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Femtosecond laser cleaving of polymers with a non-diffracting beam

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Abstract

High-quality processing of polymers is one of the most important applications of ultrafast lasers. Heat-sensitive polymers with poor thermal conductivity require an ultrashort pulse duration and reduced repetition rate to minimize a heat-affected zone. Cutting thick polymeric samples is challenging because it often requires multi-contour scanning, which slows down the process and promotes thermal accumulation. This work presents a new approach based on non-diffracting beam cleaving using tailored ultrashort pulses.
Cleaving of different polymers, including poly (l-lactide) and poly (methyl methacrylate), with up to 3 mm thickness and a speed exceeding 0.7 m/s is demonstrated. An essential advantage of processing with a non-diffracting beam is negligible HAZ, kerf reduced to single microns, and no taper. This technique has considerable potential in processing polymer samples for special applications like optics and medical devices where the chemical composition of material during the process cannot be altered.

Keywords: polymer cleaving; femtosecond laser; non-diffracting beam

1. Introduction

Ultrafast laser processing of materials with non-diffracting beams has found many interesting applications and industrial implementations in recent years. The main application and the most significant market is glass cleaving for consumer electronics manufacturing. The principle of laser cleaving is a generation of microcracks in a controlled way inside the glass, causing efficient material separation after applying mechanical force or thermal stress [1]. Compared to ablation-based processing, femtosecond laser cleaving accelerates the processing speed, reduces kerf width, and provides HAZ-free material separation without taper. This technique has limitations for soft transparent materials such as polymers which exhibit plastic deformation. For this reason, generating microcracks with the laser beam is challenging. Successful polymer cleaving would be

especially beneficial for medical grade polymers and high-quality products made of substrates much thicker than laser spot size for which multi-contour ablation must be applied due to ablation rate saturation in V-groove. Effective cutting speed decreases quickly with a multi-contour approach that intensifies thermal accumulation. The elongated defects inside polymers can be generated using self-focusing and filamentation however, these modifications do not cover the entire sample cross-section. The pulse pitch cannot be low enough for easy fracture due to possible surface ablation that blocks the filamentation of the next pulses [2]. Until now, Bessel beam processing of PMMA has been investigated as a method of drilling [3].

This paper investigates the possibility of cleaving PMMA and PLA using a high-power femtosecond laser source generating ultrashort pulses with tunable duration. The non-diffracting Bessel-like beam allows narrow longitudinal modifications that can be induced with high spatial frequency. We show that bringing these modifications closer together creates a line of weakened material that is prone to fracture.

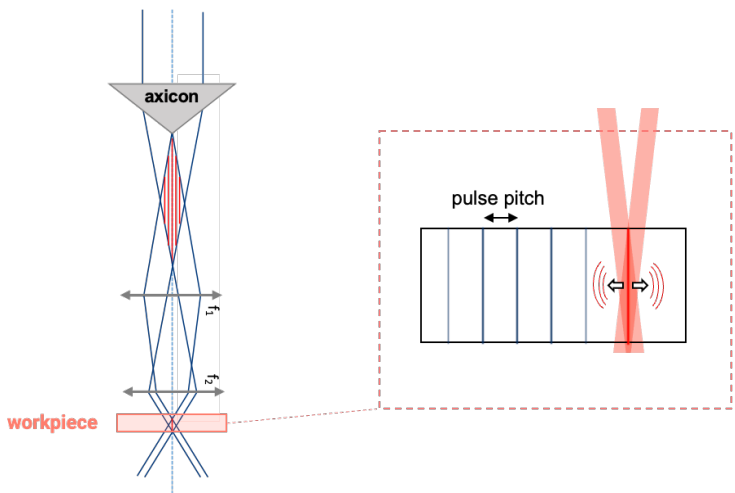

Fig. 1. A typical optical setup for Bessel beam generation with secondary Bessel focus inside transparent polymer causing adjacent longitudinal modifications covering the entire sample thickness

An interesting application of polymer cleaving is medical implants, where the material comes into direct contact with the patient's body. A high-quality HAZ-free processing ensures better biocompatibility and overall implant performance. Other applications include the singulation of injection molded lenses for mobile devices, dicing optical filters, or polymeric diffractive optical elements (DOE).

2. Experimental setup

The material processing was performed using Fluence's Jasper X0 femtosecond fiber laser operating at an average power level of 20 W, with an available output of 100 uJ pulse energy in a single short pulse. The laser generates a high-quality Gaussian beam with M^2<1.1. The pulse duration is tunable between 250 fs and 8 ps. The repetition rate was reduced using a built-in pulse picker. Built-in AOM modulates the laser power. In the experiment, the fundamental wavelength of 1030 nm was used. The applied DeepCleave optical module generates a non-diffracting beam having a 1.8 µm central lobe diameter (FWHM) of 1.0 mm length (in the air). The working distance of the used optics is 7.4 mm. The samples were positioned under fixed optics using

stacked XY direct drive linear stages with a positioning accuracy of ± 1µm. The polymer samples included PMMA and PLA polymers of 0.3 up to 3 mm thickness.

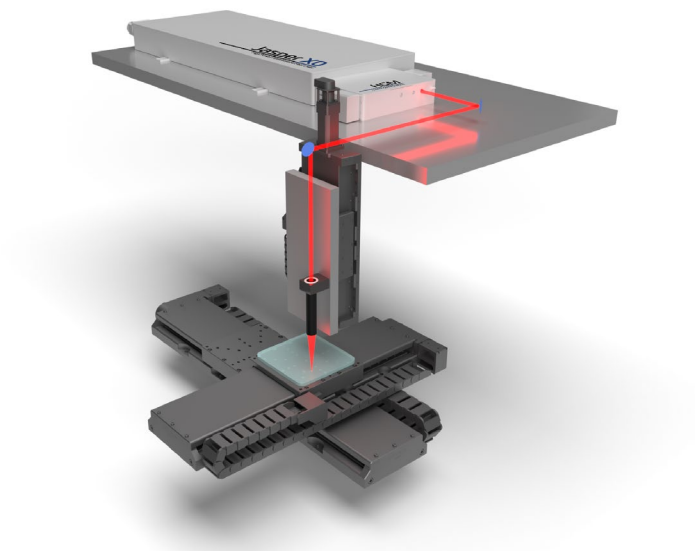

Fig. 2. Experimental setup with Jasper X0 femtosecond fiber laser, XYZ precision positioning system, and beam shaping optics.

3. Results

The experiments were performed using different laser pulse duration, pulse pitch, and material type/thickness. The most important observation is related to the pulse duration. The easiest mechanical fracture of different samples was obtained for the shortest pulses of 250 fs. When using picosecond pulse duration, breaking the samples was nearly impossible. A detailed SEM analysis was performed to investigate the reason behind this relation. For the SEM analysis, the samples processed by ps pulses were broken using additional tools. As presented in Fig. 3, the modifications created by ps pulses are well-defined elongated voids with no visible damage between modifications. Each void was created by a single laser pulse. In contrast, along with modifications induced by 250 fs we can see additional damage indicating strong compression of material as a result of the expansion of ionized material (Fig. 4). The visible periodic nanostructures perpendicular to the propagation direction indicate the nonlinear optical effects that may cause additional material defects. The fs-pulse-induced modifications are wider. These together suggest that shorter pulses cause more damage to the material between the elongated voids, leaving stress in these regions.

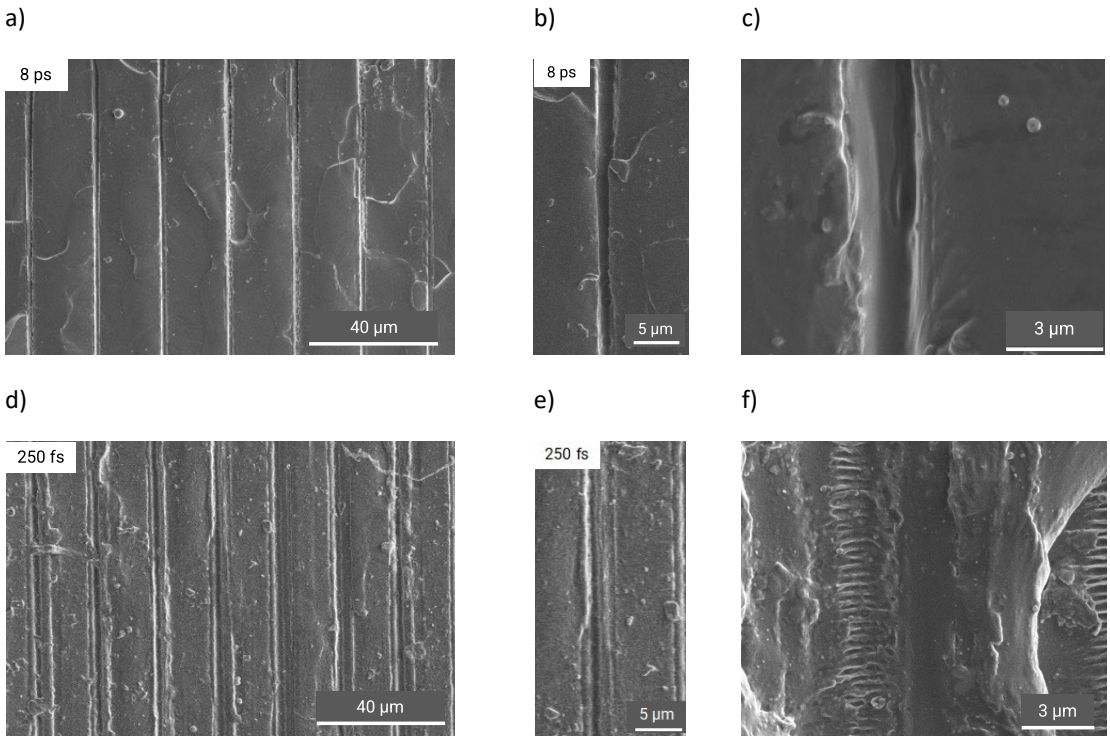

Fig. 3. a) Amorphous PLA cross-section after 8 ps pulse treatment and breaking, b-c) close-up of a single modification in the material, d) PLA cross-section after 250 fs pulse treatment and breaking, e-f) close-up of a single modification in the material.

The second critical parameter is pulse pitch. The experimental investigations showed that for PMMA samples, the pulse pitch needs to be in the range of 2 - 4 µm. The reason behind this low pulse pitch is that this polymer can absorb more energy during breaking before failure, and therefore laser-induced modifications must be as close as possible. On the other hand, polylactide is slightly more brittle; therefore, an acceptable pulse pitch can be higher. We also investigated crystallized PLA, which concluded that for more brittle samples with higher crystallinity, the pulse pitch can be much higher. In the extreme case, we applied a 30 µm pulse pitch, which means that the material can be modified with a speed of 6 m/s. The process is insensitive to the presence of crystalline fractions despite strong visible light scattering, which can be observed with the naked eye.

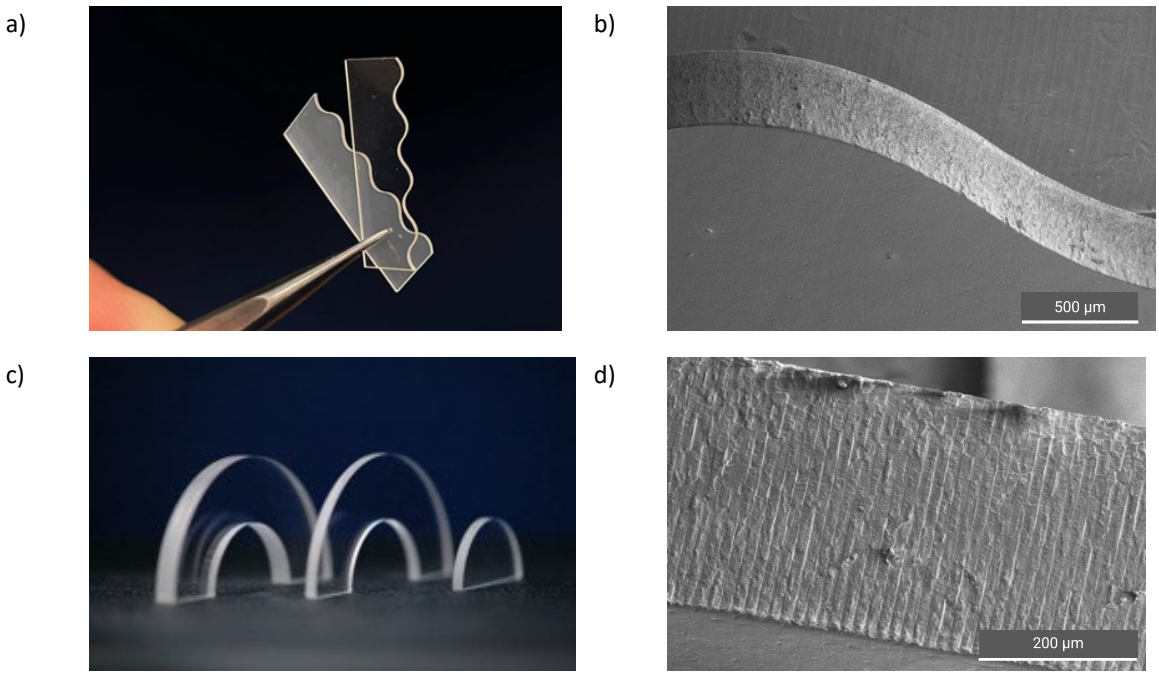

Fig. 5. Examples of polymer cleaving: a) amorphous (transparent) and crystalline (hazy) PLA thickness 0.3 mm, b) SEM image of the edge of round shape in crystalline PLA, c) edge of cleaved PMMA (thickness 3 mm – 3 laser passes and 1.5 mm – 2 passes) with the inner radius of round shape 10 mm, d) edge of crystalline PLA cleaved using 10 µm pulse pitch (2 m/s cleaving speed)

After finding the optimum parameters for each material type, we were able to fabricate different shapes in PMMA and PLA as well as crystalline PLA. For thicker (3 mm) PMMA samples multipass procedure with vertical position shift was successfully applied. The typical available scan speed for single-pass cleaving of materials up to 1 mm thickness ranges between 400 mm/s for more elastic amorphous polymers and 2 m/s for semicrystalline polymers with increased brittleness due to supramolecular structures.

4. Summary

The material edge with the described method is characterized by no heat-affected zone (HAZ) and no taper. Successful cleaving of straight and curved shapes was demonstrated as a single and multiple-pass procedure for substrates thicker than 1 mm. Maximum laser cleaving speed depends on pulse duration and the brittleness of the material, which can be tuned for semi-crystalline polymers such as PLA, PET, and PE. The pulse pitch can be higher with the higher sample crystallinity, resulting in impressive meters per second scan speed level at a 200 kHz pulse repetition rate. The easiest polymer fracture can be obtained using 250 fs pulse duration, which is critical for less brittle amorphous substrates. Surprisingly self-healing property of the Bessel-like beam allows for the cleaving of even crystallized hazy polymer samples that reveals strong visible light scattering. This non-invasive and high-quality process is well suited for specialty polymers like medical grade polyesters or injection molded polymer optics that must be singulated with high quality.

Acknowledgements

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