchets" were machined out of 150 µm thick c-plane, double side polished sapphire wafers. Developing high speed processes with high laser average powers can be fairly challenging with such very thin, very brittle materials. After a careful process optimization effort with the IceFyre picosecond laser, 5 mm diameter disks were cut out in ~1.5 seconds. Camera macro and optical microscope images are shown in Figure 9.

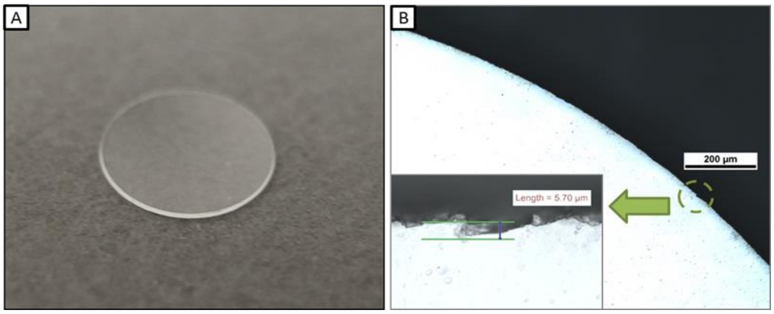

Fig. 9. Macro camera photo (A) and optical microscope photo (B) of 5 mm disk cut from a 150 µm thick sapphire wafer; the inset microscope photo in (B) shows the largest edge chip in the arc segment which was <6 µm in dimension.

The photos in Figure 9 show good machining quality of the thin sapphire material. In particular, the inset microscope photo (Figure 9(b)) shows the largest chip dimension in the arc length is <6 µm. For the faster cutting speeds such as exhibited in Figure 9 above, the sidewall roughness R_a was typically ~1.5 µm. In addition, with some tradeoff in throughput, features with R_a values in the 0.5—1.0 µm range were also machined in sapphire.

3.4. Results – hole cutting in 200 µm thick alumina ceramic

Alumina ceramic is increasingly being using in microelectronics manufacturing. Its combination of high hardness, high electrical insulation, and high thermal conductivity has made it a valuable material for various applications such as light emitting diode (LED) heat sinks, high temperature printed circuit board (PCB), and device packaging for harsh, high temperature environments. Due to its hardness and brittleness, it is also a challenging material to machine.

Using a high speed, multi pass trepanning process, 5 mm diameter holes were cut in the material with good quality and high throughput. Figure 10 below illustrates the good quality that was achieved.

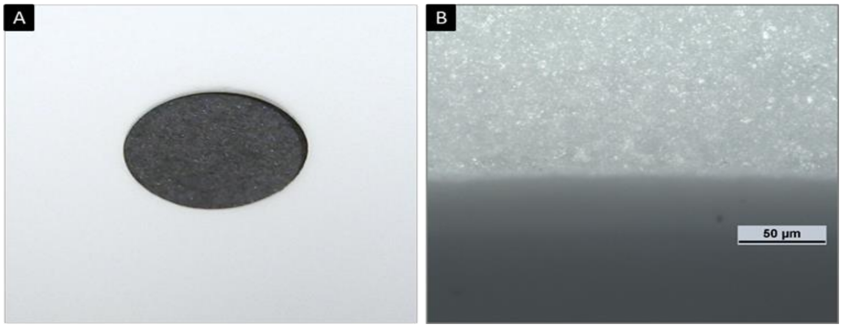

Fig. 10. Digital camera photo (A) and optical microscope photo (B) of 5 mm diameter hole machined in 200 µm thick alumina ceramic plate indicate very good edge quality.

The processing time was relatively fast at 0.8 seconds per hole, equating to a linear cutting speed of ~20 mm/s. The images in Figure 10 clearly show that no darkening and debris deposition at the edges and sidewalls of the kerf are formed that are often seen when processing with nanosecond+ pulse durations.

4. Conclusion

In this work we have explored the micromachining capabilities of a new compact picosecond pulsed laser source, Spectra-Physics' IceFyre 1064-50, which offers flexibility in pulse burst programming that is unique amongst products in the marketplace.

When machining stainless steel, it was shown that excellent quality could be achieved when the appropriate fluence level is used. In addition, ablation rates were characterized and found to be maximized at PRFs of 10 MHz or slightly higher. However, with high PRFs comes the burden of high scanning speeds to prevent heat accumulation, and for a variety of micro-processing applications, the equipment required becomes prohibitively complex and expensive. Using the IceFyre's unique TimeShift ps capability, it was shown that throughput can be regained when processing at relatively low PRFs by distributing the energy amongst several sub-pulses, with the separation time of 10 ns offering the best result for both throughput and quality. In fact, with burst mode operation, the throughput was found to surpass the maximum achievable with a single pulse output, while still maintaining good quality.

For transparent, brittle materials, the IceFyre 1064-50 also demonstrated good performance for cutting holes in thin glass, sapphire, and alumina ceramic. High speed trepanning processes were developed for cutting holes of 5 and 10 mm diameter. The resulting hole cutting times ranged from <1 to ~2.5 seconds and edge chipping for glass and sapphire were typically in the range of 0—10 µm and molten recast for alumina was minimal to non-existent. Based on the burst machining advantages that were observed in stainless steel, future work in the machining of other materials will be focused on further characterizing throughput and quality improvements that can be achieved with the unique flexibility of IceFyre's TimeShift ps technology.

References

[1] Matylitsky, V., Hendricks, F., Patel, R., 2013. Laser micromachining of bio-absorbable polymers: impact of the laser process parameters on the machining throughput and quality, Proceedings of ICALEO 2013. Miami, FL, USA.

[2] Knappe, R., Haloui, H., Seifert, A., Weis, A., Nebel, A., 2010. Scaling ablation rates for picosecond lasers using burst micromachining, Proceedings of SPIE vol. 7585 (2010).

[3] Liu, J.M., 1982. Simple technique for measurements of pulsed Gaussian-beam spot sizes, Optics Letters 7, 196-198.

[4] Neuenschwander, B., Bucher, G., Nussbaum, C., Joss, B., Muralt, M., Hunziker, U., Schuetz, P., 2010. Processing of metals and dielectric materials with ps-laser pulses: results, strategies, limitations and needs, Proceedings of SPIE vol. 7584 (2010) .

[5] Raciukaitis, G., Brikas, M., Gecys, P., Voisiat, B., Gedvilas, M., 2009. Use of high repetition rate and high power lasers in microfabrication: how to keep the efficiency high?, Journal of Laser Micro/Nanoengineering Vol. 4, No. 3, p. 186.

[6] Fauchet, P., Siegman, A.E., 1982. Surface ripples on silicond and gallium arsenide under picosecond laser illumination, Appl. Phys. Lett. 40, 824.

[7] Lauer, B., Jaggi, B., Neuenschwander, B., 2014. Influence of the pulse duration onto the material removal rate and machining quality for different types of steel, Physics Procedia 56 (2014) 963 – 972.