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Micromachining of transparent biocompatible polymers used as vision implants with bursts of femtosecond laser pulses

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Abstract

Biocompatible polymers are used for many different purposes (catheters, artificial heart components, dentistry products, etc.). One important field where biocompatible polymers are utilized is in production of vision implants known as intraocular lenses or custom-shape contact lenses. Typically, curved surfaces are manufactured by mechanical means such as milling, turning or lathe cutting. The 2.5 D objects/surfaces can also be manufactured by means of laser micromachining, however due the nature of light-matter interaction, it is difficult to produce a surface finish with a surface roughness better than ~ 1 µm Ra. Therefore, laser micromachining alone can't produce the final parts with optical-grade quality. Laser machined surfaces may be polished via mechanical methods; however, the process may take up to several days, which makes it economically challenging. The aim of this study is the investigation of the polishing capabilities of rough (~ 1 µm Ra) hydrophilic acrylic surfaces using bursts of femtosecond laser pulses. By changing different laser parameters, it was possible to find a regime where the surface roughness can be minimized to 18 nm Ra, while the polishing of the entire part takes a matter of seconds. The produced surface demonstrates a transparent appearance and shows great promise towards commercial fabrication of low surface roughness custom-shape optics.

Keywords: femtosecond micromachining, burst processing, intraocular lens, hydrophilic acrylic, surface roughness, polishing;

1. Introduction

Vision is one of the most important senses that enables us to experience and understand our surroundings. However, the eye just as any other organ or tissue in the human body deteriorates with age and vision

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worsening substantially contributes to the decrease in the quality of life. According to statistics about 50 % of Americans have developed cataracts by the age 75-79 (Congdon, 2004) and every third person in the world suffers from myopia (WHO, 2015). Todays advanced technologies provide means to cure the above-mentioned eye conditions by changing the natural lens of the eye with vision implant known as intraocular lens (IOL). But the manufacturing of intraocular lenses remains time consuming and an economically challenging procedure to this day, this is especially true when considering customized IOL's tailored for the patients individual needs.

As for today, all intraocular lenses are manufactured using lathe cutting, milling, compression molding or injection molding (Leonard and Rommel, 1981). All above mentioned methods use mechanical tools that have their downsides and shortcomings (Heberle, Häfner and Schmidt, 2018; Yu *et al.*, 2018). Despite of the method that is used to manufacture the shape of the lens, the surfaces typically do not satisfy optical-quality standards and therefore require an additional polishing step. Polishing methods such as pitch polishing, polishing using synthetic pads or Magneto Rheological Figuring (Schwertz, 2008) are not suitable for intraocular lenses as there is a high risk of damaging the lens haptics. To this day all intraocular lenses are polished using the tumbling method, where lenses are tumbled in a mixture of glass beads, alcohol and deionized water. This method is capable to produce surfaces of superb quality, i.e. Ra in the range of a few nanometers (Yamakawa *et al.*, 2003), however the tumbling process may take as long as few days (James, 1999). To avoid the stated disadvantages of mechanical manufacturing, laser micromachining could be used as alternative for mechanical manufacturing means of intraocular or other type of optical lenses. However, laser micromachining using conventional femtosecond pulses alone is not sufficient to produce an optical-grade quality surface finish resulting in surface roughness > 1 µm Ra. Such surfaces exhibit strong light scattering and may reduce imaging quality of these components to such a degree that it becomes too low for optical applications. Surface roughness is also important for the bio-compatibility of the implants (Boswald *et al.*, 1995; Bauer *et al.*, 2013; Louropoulou, Slot and Van der Weijden, 2015). Rough implant, be it bone implant or intraocular lens can damage human tissues or be rejected by the immune system. Recently it was discovered that using bursts of femtosecond laser pulses, when each pulse is divided into a sequence of sub-pulses with a temporal separation of few tens of nanoseconds or hundreds picoseconds, improves laser material processing by boosting the ablation efficiency (Knappe *et al.*, 2010; Hendow and Kosa, 2014; Gaudiuso *et al.*, 2016; Kerse *et al.*, 2016; Mayerhofer, 2017) and further decrease surface roughness compared to using the conventional single femtosecond pulse regime (Žemaitis *et al.*, 2019).

The aim of this study is the investigation of the polishing capabilities of rough (~ 1 µm Ra) hydrophilic acrylic (typical material used for vision implants) surfaces using bursts of femtosecond laser pulses, while the initial rough surface of the sample was prepared by femtosecond laser ablation to a desired shape without using bursts. It was shown, that by tailoring the properties of the burst (the shape of the burst-envelope, number of pulses, average power, etc.) it is possible to control the amount of heat flux entering the material and in such a way realize a controlled melting procedure that reduces the surface roughness from ~ 1 µm Ra to < 20 nm Ra. These results show great potential for the industrial scale production of customized optical components made from transparent, biocompatible polymer materials.

2. Materials and methods

In this work we used a multi-burst femtosecond laser "Carbide" (manufacturer: Light Conversion, Vilnius, Lithuania). With a central wavelength of 1030 nm, generating pulses of 220 fs (full width at half maximum) duration at a repetition rate of 100 kHz, with a maximum average power of 40 W. The laser was operating in burst regime, where every single pulse was divided into a sequence of sub-pulses with temporal separation of

400 ps. The laser beam was controlled using a galvanoscanner "intelliSCAN 14" (manufacturer: SCANLAB, Munich, Germany) and focused on the top of the sample using 100 mm F-theta lens (see **Error! Reference source not found.**). In addition, the scanner with the lens was mounted on a z-axis translation stage, thus enabling the manipulation of the beam in x, y and z directions. The position of the beam on the sample was controlled using micromachining software DMC. The micromachining objects were Contamac CONTAFLEX 26% UV-IOL (R) hydrophilic acrylic tablets having diameter of 15 mm and thickness of 3 mm (a common material in the manufacturing of intraocular lenses). The produced surfaces were inspected using an "Olympus BX51" (manufacturer: OLYMPUS, Hamburg, Germany) microscope and the "Sensofar PLU 2300" optical profiler

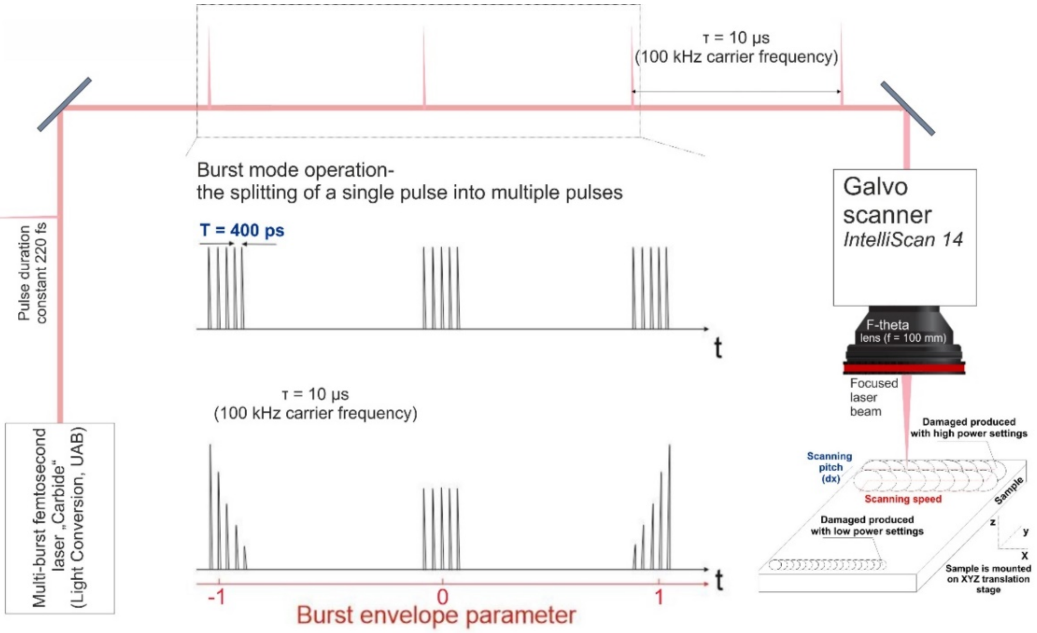

Fig. 1. Micromachining setup used for ablation and subsequent polishing of plastic materials. A single pulse may be split into a sequence of sub-pulses (bursts), the temporal separation between each sub-pulse within the burst was constant at 400 ps. Additionally, by varying the burst envelope parameter it is possible to adjust the energy distribution within the burst.

(manufacturer: SENSOFAR, Terrassa, Spain). Besides that, while conducting micromachining of samples, the temperature at the surface was monitored using a thermal vision camera "FLIR A600-Series" (manufacturer: FLIR systems, Hoogstraten, Belgium). The experiment consisted of several steps: first, a cuboid having dimensions of 10 mm × 10 mm × 0.5 mm (such dimensions are typical for eye implants) was ablated using the conventional femtosecond ablation regime (single pulses) when the laser was operating at 100 kHz. Later it was polished using bursts of femtosecond pulses. Polishing experiments were conducted using different micromachining parameters while searching for the best parameter configuration to achieve the best surface finish.

3. Results and Discussion

First, the samples were pepared for the polishing as descibed above. During this stage the ablation threshold of hydrophilic acrylic material was determined using the standard method of (Bonse *et al.*, 2000). It was found to be 2.7 $\mathrm{J/cm^2}$, the determined value agrees with the results published by other parties when similar materials were investigated (Baudach *et al.*, 2000; Nam *et al.*, 2006; Heberle *et al.*, 2013). The best resulting surface roughness was around ~ 1 µm, requiring further processing to enhance surface quality. In next step, we used bursts of femtosecond laser pulses to further reduce the surface roughness. The optimal regime for laser polishing was investigated when changing the average laser power, the scanning pitch of the hatching lines, the number of sub-pulses within the burst and the scanning speed of laser beam. In the framework of this article, surface polishing is regarded as a sensitive thermodynamical process that is based on remelting of a thin surface layer. While the material is in the liquid state it is pulled in the directions where the surface tensile force is strongest, meaning that it is pulled mainly into various valleys and cavities, hence the surface roughness after solidification may get smaller if the correct laser heating parameters are found. However, it was unknown what is the best parameter combination that produces the highest heat flux onto

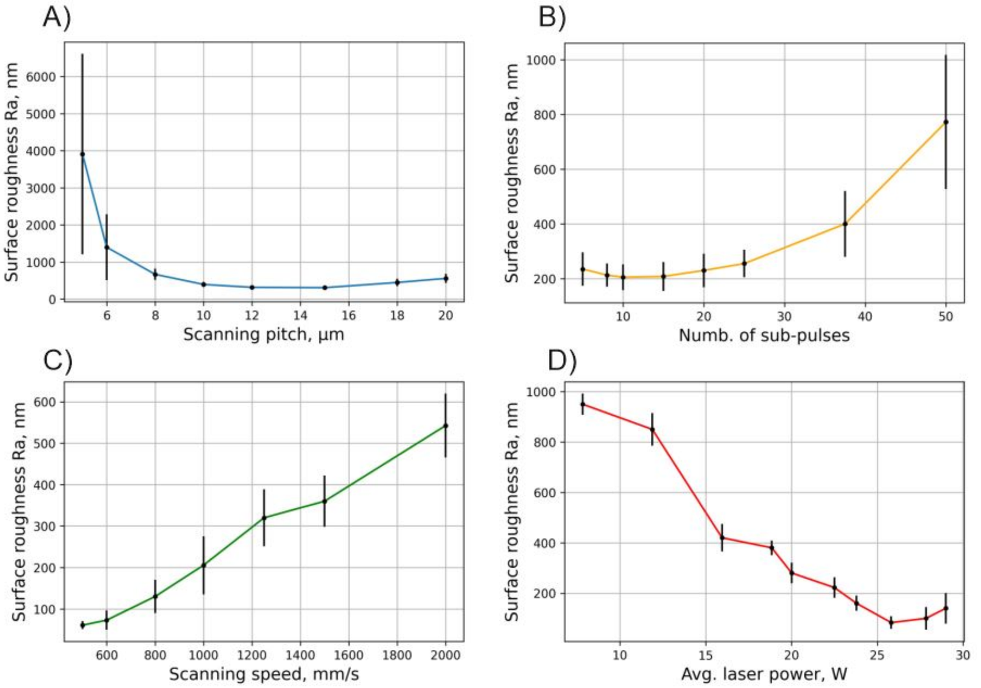

Fig. 2. Surface roughness after polishing ablated samples dependent on different polishing parameters. Other fixed parameters in case of (**A**): P = 29 W, N_p = 10 and v = 1000 mm/s; in case of (**B**): P = 19 W, dx = 10 μm and v = 1000 mm/s; in case of (**C**): P = 25.8 W, dx = 10 μm and N_p = 10; and in case of (**D**): v = 1000 mm/s, dx = 10 μm and N_p = 5.

the surface. After performing the parametric study (after the polishing procedure with different micromachining conditions) the roughness of the surface was analysed. The summarized results are shown in *Fig. 2*. The results show that, under certain burst pulse parameter settings, it is possible to reduce the initial roughness of the sample made with the single pulse ablation mode. At 5 sub-pulses in the burst and low average power (~15 W) settings the achieved reduction in surface roughness is already about 2.5-fold, from ~1 µm to ~400 nm. We found that with higher average power settings (~24 W) it was possible to reach a surface roughness value below 100 nm (Ra). This result shows that depending on the scanning speed and spatial pitch settings a significant amount of laser power is required to be applied onto the surface to initiate melting and surface smoothening. On the other hand, too much power can result in increase of surface roughness when the scanning speed is too high. As evident from the roughness dependence on the scanning speed graph, the surface roughness increases as the scanning speed increases, leading to insufficient thermal accumulation on the surface. However, it was noticed that if the thermal input is too large, boiling of the material can occur and large craters form on the surface producing a rise in the surface roughness as in the case of the low scanning pitch (5 µm) setting. These results indicate that, laser polishing using bursts of femtosecond pulses is a sensitive thermal process and fine-tunning of the process is required.

To investigate the melting regime further the temperature of the surface during polishing was monitored with an IR camera using different average power settings and number of sub-pulses within the burst. The 5 and 10 sub-pulses within the burst and the change of laser power from 8 to 32 W were chosen for comparison. The main findings are displayed in Fig. 3. Correlation between the achieved surface roughness and surface

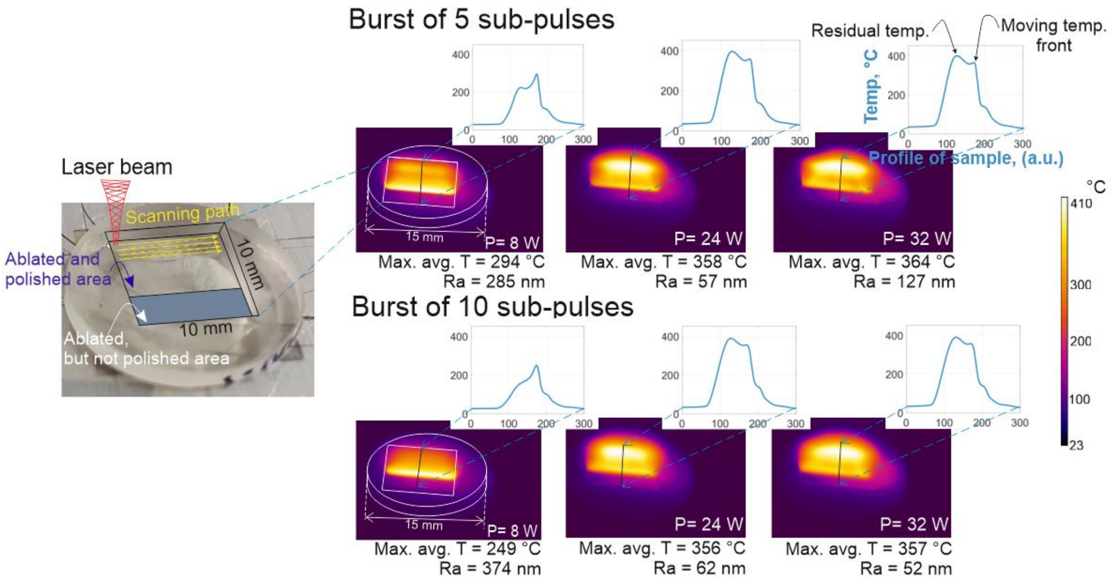

Fig. 3. Temperature maps of the sample's surface during micromachining and profiles of temperature maps averaged through the working area using different average laser power for bursts of 5 and 10 sub-pulses per burst. Max. avg. T listed below the images stands for maximum averaged temperature of the moving laser front. Other parameters used for polishing were: dx = 10 µm, v = 700 mm/s and number of scans = 2. Ra of the surface are partially dependent on the position where the measurement was performed, thus errors of ±25 nm must be taken into account.

temperature is evident (e.g., $N_p = 5$, P = 24 W and $N_p = 10$, P = 32 W). The measured surface roughness (57 nm and 52 nm respectively) reached low values if the maximum temperature of the surface is raised to around 357 °C. This shows, that multiple parameter combinations are feasible for the polishing process as long as the optimal micromachining temperature (approximately 357 °C) is reached. If the temperature of the surface is further increased larger surface roughness values are registered after the polishing step (as can be seen in Fig. 3 $N_p = 5$, P = 32 W). When the surface temperature increases > 360 °C, bubbles form below the surface. The bubbles are the release of gas trapped inside the volume which explode upon reaching the surface, this causes sputtering of the molten material and creates micro-valleys. In turn, this causes an increase in the surface roughness (Huang *et al.*, 2010). Further findings showed that the final surface roughness has a dependence on the number of performed scans, as it is related to the achievable micromachining temperature. The minimal surface roughness achieved after a single scan over the surface was ~250 nm. It was noticed that scanning twice (a change in the scanning angle by 90° is produced after each pass) improves the surface finish as compared to the single scan case; however, when the scanning was done more than twice the surface roughness increases again and the sample becomes non-transparent, meaning that the optimal temperature for polishing was exceeded. Another temperature related phenomenon was observed when looking into number of sub-pulses per burst. It was found that by splitting a single pulse (using burst regime) into 3 or more sub-pulses with temporal separation of 400 ps the maximum reachable micromachining temperature is ~ 60 °C higher than compared to using a single conventional femtosecond pulse. This shows that only when operating the laser in burst-mode it is possible to reach higher surface temperature levels. The best results (roughness Ra < 20 nm) were achieved when using the parameter combination: P = 22 W, N_p = 5, v = 620 mm/s, dx = 10 µm, number of scans = 2 and f = 100 kHz.

In addition, for demonstration purposes, a concave lens of 13.5 mm diameter and having a radius of curvature of 20.5 mm was fabricated. The result is shown in Fig. 4 It is evident that the fabricated concave lens is fully transparent, smooth and bends the image like a lens.

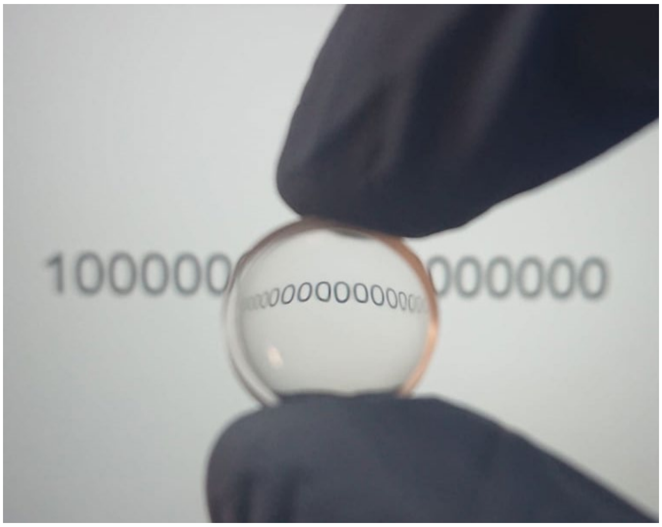

Fig. 4 Polished concave surface.

4. Conclusions

In this study we have investigated the ability to polish the hydrophilic acrylic polymer Contamac CONTAFLEX 26% UV-IOL (R), which is used as a bio-compatible polymer for body-implant manufacturing, using bursts of femtosecond laser pulses. A parametric study of the polishing processed was performed when varying the laser micromachining parameters: average laser power, scanning speed, scanning pitch and number of sub-pulses within the burst. The parametric study showed that polishing up to a surface roughness value of < 20 µm Ra is possible. The analysis of the surface temperature during micromachining showed that the polishing process depends on the thermal heat flux which initiates thermodynamical processes that change the surface roughness of the sample. The optimal surface temperature was found to be approximately 357 °C, at which it was possible to polish the material up to 18 nm Ra, resembling a transparent surface which meets optical-quality standards. The correlation between the temperature at the surface and the achieved surface roughness values is presented which shows that such roughness values are achievable due to the variation of the number of sub-pulses within the burst. In addition, it was shown that in order to reach the stated temperature levels, it is necessary to split the single pulse into at least more than three sub-pulses. However, if the number of sub-pulses is increased futher, similar results in terms of surface temperature may be achieved. If the surface is overheated to above 360 °C, micro bubbles form which rise to the surface and produce surface craters upon exploding, dramatically reducing the surface quality.

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