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Dielectric materials cutting using Bessel beams with a femtosecond laser configured in MHz and GHz burst regimes.

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Abstract

Ultra-Short Pulse (USP) lasers are nowadays widely used in various industrial applications. Femtosecond lasers, in particular, are largely applied in precise micromachining thanks to their ability to process materials without causing thermal damage. For some applications, burst regimes containing trains of femtosecond pulses are advantageous, for example MHz bursts for dielectrics cutting with tailored Bessel beams. These beams offer an efficient cutting process due to their extended focus depth, which is 100 times longer than that of a standard Gaussian beam. Moreover, the central beam size limit is smaller than the diffraction limit by a factor of 2, thanks to their interference-based generation. In this contribution, we show a study on cutting transparent dielectric materials like glass and sapphire exploring various Bessel beam configurations using different types of axicons with a femtosecond laser operating in eighter MHz or GHz burst regime.

Keywords: Laser; Femtosecond; dielectric; cutting; MPLC; beam shaping; Bessel; axicon; pulse; glass; micromachining

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1. Introduction

1.1. Glass cutting challenges.

Glass cutting poses significant challenges, especially in the growing market of cell phones. The demand for higher quality glass is increasing due to its complex nature. Traditional cutting processes have limitations, resulting in poor surface quality and often requiring additional post-cutting treatments. However, there are promising developments in USP (Ultra-Short Pulse) laser processes (Gattass et al., 2008), offering a high-quality finish without causing heat damage. The current focus is on enhancing cutting yield while maintaining exceptional quality.

1.2. USP laser cutting quality improvement with a tailored beam.

Bessel beams, also known as conical phase beams, exhibit interferences over their depth of field and possess self-focusing properties, making them "diffraction free". These beams are typically generated using transparent axicons. Bessel beams enable high aspect ratio focusing which may be 100 times higher than Gaussian beams, making them ideal for deep drilling (Bhuyan et al., 2010) and dicing applications.

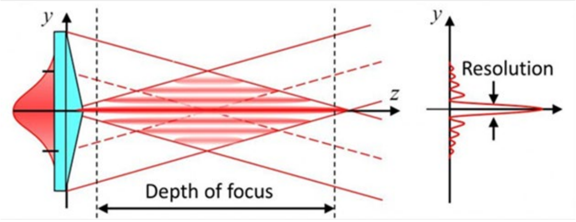


Fig. 1. Bessel beam generation with refractive axicon – principle

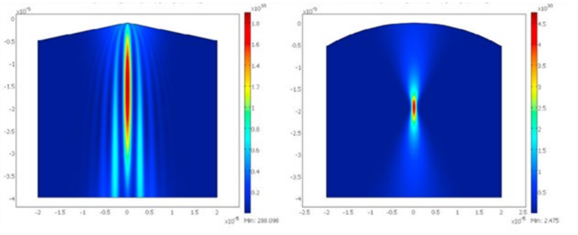


Fig. 2. Comparison between Bessel focusing (left) and gaussian focusing (right) in air

1.3. Glass cutting process.

The ablation-free and zero-kerf glass cutting process involves several steps (Mishchik et al., 2017). First, laser pre-cutting is performed to create a cutting plane using successive Bessel beams. Then, mechanical stress is applied to cleave the sample along the trajectory of the Bessel beam. Setting the correct pitch between two consecutive Bessel beams involves adjusting the repetition rate and feed rate. This approach allows for precise control over the glass cutting process using USP lasers, achieving high levels of accuracy and quality for applications related to cell phones and other products that require intricate glass cutting.

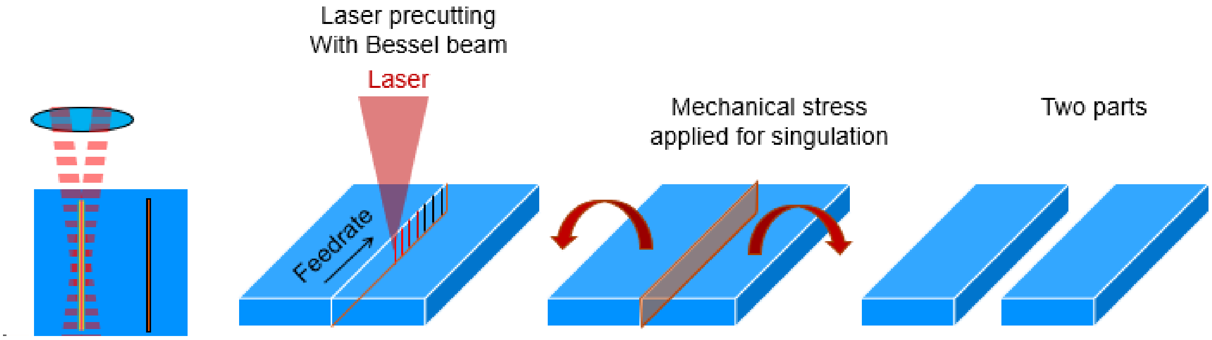


Fig. 3. Glass Cutting Process

2. Solution research

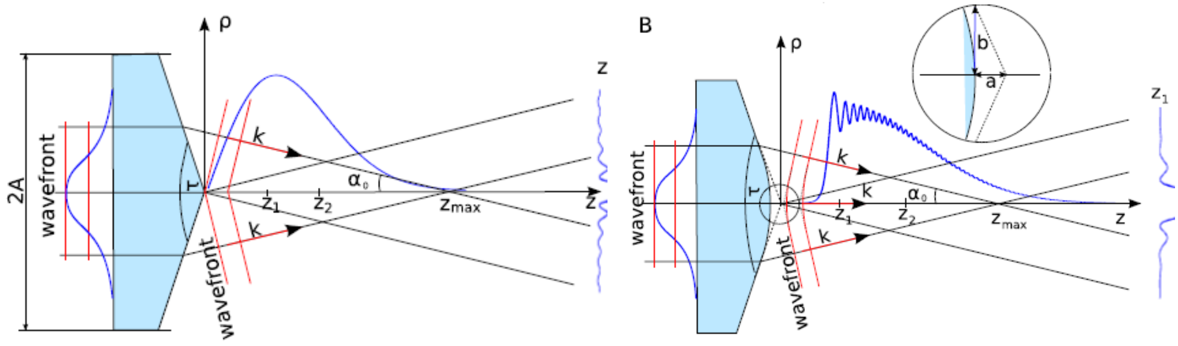
2.1. Transparent Axicons Limits

The use of transparent axicons can produce high aspect ratio Bessel beams, but they come with certain limitations. One of the main issues is the generation of a blunt tip in the Bessel beam due to fabrication limits leading a part of the beam having a spherical phase which interferes with the Bessel beam too and causes oscillations in the energy distribution along the optical path. Therefore, the ablation in the material when using transmissive axicons is non-uniform. This non-uniform ablation can create inconsistencies and irregularities in the cut, potentially compromising the desired cutting outcome.

According to the paper Brzobohaty et al, Opt. Express 16.12688 (2008), the following equation describe this phenomenon in the air along the z-axis of propagation:

$$z = -\sqrt{a^2 + \frac{\rho^2}{\tan^2\left(\frac{\tau}{2}\right)}}.$$

α is the polar angle
k is angular wavenumber
ρ denotes radial distance from the optical axis z
τ is the apex angle of the perfect axicon (angle between asymptotes of the hyperboloid)



a) Left: perfect axicon illuminated by a Gaussian beam

b) Right: Influence of the rounded tip of the axicon

Fig. 4. Illustration of Fabrication limits

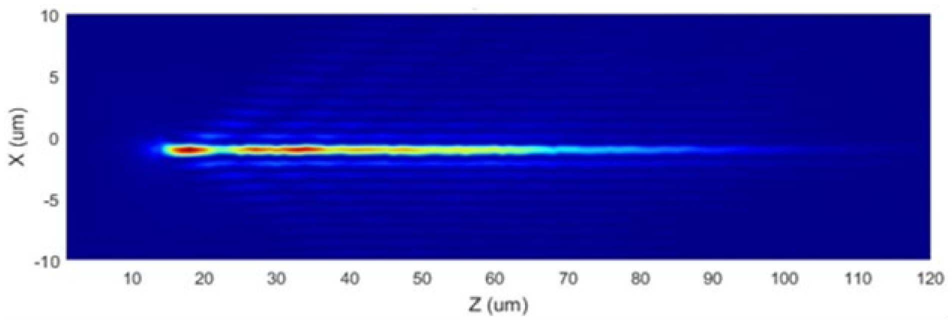


Fig. 5. Beam profile on the processing plane with transparent round tip axicon

2.2. Reflective Axicon

It is possible to generate Bessel beams with reflective optics too, which provides several advantages over traditional transparent axicons. The reflective optics offer high reflectivity, surpassing 99%, ensuring minimal energy loss and maximizing the efficiency of the laser cutting process. This high peak-power handling capability allows the Bessel beam to handle pulse energies of up to 1 mJ, making it suitable for demanding laser cutting applications. One significant benefit of using reflective optics is the absence of chromatic dispersion. This means that the pulse duration of the laser remains preserved, resulting in consistent and precise cutting performance across different wavelengths. Additionally, reflective optics enable the Bessel beam to maintain its focus even at high powers, eliminating the focus shift issues encountered when using transparent axicons. This technology proves to be particularly advantageous when used in conjunction with Ultra-Short Pulse (USP) lasers. At last, the tip is reduced with a reflective axicon thanks to a different manufacturing process eliminating the oscillations along the propagation axis. The combination of reflective Bessel beam and USP lasers allows for high precision cutting applications in various industries.

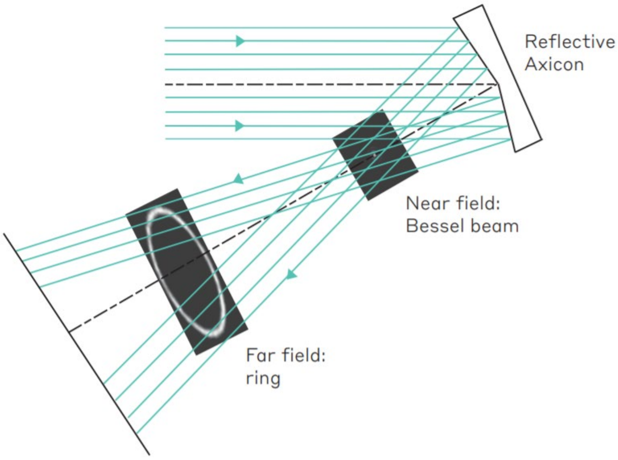


Fig. 6. Principle of Reflective Axicon under a 30°-incidence

2.3. A solution compatible with an industrial environment

A compact module for glass cutting that combines the reflective Axicon and beam magnification has been developed and implemented in a homemade 3-axis micro-machining workstation equipped with NEWPORT motorized stages and DMC pro software control. The use of Bessel beams, produced with the advantages of reflective optics, ensures high-quality cutting results, as previously discussed.

Additionally, the workstation incorporates sideview plasma luminescence and shadowgraph imaging to assess the elongated and uniform energy deposition along the glass thickness. This device is crucial to tune the laser parameters and to set the right positioning of the Bessel beam into the glass sample to obtain a good cutting quality. This imaging technique provides valuable insights into the cutting performance and the overall quality of the glass cut. By observing the plasma luminescence from the side, operators can monitor and analyse the cutting process in real-time, identifying any potential irregularities or issues that may arise during the operation.

The combination of Bessel beam technology, beam magnification, and plasma luminescence imaging makes this micromachining workstation an advanced and efficient tool for precise glass cutting applications. Its compact design makes it suitable for various manufacturing environments.

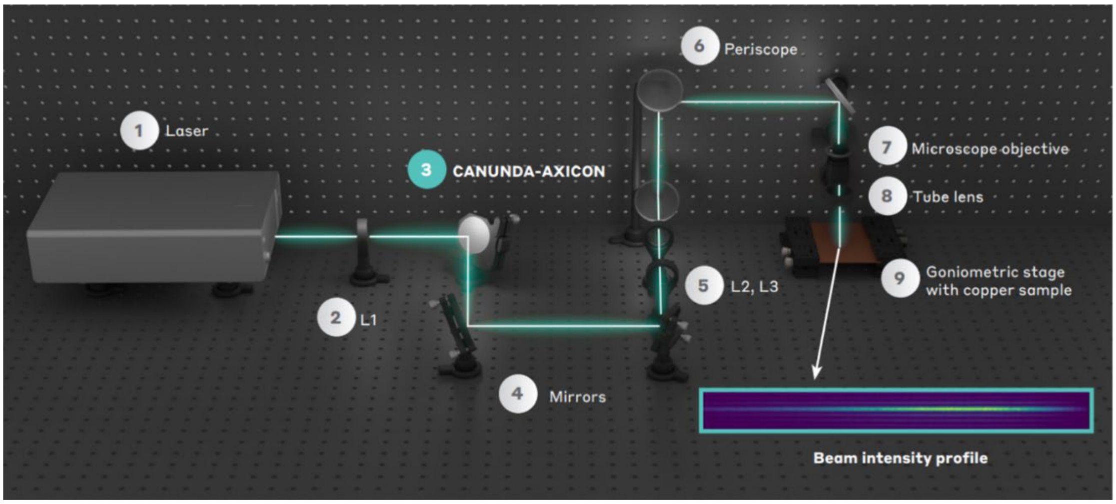


Fig. 7: Typical Reflective Axicon integration

3. Process results obtained with the Celia.

3.1. Test Parameters

To demonstrate its effectiveness, the reflective axicon designed and fabricated specifically for this experiment with an off-axis of 0° was used at CELIA to cut 1 mm thick dielectric soda lime glass. The goal is to test different parameters to optimize the quality of the cut and to compare the results with a standard refractive axicon.

The custom axicon has an angle of incidence of 0°. The focusing lenses are L1= 200 mm and L2 = 10 mm. The Bessel beam divergence angle is 22.2°, and a diameter of 4 µm is obtained.

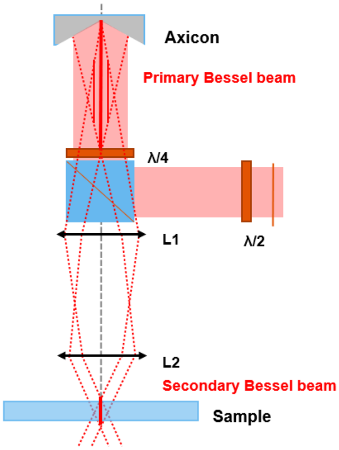


Fig. 8. Reflective 0° AOI (angle of incidence) axicon setup

For the solution with the refractive axicon, a 170° angle axicon has been chosen. The focusing lenses are L1= 125mm and L2 = 10mm. The Bessel beam divergence angle is 27.3°, and a diameter of 4 µm is obtained.

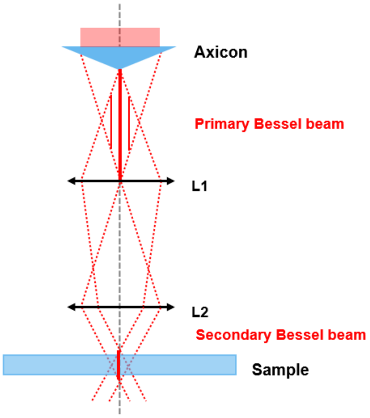


Fig. 9. Refractive (transmissive) axicon setup

The tests were carried out in both cases with bursts containing 4 pulses at 40 MHz repetition within the burst, an energy of 130 µJ to 220 µJ per burst and a burst repetition rate of 1-100 kHz.

3.2. Results

By comparing plasma luminescence imaging, we see that the profile is more homogeneous with the reflective axicon. A very homogeneous luminescence allows for a uniform energy deposit as indicated by the red rectangle in Fig. 10 at a power of 188 µJ (85% of power). Moreover, the measured optical transmission is 79% for the reflective axicon against only 70% for the refractive axicon attesting for less losses with the reflective axicon.

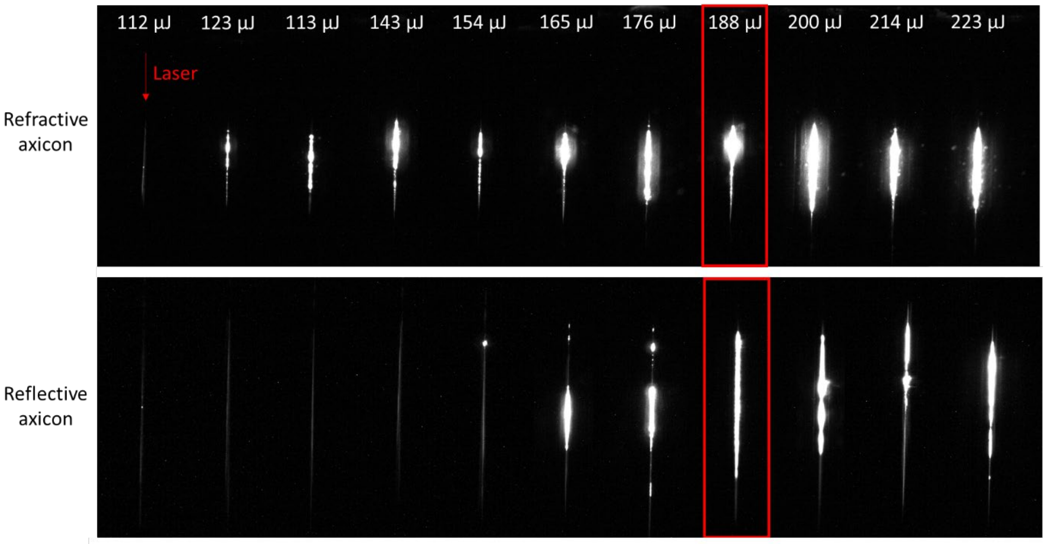
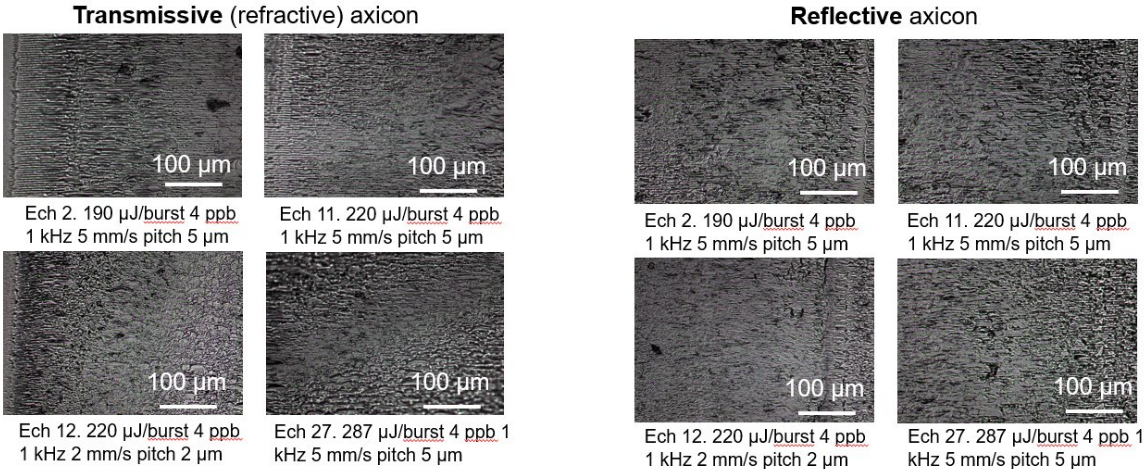


Fig. 10. Sideview of plasma luminescence of Bessel beam in sodalime glass, with burst energy ranging from 112 to 223 µJ, for refractive axicon (top) and for reflective axicon (bottom).

Then, by comparing the cutting results of the two modules, similar cutting qualities are observed for axicon configurations. The microscope images in Figure 11 and the roughness analysis in Figures 12 and 13 show high quality sections. The surface roughness Sa of the cutting planes is less than 1 µm.



Transmissive (refractive) axicon

Ech 2. 190 µJ/burst 4 ppb 1 kHz 5 mm/s pitch 5 µm

Ech 11. 220 µJ/burst 4 ppb 1 kHz 5 mm/s pitch 5 µm

Ech 12. 220 µJ/burst 4 ppb 1 kHz 2 mm/s pitch 2 µm

Ech 27. 287 µJ/burst 4 ppb 1 kHz 5 mm/s pitch 5 µm

Reflective axicon

Ech 2. 190 µJ/burst 4 ppb 1 kHz 5 mm/s pitch 5 µm

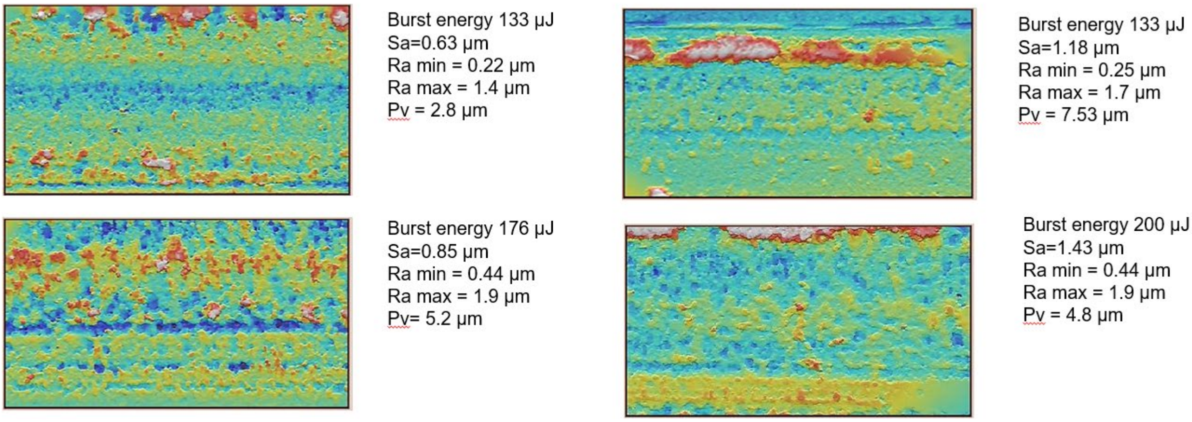
Ech 11. 220 µJ/burst 4 ppb 1 kHz 5 mm/s pitch 5 µm

Ech 12. 220 µJ/burst 4 ppb 1 kHz 2 mm/s pitch 2 µm

Ech 27. 287 µJ/burst 4 ppb 1 kHz 5 mm/s pitch 5 µm

Fig. 11. Microscope images with 20x-objective of the cut side for refractive axicon (left) and for reflective axicon (right)

In terms of cutting quality, the best result is obtained at 133 µJ with a 2 µm pitch. This gives Ra roughness values of 0.2 µm and Sa roughness values of 0.63 µm for the reflective axicon. For the refractive axicon, Ra =0.14 and Sa = 0.67 µm, respectively. Overall, the results are relatively similar, indicating very good cutting quality (low roughness).



Burst energy 133 µJ
Sa=0.63 µm
Ra min = 0.22 µm
Ra max = 1.4 µm
Pv = 2.8 µm

Burst energy 133 µJ
Sa=1.18 µm
Ra min = 0.25 µm
Ra max = 1.7 µm
Pv = 7.53 µm

Burst energy 176 µJ
Sa=0.85 µm
Ra min = 0.44 µm
Ra max = 1.9 µm
Pv= 5.2 µm

Burst energy 200 µJ
Sa=1.43 µm
Ra min = 0.44 µm
Ra max = 1.9 µm
Pv = 4.8 µm

Fig. 11. Roughness measurement with optical profilometer of the cut side obtained with reflective axicon.

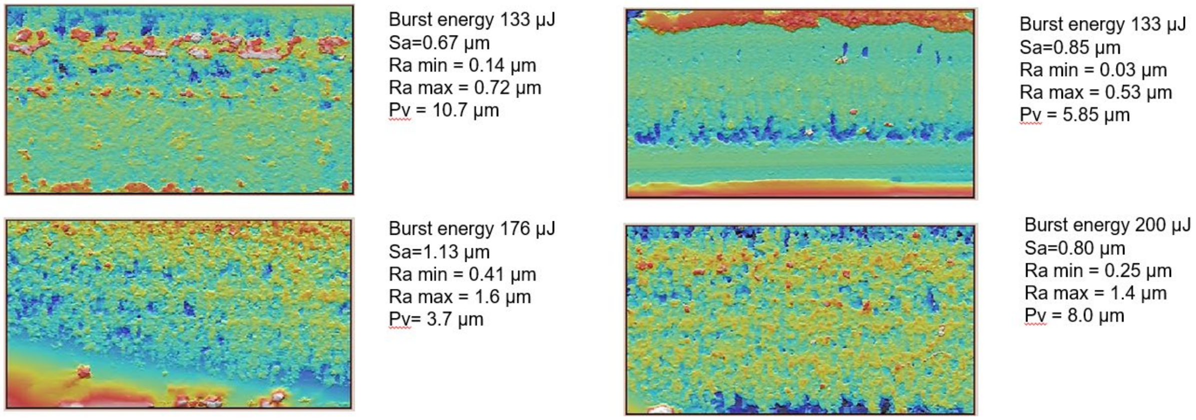


Fig. 12. Roughness measurement with optical profilometer of the cut side obtained with refractive axicon.

4. Conclusion

We conducted experiments on dielectric 1 mm-thick sodalime glass cutting using a high power Yb-doped femtosecond laser operating in MHz-burst regime with a comparative study between a reflective and a refractive axicon.

The reflective axicon used in the study proved to be advantageous for several reasons. Firstly, it was easy to mount and align, even at 0° off-axis angles, simplifying the setup process. Additionally, the reflective axicon demonstrated better transmission properties, allowing more of the laser energy to be efficiently used for cutting.

Moreover, the reflective axicon setup produced a Bessel beam with two times more uniformity compared to the refractive axicon. This enhanced beam uniformity contributed to achieving good cutting quality, as evidenced by surface roughness values Sa ≈ 0.6 µm and roughness levels below 1 µm.

Excitingly, the successful results with reflective axicons have motivated further developments. In the upcoming months, the researchers plan to conduct tests with a unique profile featuring a uniform axial intensity, known as the Z-Flat Bessel beam. This innovative profile holds promise for even more precise and controlled cutting processes, potentially paves the way for advanced micromachining applications in various industries.

The collaboration between Cailabs and CELIA-CNRS showcases the continuous progress in laser cutting technologies, particularly with reflective axicons, and paves the way for future advancements in achieving higher cutting precision and quality for various materials, including glass.

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