Ultrashort Pulse Laser Technology for Processing of Advanced Electronics Materials

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Laser technology is increasingly being employed for an ever expanding range of applications in a variety of industries. The success of laser processing is due in large part to manufacturers understanding the benefits of non-contact, precise processing and a growing need for machining smaller and more precise features. In a broader view, it is also the continual evolution of laser technology—with related improvements in the cost, capability, and reliability of product offerings—that further drives its adoption. Indeed, the laser product marketplace has seen product offerings expand in nearly every conceivable way: higher power and pulse energy, higher pulse repetition rate, shorter wavelengths, better beam quality, shorter pulse widths, pulse shape tailoring and burst-mode operation—and all of these with lower costs and improved reliability. In this work, we present processing results achieved using Spectra-Physics' state-of-the-art ultrashort pulse laser technology. This laser provides both high pulse energy and high average power, both of which are attractive to industry. We have processed materials commonly used in advanced electronics and semiconductor manufacturing industries. The high energy pulses are shown to effectively ablate hard to machine materials—such as alumina ceramic–with good quality. For lower-threshold materials such as silicon and copper, we demonstrate that certain pulse parameters result in more fully optimized volumetric ablation efficiencies.

Keywords: Picosecond laser, volume ablation rate, copper ablation, silicon ablation, burst machining

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 relevant to a wide range of applications. Generally, the excellent quality is a result of the pulse widths being similar to or shorter than the time required to convert the energy of excited electrons into thermal energy. This results in the ability to remove material while leaving minimal residual heat that otherwise could lead to unwanted heating effects such as oxidation, melting, etc.

Relatively new laser technology has been developed which allows for material processing with a 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 [1]. 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 can have such high pulse energies that small focus spots used for micromachining create fluences well above the optimal required for best efficiency and quality. One simple 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 are too high for the beam scanning equipment used and/or may lead to some unwanted heating effects due to heat accumulation between pulses. In such cases, it can be beneficial to operate at a lower PRF and use burst machining as a way to operate in a more optimal fluence regime without heating effects.

Here, we report micromachining results using Spectra-Physics' IceFyre™ 1064-50, a new versatile, high power yet compact industrial picosecond laser. Using burst mode, volume ablation rates of copper and silicon are characterized with respect to variation of (a) number of pulses within the burst and (b) temporal separation of pulses within the burst. In addition, effects of increased PRF (single pulse output) and number of burst pulses on the quality of the features is assessed.

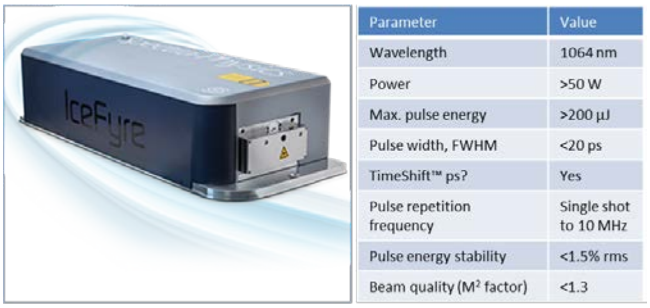
2. Experiment

The experiment consisted of pocket milling volumetric regions in copper plates (polished, ¼" thick) and silicon wafers (polished, 700 µm thick) with various process parameters, measuring the depth of the milled pockets, and calculating volume ablation rates. In addition, some quality assessment was performed using optical microscope inspection and macro digital photography.

2.1 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.

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 intensity 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 burst envelop.



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 (M² factor)	<1.3

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

2.2 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. A schematic representation of the scan pattern, laser pulse layout, and resulting feature can be seen in Figure 2.

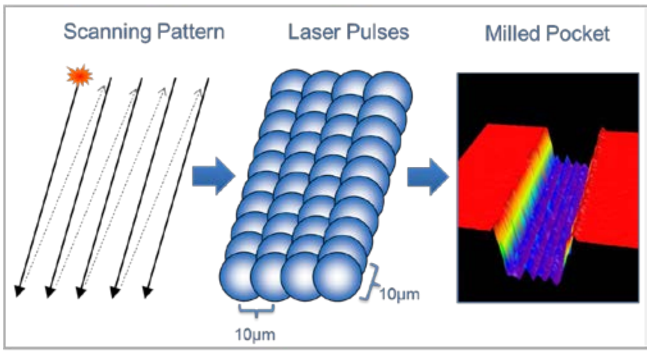


Fig. 2 Multiple parallel lines scanned with 10 µm pulse spacing in both axis were used to fabricate milled pockets.

For all tests, the laser power at the workpiece was set at 43 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 3.2 MHz. The measured pulse width for all operating conditions of the laser was ~16 ps. For burst mode milling experiments there were up to 50 pulses included in a single burst and the separation times between burst sub-pulses was varied from 10 to 500 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 all cases, even when operating at higher PRFs. Relative to the 28 µm beam focal diameter, the 10 µm offset perpendicular to the scanning direction equates to an overlap of ~64%. With a scan speed of 4 m/s and PRF of 400 kHz, the pulse-to-pulse spacing in the scanning direction is also 10 µm, witch therefore results in the same ~64% overlap in the scanning direction. Multiple repeat iterations (5 – 40) of the pattern were used to generate features of sufficient depths, as measured with 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. Table 1 summarizes the process parameters used in the tests.

Table 1 Summary of parameters used in the milling experiments

Parameter	Value
Average power at target, P_{avg}	43 W
Pulse repetition frequency, *PRF*	400 kHz (burst); 400-3,200 kHz (single pulse)
Pulse duration	16 ps
Scan speed, V_s	4 m/s
Pulse spacing, scan direction	10 µm (400 kHz)
$1/e^2$ focus diameter, $2W_o$	~28 µm
Scanning spot overlap	64%
Raster line spacing, Λ	10 µm
Stepping spot overlap	64%
Number of pulses in burst	1-50
Pulse separation time, T_{sep}	10-500 ns

3. Results

Results include data plots showing volume ablation rates (in mm^3/min.) as it varies with different independent variables such as PRF (for single pulse), and number of burst pulses as well as separation time of pulses within a burst when using the TimeShift ps feature of the IceFyre laser.

3.1 Copper ablation

Initially, single pulse ablation rate data was generated in copper using a range of PRFs beginning at the laser's nominal 400 kHz and increasing to several MHz until a reduced ablation rate was observed, which occurs when the energy and hence fluence becomes too low for meaningful material removal. Following this test, the laser was operated in burst mode and both the number of pulses within a burst and the temporal separation between adjacent pulses within the burst were varied and the effect on volume ablation rate was quantified.

3.2 Copper single pulse ablation rate

When using a single pulse at 400 kHz, the ablation rate was found to be lower compared to that at higher PRFs. Increasing the PRF resulted in a steady rise in ablation rate up to values of several MHz. Beyond 3.2 MHz, however, the ablation rate started to decrease, which indicates the optimal fluence point for efficient material removal has been crossed. Figure 3 shows the single pulse volume ablation vs. laser PRF.

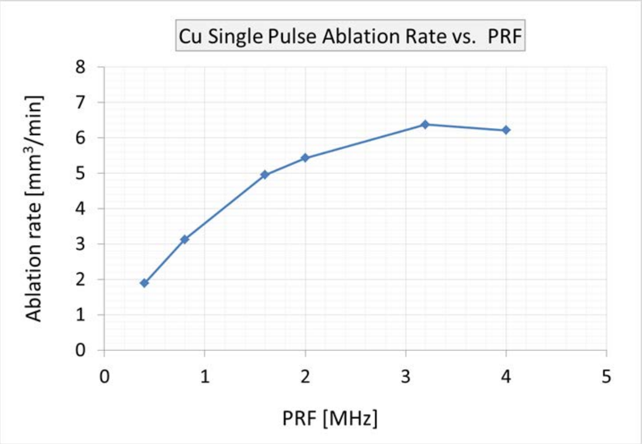


Fig. 3 Volume ablation rate using a single pulse improves with higher PRF (lower energy per pulse) operation.

The data in figure 3 show a three-fold increase in the ablation rate is achieved merely by increasing the PRF of the laser, with a maximum of about 6.4 mm^3/min. Beyond about 3.2 MHz, however, the rate begins to decrease: at the lower pulse energy/fluence, the volume ablated per pulse is so far reduced that the higher pulse frequency does not compensate for it.

3.3 Copper burst pulse ablation rate

While higher PRF yields a higher ablation rate due to a more optimal fluence condition and at the same time more pulses per unit time, from a system perspective one needs a very fast scanning system to take advantage of such higher ablation rate. An alternative approach is to use the TimeShift ps capability of the laser for burst mode machining of the material which does not required a very high speed scanning system. While keeping the PRF at 400 kHz, a single higher energy pulse can be divided up into multiple lower energy pulses, each having a fluence that is more optimal for efficient machining. Furthermore, at the relatively low PRF (compared to for example 3.2 MHz), the time between pulse bursts may allow for some material cooling that may be beneficial for reduced heating effects of one form or another. Lastly, the temporal separation of pulses within the burst can also be varied, and this could potentially further affect the results in terms of throughput and or quality.

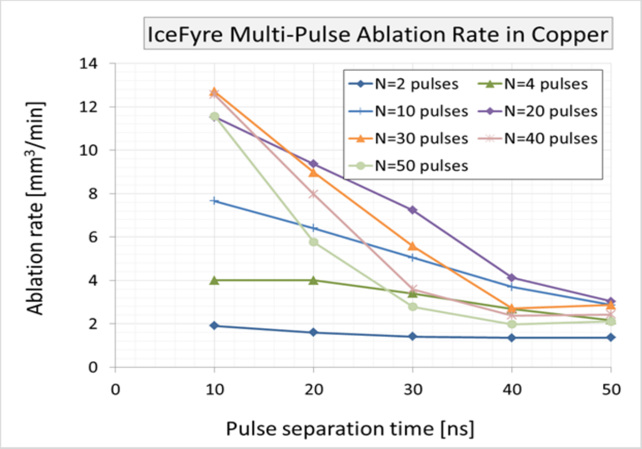


Fig. 4 Volume ablation rate with pulse bursts improves with higher number of pulses and shorter separation times.

The data in Figure 4 shows clearly that increasing the number of pulses in the burst is beneficial for increasing removal rates, especially with shorter pulse separation times. At the shortest separation time of 10 ns the overall maximum material removal rate of ~12.6 mm^3/min is achieved with 30-40 pulses in the burst. Further increasing the number of pulses to 50 results in a reduced ablation rate, indicating that optimal ablation rate condition has been crossed. Compared to the highest ablation rate with a single pulse of 6.5 mm^3/min, the rate with a 30-pulse burst is approximately a 2× improvement.

Burst ablation rates for longer separation times were also determined. Figure 5 shows ablation rate data out to pulse separation times of 500 ns.

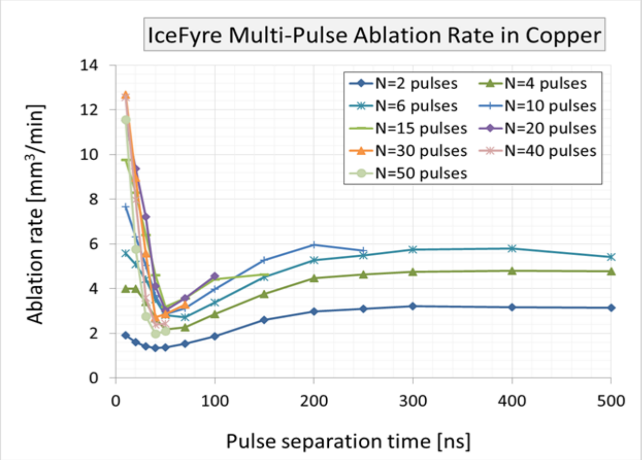


Fig. 5 Burst volume ablation rate trend with pulse separation times beyond ~50 ns.

Figure 5 shows that, interestingly, the trend somewhat reverses and the ablation rate for all burst pulse conditions begins to increase slightly as the separation time exceeds about 40-50 ns. The rate for the 6- and 10- pulse bursts approaches 6 mm^3/min, which is just below that for a single pulse at 3.2 MHz. This is consistent with the perspective of an optimal fluence for ablation since the fluence for a single pulse at 3.2 MHz corresponds to that of a single sub-pulse within an 8-pulse burst at 400 kHz. Comparatively, with the short 10-ns burst separation time, the optimal number of pulses is between 30 and 40 which equates to a fluence of just one-fourth of that which is optimal for a single pulse.

For the unique case of pulse separation times of 10 ns, which results in the highest ablation rates for a given number of pulses in the burst, the ablation rate vs. number of burst pulses is plotted in Figure 6 below.

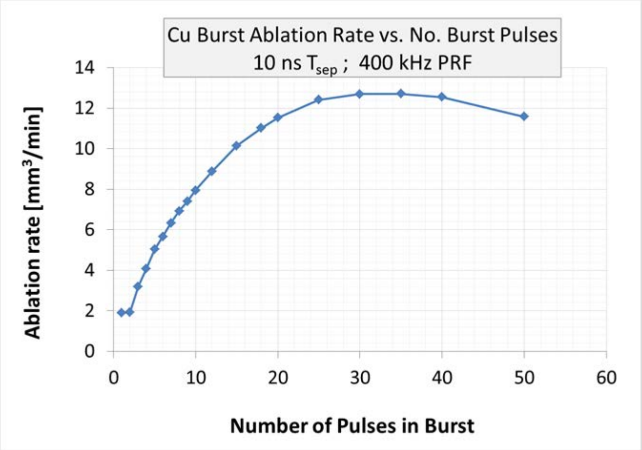


Fig. 6 With 10 ns pulse separation, ablation rate is broadly peaked with 25-40 pulses within a burst

While the increasing ablation rate with increasingly large burst pulses is clearly evident—with a broad peak for ~25-40 pulses—there is also a discrepancy in the first two data points, a single pulse vs. a burst of 2 pulses. The fact that the volume ablation rate is the same for both cases implies that two pulses with half the energy of the single pulse have an ablation rate that is also halved. For such high fluences, the ablation rate for each of the two pulses in the burst should theoretically be only slightly lower than that of the single high energy pulses. In contrast, when increasing from 2 to 3 pulses in the burst, the expected increase in ablation rate due to more optimal fluence is observed. While the authors do not currently have an explanation for this apparent deviation from theory, it should be noted that other researchers have seen similarly discrepant ablation rate behavior in copper when comparing 1 vs. 2 vs. 3 pulses in a burst of picosecond pulses [2].

3.4 Copper machining quality

Some quality assessment of the machined features was undertaken using optical microscopy and digital camera macro photography. While ablation rates using burst machining is clearly advantageous compared to a single pulse, there should also be a consideration for quality, especially given that laser users typically turn to ultrafast lasers to improve it.

For the highest ablation rate using a single pulse (at 3.2 MHz) and a near-best ablation rate using a burst of 50 pulses (10 ns separation) at 400 kHz, a comparison of digital macro photos is shown in Figure 7 below.

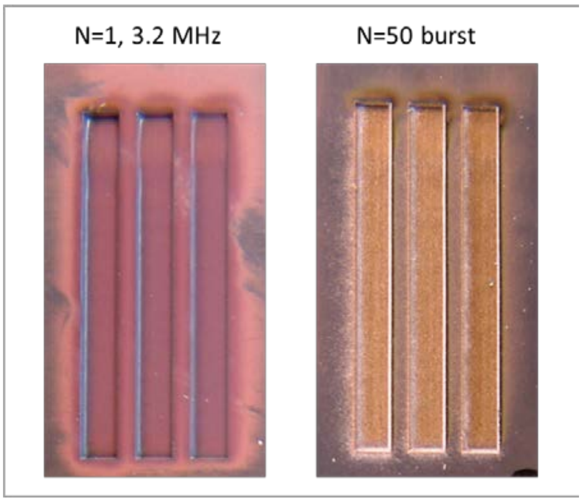


Fig. 7 Digital macro photos of 1 mm wide milled regions with a single pulse vs. a burst of 50 pulses

From the photos, there is clear evidence of higher oxidation formation with the single pulse output as well as a significant amount of residual debris surrounding the machined features. On the other hand, the features machined with a burst of 50 pulses show no oxidation formation (judged as a discoloration of material) and minimal debris deposition surrounding the features, though the machined surface at the bottom of the trench does appear to be somewhat rougher. It is interesting that while the ablation rate is nearly double for the 50-pulse burst, there is significantly less debris surrounding the features. It is not clear why this is the case. Many microelectronics and printed circuit board manufacturing applications use lasers for machining of copper, and the presence of debris and oxidation can present various manufacturing hurdles ranging from cleanliness of the parts to good electrical contact formation when adding subsequent copper layers.

Using optical microscopy, machined surfaces were observed more closely. Figure 8 shows optical photomicrographs of machined surfaces for single pulse output (low and high PRF) as well as burst output (N = 5, 10, 20 pulses in the burst).

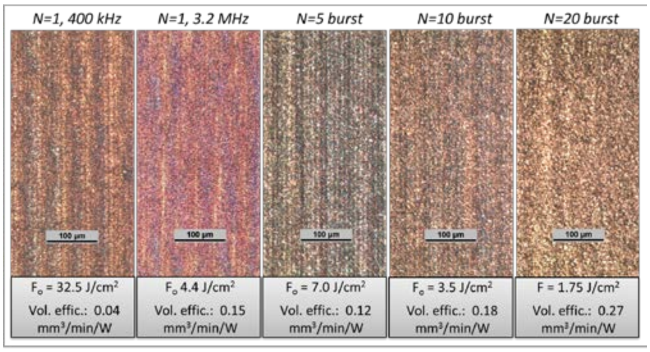


Fig. 7 Optical microscope photos of milled surfaces for single and burst pulse machined features; fluence and volume ablation efficiency are also shown.

The photos in Figure 7 indicate that for a single pulse, the surface is somewhat smoother at 3.2 MHz vs. 400 kHz, yet it is also more oxidized (evidenced by the reddish color of the surface). For the features machined with pulse bursts, increasing from 5 to 20 pulses in the burst shows an increase in overall cleanliness as well as reduced oxidation of the machined surface.

3.5 Silicon ablation

Preliminary volume ablation rate data was also generated for machining crystalline silicon material. Single pulse ablation rate data was generated for two PRFs (400 kHz and 1.6 MHz). Burst machining data was generated for up to 10 pulses in a burst for the range of 10-50 ns pulse separation times. For the unique case of 10 ns pulse separation (which had shown to be most beneficial), ablation rate data was generated for up to 50 pulses in a burst.

Figure 8 shows the ablation rate data for single pulse output as well as up to 10 pulses in a burst with pulse separation times between 10 to 50 ns.

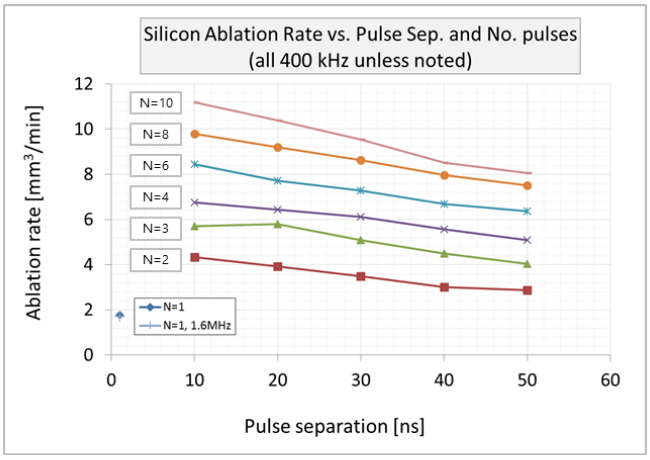


Fig. 8 Ablation rate data for single and burst pulse output for silicon.

Using a single pulse, operating at both 400 kHz and 1.6 MHz resulted in nearly identical ablation rates. For each burst output studied (2 to 10 pulses in a burst), shorter pulse separation times resulted in higher ablation rates. For pulse separation times from 50 to 500 ns, additional ablation rate data was generated for the case of a 4 pulse burst. The result was that ablation rates continued to decrease monotonically without reversing to higher rates as had occurred with copper.

The machined surfaces for select features were imaged with an optical microscope, and photomicrographs are shown in Figure 9 below.

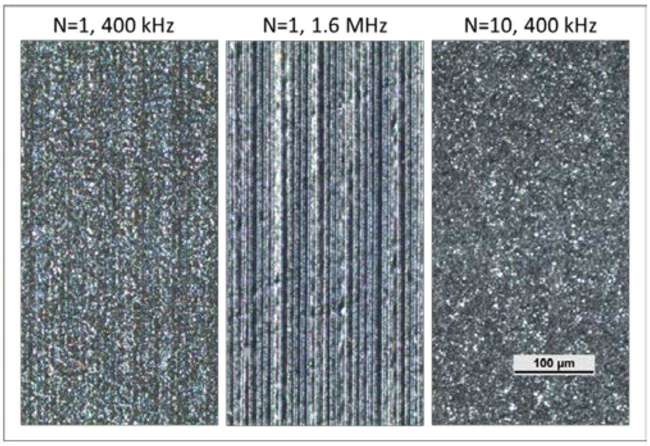


Fig. 9 Optical microscope images of machined silicon surfaces for a single pulse at high and low PRFs as well as that for a 10 pulse burst at low PRF.

For single pulse output at 400 kHz and 1.6 MHz, Figure 9 shows a clear difference in the surface appearance, and with the higher PRF condition some evidence of melting can be seen. With a burst of 10 pulses, the surface is more granular with no evidence of melting and, at the same time, the ablation rate is nearly 6× the single pulse result.

For 10 ns pulse separation time, ablation rate data for up to 50 pulses in a burst was also generated, and is plotted in Figure 10 below.

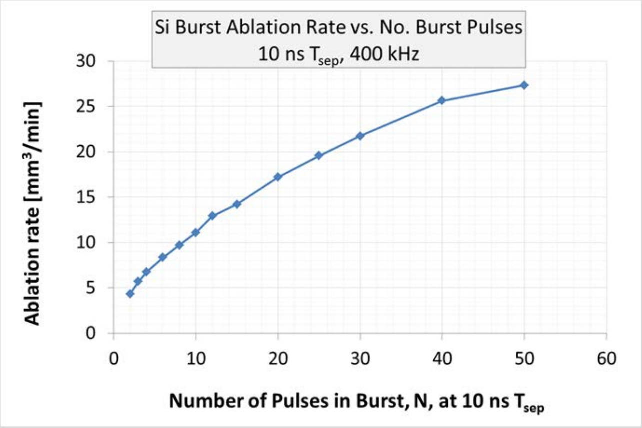


Fig. 10 Ablation rate data for burst machining of silicon with up to 50 pulses per burst.

The data shows a continued increase in ablation rate even with the pulse energy distributed amongst up to 50 pulses within the burst. However, the trend of the data does show that near bursts of ~40-50 pulses the rate of improvement is lessening and indicates that a maximum rate of about 30 mm^3/min would be achieved somewhere between 50 and 70 pulses in the burst.

4. Conclusion

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

When machining copper, it was shown that for a single pulse output a pulse frequency of ~3.2 MHz resulted in maximum material removal rate of nearly 6.5 mm^3/min. For burst machining, significant advantages were gained, with a doubling of the ablation rate to nearly 13 mm^3/min. When processing silicon, a similar result was found, with burst machining offering >6× higher ablation rate compared to a single pulse. For a single pulse, the ablation was similar at both 400 kHz and 1.6 MHz; however the 1.6 MHz PRF appeared to generate melting. For both copper and silicon, the shortest pulse separation time of 10 ns generally offered the highest ablation rate. Also, in both materials we have shown that with optimal burst machining parameters, improved quality is achieved along with the higher ablation rates.

Using the IceFyre's unique TimeShift ps capability, it was shown that throughput can be improved 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.

References

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