HIGH-QUALITY CUTTING OF POLYMERS WITH FEMTOSECOND LASERS

Polymers play a vital role in various technology sectors. They offer a range of properties in terms of mechanical strength and flexibility, electrical insulation, and thermal and chemical resistance. Two polymers of particular note are polyimide (PI) and polyethylene Terephthalate (PET). Polyimide, known for its high mechanical strength and thermal/chemical resistance, continues to be a mainstay in the flexible printed circuit board market, serving as a robust dielectric material to manage the flow of electrical current. In resin form, PI is also used in thermoset carbon fiber constructs as well as high-temperature fiber coatings and integrated circuit passivation layers. PET on the other hand is a general-use polymer, with applications ranging from medical devices to food packaging. As a bulk material, PET is attractive due to its good strength-to-weight ratio and overall break resistance; in fiber form it comprises durable, water-resistant and wrinkle-free fabrics. The two materials, PI and PET, do however share a significant common application space: OLED flat panel displays. PET, having good temperature resistance relative to other low-cost polymers, is historically a common substrate material but is also used elsewhere. In more demanding applications, the superior strength, thermal, and electrical properties of PI provide benefit. For both materials, thicknesses used throughout an entire flat panel or OLED display can range from thin films of several microns to thicker sheets of several 10's of microns or more. As devices and displays become more lightweight and flexible/foldable, overall thicknesses are likely to decrease.

Lasers have been used to process polymers for many years and in many industries. While it can be difficult to avoid melting and other heat-affected zone (HAZ) formation, ultrashort pulse (USP) lasers are known to be up to the challenge. To further our understanding of USP processing of PI and PET, researchers at our application lab conducted a comprehensive ablation phenomena study using a high-power femtosecond laser, the Spirit® 100 W laser at both the infrared (IR) fundamental (1030 nm) and the green second harmonic (515 nm) wavelengths (50 W average power). The study encompassed ablation thresholds determination for single- and multi-pulse irradiation (including determination of the so-called "incubation coefficient"), and application of this information toward developing

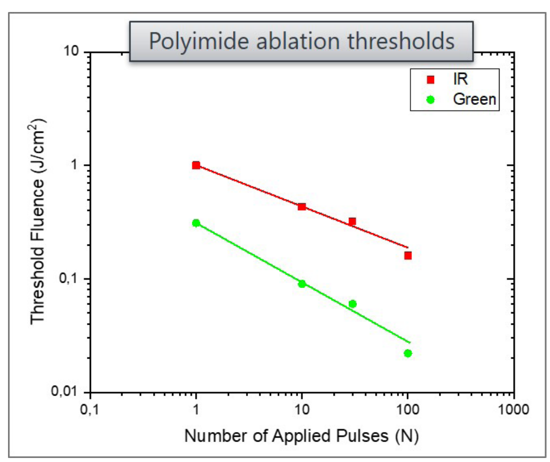

Figure 1: Single- and multi-pulse ablation thresholds in Polyimide.

and optimizing full-cutting processes with both single- and multi-pass approaches. Thresholds were determined for stationary beam (percussion) exposures ranging from 1–100 pulses using a focus spot size of ~17 μm ($1/e^2$ diameter) for both wavelengths. Methods used for single- and multi-pulse thresholds determination and analysis were those of *Liu*[1] and *Jee et. al.*[2], respectively. To differentiate any threshold dependence on heat accumulation, tests were also performed at a wide range of pulse repetition frequencies (PRFs), from 1 kHz to 2 MHz. The samples used in the experiments were PI and PET plain sheets of various thicknesses procured from Creative Global Services Inc. (Newmarket, ON, Canada) At the Spirit laser's nominal PRF of 1 MHz, ablation thresholds in PI for 1–100 pulses at the IR and green wavelengths are plotted in Figure 1.

For both wavelengths, we see a strong decline in ablation thresholds with increased number of applied pulses. This is a known phenomenon in laser material processing and is due to the formation of material defects by lower energy pulses. Such defects are not generally observable as true "damage" to the material in single-pulse ablation studies, but they do subtly modify the material such that subsequent pulses of the same (low) energy are able to cause damage, i.e. a detectable ablation feature. The amount of threshold reduction with number of applied pulses is characterized by the incubation coefficient, with a lower value corresponding to stronger threshold reduction. Table 1 below summarizes the thresholds and incubation coefficients found in PI and PET for both wavelengths of the Spirit laser.

Ablation Threshold Fluence- F_{th}(N)-(J/cm²)	N=1	N=10	N=30	N=100	Incubation Coefficient (S)
Polyimide- IR	1.00	0.43	0.32	0.16	0.63±0.02
Polyimide - Green	0.31	0.09	0.06	0.022	0.47±0.02
PET - IR	1.09	0.40	0.32	0.16	0.60±0.02
PET - Green	0.73	0.04	0.02	0.008	0.32±0.06

Table 1: Summary of thresholds in PI and PET by wavelength and number of irradiation pulses.

We see the green wavelength shows enhanced threshold reduction with higher pulse counts compared to IR, especially in the case of PET, where the threshold is reduced by 9× going from 1 to 100 pulses. Also of note is that the IR thresholds are remarkably similar in both materials for all pulse exposures.

Given that polymers are thermally insulating, it is conceivable (or even expected) that, at higher PRFs, heat accumulation between pulses could serve to effectively decrease multi-pulse ablation thresholds. To test for this, thresholds were determined for the case of a 30-pulse exposure at PRFs from 1 kHz to 2MHz, with results for polyimide in Figure 2.

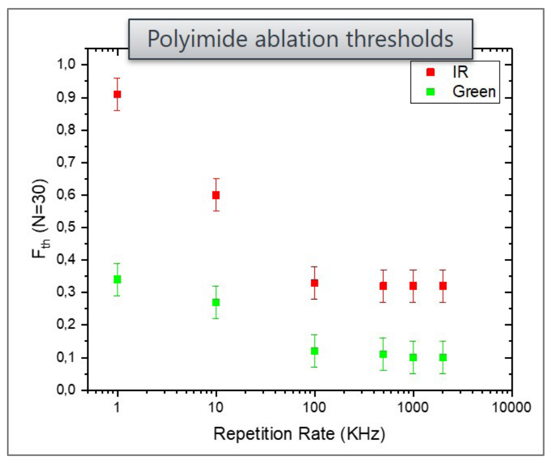

Figure 2: PRF-dependent threshold reduction in polyimide with 30 applied pulses.

The data indicates that increasing the laser PRF from 1 kHz to 100 kHz causes a significant threshold reduction, while thresholds beyond 100 kHz are relatively unchanged. It is worth noting that there is no observed increase in threshold, which would occur if there were issues relating to plasma and/or debris-shielding of laser pulses. Such phenomena are known to occur with some materials and serve to hamper the scaling up of throughput via higher PRFs. Hence, from this perspective, there is no penalty for processing at the very high PRFs at which the Spirit offers the highest output power levels. Having determined the ablation threshold behavior for various pulse exposures and frequencies, processes for full-cutting of 75- and 125-µm thick PET and PI films were developed for the two wavelengths. Cutting speeds at 2 MHz PRF for both single- and multi-pass processes are tabulated in Table 2.

	75 µm (3 mil)		125 µm (5 mil)	
Cutting Speed (mm/s) (2 MHz PRF)	Single-pass cutting	Multi-pass cutting	Single-pass cutting	Multi-pass cutting
Polyimide – IR, 70 W	540	400	390	363
Polymide – Green, 42 W	540	363	420	307
PET – IR, 70 W	900	800	470	400
PET – Green, 42 W	880	666	510	363

Table 2: Various cutting speeds achieved with the Spirit laser using 2 MHz PRF.

Various trends can be observed in the data. For example, single-pass cutting is found to be faster than multi-pass across all materials, wavelengths, and thicknesses. Regarding the effect of wavelength, IR is faster than green for all cases with multi-pass cutting while green is the same speed or faster for single pass cutting. Given that the IR average power is significantly higher than green, the shorter wavelength is more efficient in terms of throughput per unit power (i.e. mm/s/W) in all cases.

While single-pass cutting is faster, the benefit of highest quality USP processing is more fully achieved with the lower pulse overlap of multi-pass cutting. This excellent quality for both IR and green is evident in the microscope photos of cuts in 125 µm thick PI in Figure 3.

For both wavelengths, low or no HAZ is evident. While the IR cut does exhibit some fine particulate debris along the edges, this would likely be easily removed with mild post-process cleaning. With green, the lack of HAZ and debris is particularly noteworthy. There is the added benefit of a much narrower kerf with the green wavelength as well,

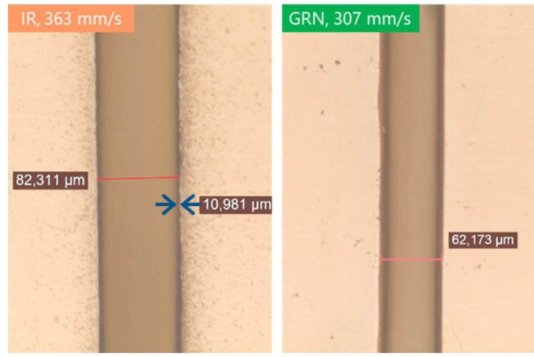

Figure 3: Excellent quality, minimal HAZ for multi-pass cutting of 125 µm thick PI with IR and green wavelengths.

which may be important in some applications. Turning to multi-pass cutting of PET, we find similar—but not identical—results (Figure 4).

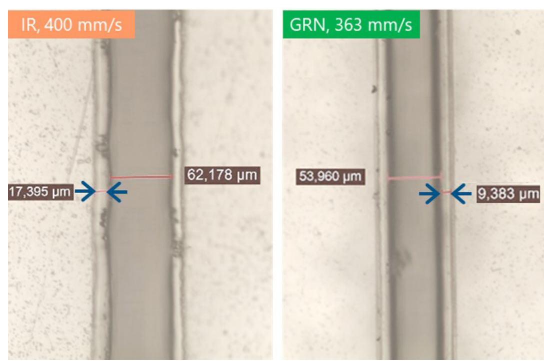

Figure 4: IR vs. green comparison photos of multi-pass cutting in 125 µm thick PET.

A key observation is the presence of minor swelling at the edge of the cutting kerf, seen with both green and IR, and likely due to the much lower softening/melting temperature of PET compared to PI. This melt effect results in a less significant quality difference between IR and green compared to what is seen with PI. There is still, however, the advantage of less residual debris for the case of green processing.

PET and PI polymers play an increasingly significant role in critical applications from medical devices to OLED displays. The ablation threshold data presented here characterize the expected processing advantages and/or tradeoffs when processing with IR or green wavelength, high or low pulse exposure, and with low to high PRF. In using this data to derive full cutting processes, the excellent quality and high throughput that can be achieved with the Spirit femtosecond laser are demonstrated.

REFERENCES:

1. J. Liu, 1982. *"Simple technique for measurements of pulsed Gaussian-beam spot sizes," Opt. Lett. 7, 196-198.*
2. Y. Jee., M. Becker., and R. Walser., 1988. *"Laser-induced damage on single-crystal metal surfaces," J. Opt. Soc. Am. B 5, 648-659 (1988).*

PRODUCT

Spirit® 1030-100 and 515-50

The Spirit 1030-100 and 515-50 lasers set new standards for femtosecond lasers in high-precision industrial manufacturing. These lasers deliver high average power, high pulse energy, and high repetition rates for increased throughput. Customers benefit from the shortest industrially available pulse duration and superior beam quality that in turn enables machining complex and challenging parts with highest precision and quality with literally no heat affected zone (HAZ) at the highest throughput. Spirit 1030-100 and 515-50 are designed for industrial use and offer reliable and robust 24/7 operation with lowest cost of ownership.

	Spirit 1030-100	Spirit 515-50
Wavelength	1030 nm ±5 nm	515 nm ±3 nm
Output Power	>100 W	>50 W
Pulse Energy	>100 µJ	>50 µJ
Repetition Rates	1–30 MHz	
Pulse Selection	Single shot to 2 MHz using Integrated Pulse Picker (AOM)	
Pulse Width	<400 fs	
Power Stability	<1% rms over 100 hours	
Pulse-to-Pulse Stability	<2% rms	
Spatial Mode	TEM_{00} (M^2 <1.2)	
Beam Diameter	2.5 mm ±0.5 mm	
Beam Divergence, full angle	<1 mrad	<0.5 mrad
Burst Mode	>100 µJ/burst, up to 12 sub-pulses	N/A
Pre-Pulse Contrast Ratio	>250:1	
Polarization	Horizontal	
Cold Start Time	<30 min.	
Warm Start Time	<15 min.	

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