A Comparative Study of Laser Induced Plasma Micro-Machining and Laser Ablation of Low Melting Point Polymers

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Laser Induced Plasma Micro-Machining (LIPMM) has emerged as a viable alternative to laser ablation for precision micro-machining and surface texturing of several classes of materials. Soft polymers that have low melting temperatures of typically below 200^{0}C are particularly susceptible to heat affected zones and other forms of thermo-mechanical damage via direct laser ablation owing to their thermo-mechanical as well as optical properties. This study investigates the effectiveness of the LIPMM process for machining low melting point polymers as compared to laser ablation. The laser system used is a highly compact, low power and cost-effective solid state laser that is inefficient at processing these polymers via direct ablation. Single-pass micro-channels are machined on the polymer surfaces, and a comparative assessment is done to determine the benefits of LIPMM in terms of achieved depths and aspect ratios of the channels at the best focusing condition, as compared to laser ablation. The greatest benefit is seen for the polymer with the lowest melting point (ABS plastic), with a depth improvement of up to 86% and aspect-ratio improvement of up to 260%. For LDPE and HDPE, the improvement was within 60-65% with no significant reduction in channel width. Moreover, the benefit of LIPMM process was maximal at the highest power and minimal near the threshold power.

NOMENCLATURE

ABS = Acrylonitrile Butadiene Styrene
LDPE = Low Density Poly Ethylene
HDPE = High Density Poly Ethylene
LIPMM = Laser Induced Plasma Micro-Machining

1. Introduction

Surface texturing and modification of polymer materials has been employed for critical applications in the field of bio-medical devices [1], photonics devices [2], MEMS and micro-fluidics [3, 4]. Particularly, bio-degradable polymers have been recently used for making coronary stents [5-7] and for drug delivery applications [7]. These polymers typically have low melting points (glass transition temperatures), in the range of 100-200 degrees Celcius [8], therefore, stent fabrication via laser ablation becomes challenging due to heat diffusion into the region surrounding the machined geometry leading to heat affected zones and distortion [9]. Owing to certain optical properties such as low absorption coefficients and low opacity, these soft polymers are also difficult to machine via visible-wavelength laser beams.

A wide variety of polymers have been reported to be machined by short UV laser pulses generated by Excimer lasers [10] due to the higher absorptivity of polymers at wavelengths ranging from 193 nm to 351 nm, and also due to the higher photon energy at these wavelengths (6.4 eV at 193 nm) that surpasses the polymer bond strength estimated at 4-5 eV. However, excimer laser systems suffer from several drawbacks such as relatively less power stability, high cost of the laser system and optics, large size, and environmental hazards due to noise and usage of excimer gas and filters [11]. Solid state diode lasers operating in the visible wavelengths offer higher stability, compactness and are more cost-effective [12]. However. precision micro-machining of polymers using visible wavelengths is challenging due to several aspects of polymer processing by photo-thermal interaction with visible laser beams, with the exception of femtosecond lasers. The foremost controlling factors in polymer processing are beam power and pulse duration [6], since these directly control the intensity and peak power of the beam interacting with the polymer surface.

Presently, femtosecond lasers have been used for fabrication of low melting point polymers [9]. The ultra-short pulse duration, the peak power and intensity of the femtosecond lasers leads to cold (athermal) ablation in materials [13], in which the duration of the pulse itself is much shorter than the time taken for heat dissipation into the surrounding material. Moreover, the bulk of the laser intensity is utilized in optical photo-ablation rather than thermal ablation. Due to these reasons, ultra-short pulsed (femtosecond) laser ablation is desirable for processing heat-susceptible materials. However, pico-second and nano-second laser systems are more compact, cost-effective and energy efficient alternatives, with the same average power as typical femtosecond laser systems. As a consequence, the motivation of this study is to employ a low power pico-second laser system to perform precision micro-machining of a variety of low melting point polymers via the process of laser induced plasma micro-machining (LIPMM).

LIPMM [14] is a micro-texturing process recently proposed by the authors of this work as an alternative to direct laser ablation. In LIPMM a laser beam is tightly focused inside a dielectric media, usually distilled water or kerosene, to generate plasma at the focal volume. When the substrate is placed a few microns below the created plasma spot the plasma matter interaction causes material removal by thermo-mechanical ablation. Since material removal rate in LIPMM depends on the electron density of the plasma and the ablation threshold of the material the issue of low material removal rates for materials with high absorptivity and reflectivity is resolved. Materials reported to be machined by LIPMM include highly polished metal alloys, silicon wafers and transparent materials like borosilicate glass and quartz [14]. Evidently, LIPMM offers a significantly enhanced multi-materials processing capability as compared to conventional laser texturing.

2. Materials and Processing Conditions

2.1 Polymers

Three low melting point polymers were used in this study, as described in Table 1. These polymers are commercially available with a variety of properties such as color, surface finish, rigidity and shape. For this study, the three polymers used have melting points in the range of 105-180^{0}C and opacity ranging from translucent to completely opaque, the gradient color being white.

2.2 Experimental Setup

A commercially available Nd-YVO_4 laser (Lumera Lasers Inc.) with 8 ps pulse duration operating at its second harmonic (532 nm wavelength) was used for machining, in both laser ablation as well as LIPMM. The operating pulse repetition frequency was set to 20 kHz and average power was varied in the range of 50 – 70 mW, yielding a maximum pulse energy of 7 μJ after reflection and transmission losses within the beam delivery system, as measured by an external power meter (Gentec Solo 2(R2)). The Gaussian beam (M^2 < 1.2) was brought to focus with a 25 mm triple-element focusing lens to a diffraction-limited focus of 10 μm spot size ($1/e^2$). The substrate, kept in air at room temperature, was mounted on a 5-axis motion stage with a translation resolution of 10 nm and rotational resolution of 0.0001 degrees.

Table 1. Polymer materials used in experimentation

Polymer	Melting Point	Optical Properties
Acrylonitrile Butadiene Styrene (ABS)	105 ^{0}C	Opaque
Low Density Poly Ethylene (LDPE)	120 ^{0}C	Translucent
High Density Poly Ethylene (HDPE)	180 ^{0}C	Translucent-Opaque

2.3 Methodology

A 2% beam splitter was mounted coaxially with the laser beam to send a visual feedback into a high resolution CCD camera for monitoring the machining process and to assist in manually translating the substrate in the vertical direction to focus the laser beam. The focused laser spot (in case of laser ablation) or plasma plume (in case of LIPMM) was translated to machine a micro-channel. A single-pass micro-channel is created when craters machined by consecutive laser pulse discharges are overlapped by moving the workpiece at typical feed-rate values. The geometric characteristics of the single-pass micro-channel depend on the feed-rate and pulse energy level of the incident laser beam. The same operating parameters were used for LIPMM, but with the presence of a transparent dielectric media (distilled water) that the beam was brought to focus within, and a stable plasma was observed. This plasma plume was brought in contact with the workpiece (also immersed into the dielectric) to machine features via thermo-mechanical ablation. Figure 1 shows an image of the plasma plume inside the dielectric while it is not in contact with the workpiece. The laser beam is incident from the top of the image into a beaker filled with distilled water, and the workpiece, immersed into the liquid, is below the plasma plume. The horizontal translation speeds of the workpiece were kept below 0.2 mm/s to avoid ripples on the surface of the dielectric, in order to maintain geometric focus at the workpiece. Post machining, the samples were cleaned ultrasonically, to eliminate debris and depositions. The depth and width of the machined channel was measured at three different cross-sections along its length.

All features were characterized using an Alicona Infinite Focus Measurement (IFM) 3D metrology system with an optical resolution of 1 micron (horizontally) and 0.3 micron (vertically).

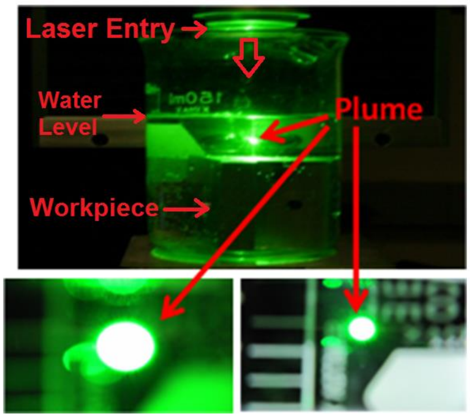


Fig. 1: Plasma plume inside the dielectric media (beam incident from the top)

Due to poor visibility through the monitoring CCD camera, multiple channels were machined on the surface, at different heights of THE beam focal spot with respect to the surface, see Fig. 2. From left to right, the focal spot was offset vertically up with respect to the surface, to vertically down in the rightmost channel. The step of vertical offset was 50 µm between consecutive channels. This process ensured that the 'best focus' channel was determined experimentally by observation.

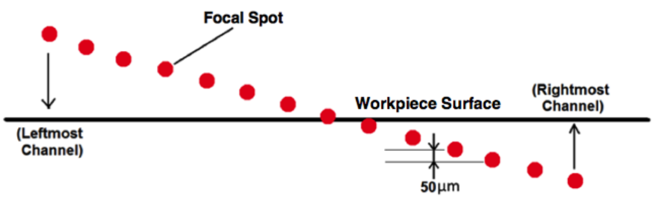


Fig. 2: Schematic representation of micro-channel fabrication at different positions of the focal spot with respect to the workpiece surface

2.4 Process Parameters

Table 2 describes the various process parameters used while machining all of the polymers. The average power, determined by the laser system limitation, was in the range of 50 – 70 mW for a pulse repetition frequency of 20 kHz. Due to energy losses in the intervening beam delivery system, the energy was measured by an external power meter.

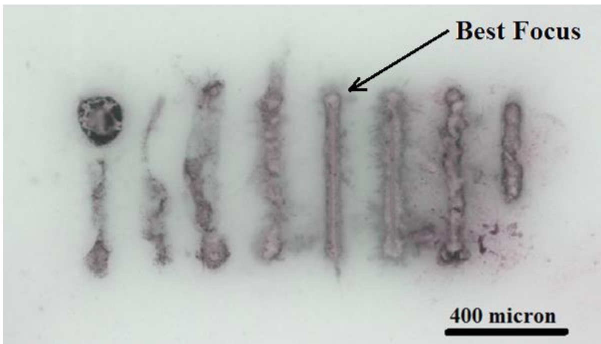
Table 2: Process parameters and their values

Process Parameter	Value
Average Power	40 – 70 mW
Pulse Repetition Frequency	20 kHz
Feed rate	0.2 mm/s
Step size in depth	50 µm
Channel length	0.5 mm

3. Results

3.1 ABS Plastic

ABS plastic, with a melting point of 105^{0}C, is hard to machine with conventional laser ablation due to its high susceptibility to heat dissipation into the region surrounding the machined area. A 1"x1" strip of white and optically opaque ABS plastic was used as a target substrate. The surface roughness was approximately 0.5 micron R_a value. Figure 3 shows a visual comparison of the machined surfaces for both processes that were carried out using the strategy discussed in Section 2.3. Moreover, the channel obtained at the best focusing condition, as indicated, has the greatest cross-section depth. Evidently, the heat affected zone formation around the channel is significantly more in laser ablation, due to heat dissipation. The melting followed by re-solidification of the material around the channel leads to thermal distortion, irregular wall geometry, compromised material strength, bond strength and other thermo-mechanical and optical properties [15]. Also, the typical cross-section of the best focus channel has a much smaller depth and aspect ratio as compared to the LIPMM channel, see Fig. 4.



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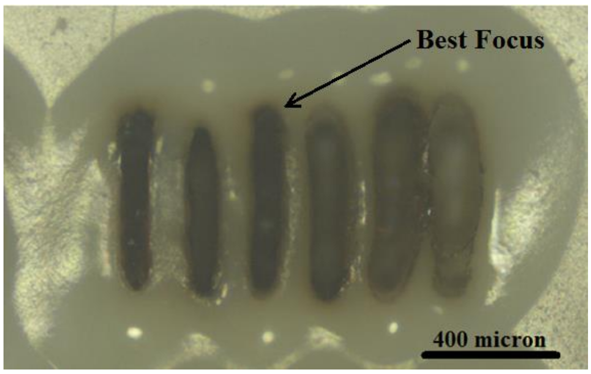

(b)

Fig. 3: Surface image of micro-channels machined in ABS by (a) LIPMM, and (b) Laser ablation, by focusing the plasma at different heights with respect to the substrate surface

Figure 5 shows a comparative assessment of micro-channel depths obtained by the LIPMM and laser ablation processes. It can be seen that LIPMM produces up to 86% deeper channels with up to 260% higher aspect ratios at the highest power used.

The improvement in depth and aspect ratio, however, reduces with average beam power, owing to the fact that with lower intensity a less dense plasma is formed, thereby allowing photo-ablative processes to take place alongside plasma-material interaction.

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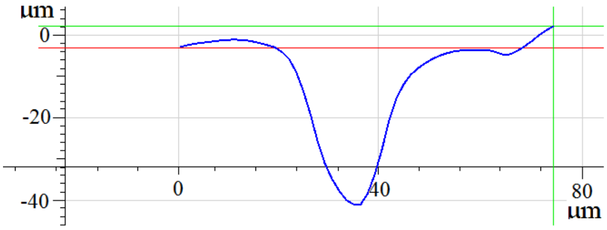

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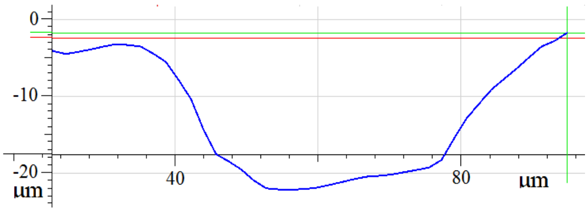

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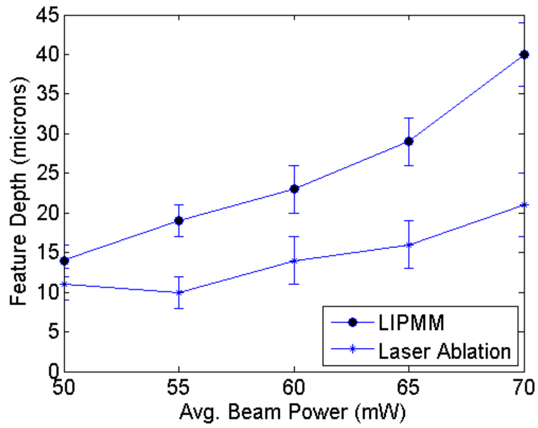
Fig. 4: Typical cross-section profiles of best focus micro-channels machined by (a) LIPMM, and (b) Laser ablation, at a 20 kHz pulse repetition frequency and 70 mW power



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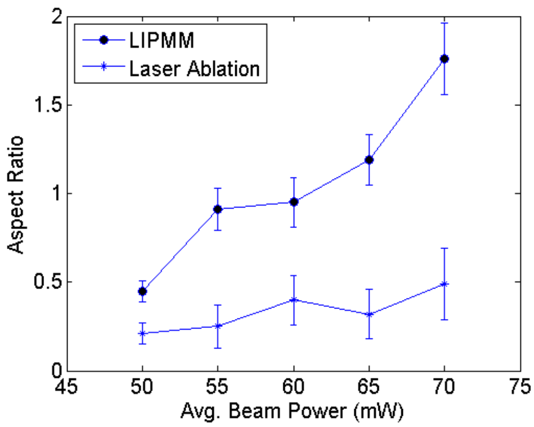

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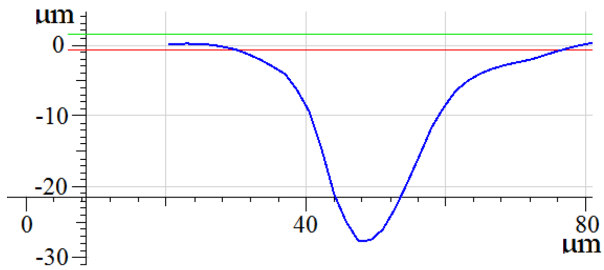
Fig. 5: (a) Depth, and (b) Aspect ratio of best focus micro-channels vs. beam power for ABS, obtained by LIPMM and laser ablation

3.2 LDPE

Low Density Poly Ethylene has a melting point of 120^{0}C, which makes it difficult to machine with conventional beam-based processes. Moreover, the LDPE used as a substrate is transluscent, thereby disabling an efficient radiation-material coupling. Micro-channels were machined on the LDPE surface via LIPMM and the laser ablation process. Typical cross-sections of best focus micro-channels are shown in Fig. 6. The improvement in depth by LIPMM as compared to laser ablation is up to 80% for the highest beam power. Moreover, the wall geometry obtained by LIPMM is smoother and more uniform. However, the channel widths obtained for both materials were similar, due to the optical properties of LDPE – namely low absorption coefficient and high ablation threshold, which reduce the overall material removal rate in laser ablation, creating a narrower channel. Also, the heat affected zones are nearly non-existent in both LIPMM and laser ablation.



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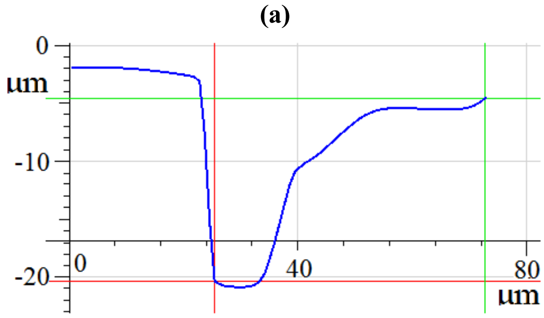


(b)

Fig. 6: Cross-section profiles of best focus micro-channels machined by (a) LIPMM, and (b) Laser ablation, at a 20 kHz pulse repetition frequency and 70 mW power

Figure 7 shows a comparison of micro-channel depths at all beam powers, for LIPMM and laser ablation. The improvement in depth is nearly constant, and in the range of 60 – 80% throughout the range of beam powers, and the variation in channel width remained within 18%. This can be attributed to the low optical absorption by LDPE throughout the range of beam intensities for visible wavelength in the case of laser ablation. In LIPMM, the thermal ablation creates deeper channels even for a weak plasma. The heat affected zones were also found to be minimal in both processes, due to the increased transmission of energy through the workpiece in the form of radiation, thereby reducing the thermal load.

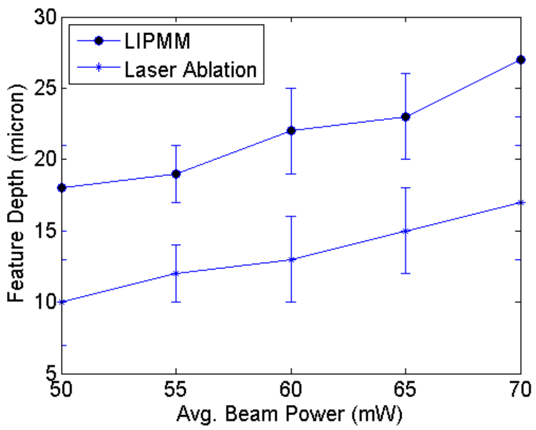


Fig. 7: Depth of best focus micro-channels vs. beam power for LDPE machined by LIPMM and laser ablation

3.3 HDPE

Surface texturing of High Density Poly Ethylene is used for specific applications in the automotive industry, food industry and even medical applications [16]. The rigid HDPE sheet used in this study has a relatively low melting point of 180^{0}C and is optically more opaque than LDPE. By both LIPMM as well as laser ablation, uniform channels were formed with visually absent heat affected zones. Figure 9 shows a surface image of micro-channels made by LIPMM. Figure 10 shows typical cross-sections of channels made by the LIPMM and laser ablation processes, at a 20 kHz pulse repetition frequency and the maximum available power (70 mW). Similar to LDPE and ABS, the LIPMM channels have a comparatively smoother and more symmetrical wall geometry, indicating that the material removal mechanism leads to minimal debris, cracking and recast layer.

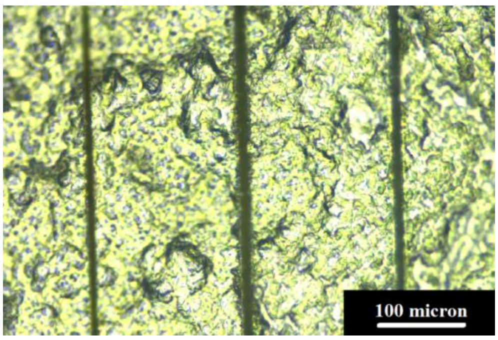
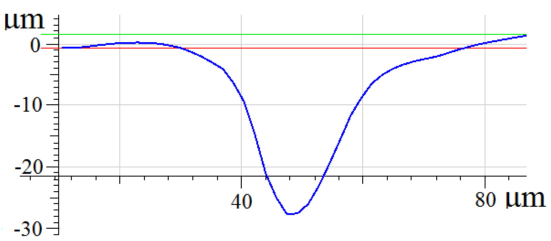


Fig. 9: Surface image of micro-channels machined in HDPE by LIPMM process



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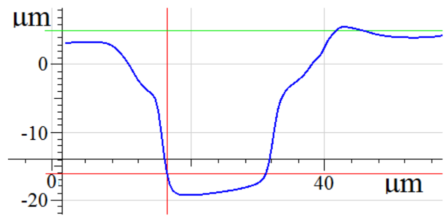

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Fig. 10: Cross-section profiles of best focus channels machined by (a) LIPMM, and (b) Laser ablation processes

A comparative assessment of micro-channel depths made by LIPMM and laser ablation is shown in Fig. 11. It is evident that the improvement in depth by LIPMM is lower near the plasma generation threshold power (approximately 50 mW), as compared to depths obtained at higher power levels, a trend similar to ABS plastic. Moreover, the overall improvement is the least amongst the three chosen materials in this study, between the range of 20-65%. This observation can be explained by the low density of free electrons in the plasma at low power, as well as high mass attenuation coefficient and high ablation threshold of HDPE owing to its higher density.

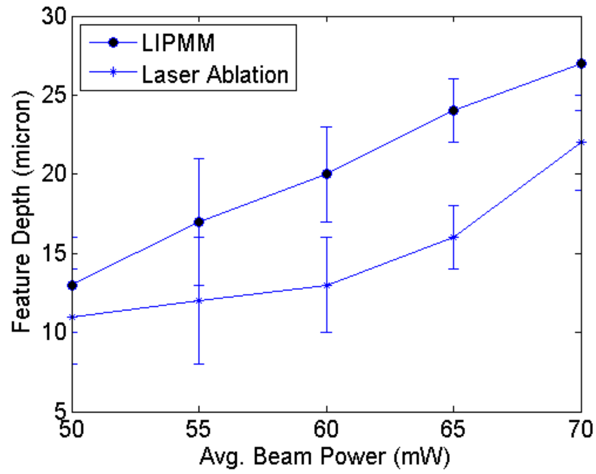

Fig. 11: Depths of best focus micro-channels made by LIPMM and laser ablation processes at different beam powers

4. Summary

Some key conclusions from this study are summarized as follows:

1. The LIPMM process involves the generation of a highly localized thermal plasma in the dielectric, which interacts with a workpiece to produce micro-features via the mechanism of thermo-mechanical plasma ablation.
2. LIPMM outperforms laser ablation for precision micro-machining of low melting point polymers, yielding greater feature depths, aspect-ratios, and superior wall geometries.
3. The improvements in micro-channel depths obtained by LIPMM, as compared to laser ablation, were in the range of 40-86%, 60-80% and 20-65% for ABS plastic, LDPE and HDPE respectively.

4. The improvement in aspect-ratio was more pronounced in ABS plastic, being up to 260%, as compared to laser ablation. LDPE and HDPE did not show a significant aspect ratio improvement due to the overall reduced material removal rate caused by their higher transmittivity and melting temperatures.
5. Heat affected zone formation was observed in ABS plastic, due to its extremely low melting point and opacity which trap thermal energy as well as beam intensity near the machining zone.
6. In all polymers, the wall geometries obtained by the LIPMM process, as observed by the channel cross-sections, were much smoother and symmetrical as compared to those obtained by laser ablation, primarily due to reduced debris, cracking and recast layer.

A better understanding of the role of ablation thresholds, optical transmittivity and absorption is required to predict the material removal rate and final geometry of machined micro-structures in LIPMM.

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REFERENCES

1. C. G. K. Malek, "Laser processing for bio-microfluidics applications (part I)," Analytical and bioanalytical chemistry **385**, 1351-1361 (2006).
2. D. Cristea, P. Obreja, M. Kusko, E. Manea, and R. Rebigan, "Polymer micromachining for micro-and nanophotonics," Materials Science and Engineering: C **26**, 1049-1055 (2006).
3. C. Liu, J. Chen, J. Engel, J. Zou, X. Wang, Z. Fan, K. Ryu, K. Shaikh, and D. Bullen, "Polymer micromachining and applications in sensors, microfluidics, and nanotechnology," Urbana **51**, 61801 (2003).
4. H. Becker and L. E. Locascio, "Polymer microfluidic devices," Talanta **56**, 267-287 (2002).
5. J. Ponkala, M. Rizwan, and P. S. Shiakolas, "On the design of a biodegradable POC-HA polymeric cardiovascular stent," in *ASME 2012 International Mechanical Engineering Congress and Exposition*, (American Society of Mechanical Engineers, 2012), 379-386.
6. C. Momma, U. Knop, and S. Nolte, "Laser cutting of slotted tube coronary stents—state-of-the-art and future developments," Progress in Biomedical Research **4**, 39-44 (1999).
7. B. Jeong, Y. H. Bae, D. S. Lee, and S. W. Kim, "Biodegradable block copolymers as injectable drug-delivery systems," Nature **388**, 860-862 (1997).
8. J. Lunt, "Large-scale production, properties and commercial applications of polylactic acid polymers," Polymer degradation and stability **59**, 145-152 (1998).
9. J. Harrington, R. Vaughan, K. Jow, W. Pippey, and Y.-M. Chen, "Laser system and processing conditions for manufacturing bioabsorbable stents," (Google Patents, 2014).
10. J. T. C. Yeh, "Laser ablation of polymers," Journal of Vacuum Science & Technology A **4**, 653-658 (1986).
11. J. J. Machat, *Excimer laser refractive surgery: practice and principles* (Slack Incorporated, 1996).
12. W. Koechner, *Solid-state laser engineering* (Springer, 2006), Vol. 1.
13. C. Rulliere, *Femtosecond laser pulses* (Springer, 2005).
14. K. Pallav and K. F. Ehmann, "Laser Induced Plasma Micro-Machining," ASME Conference Proceedings **2010**, 363-369 (2010).
15. I. Savu, S. Savu, and N. Sirbu, "Heat affected zones in polymer laser marking," J Therm Anal Calorim **115**, 1427-1437 (2014).
16. D. F. F. John F. Ready, *LIA Handbook of Laser Materials Processing* (Magnolia Publishing, Inc., 2001).