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Control of wall profile of trenches produced by femtosecond laser using a flat top triangular beam shape

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Abstract

In this work we demonstrate the possibilities that beam tailoring tools offer in terms of control of shapes in small sized geometries generated using femtosecond lasers. We focused in trench depths below 20 µm and down to 1 µm, as this type of geometries are normally generated using a gaussian beam, which results in a trench shape resembling the gaussian distribution of the beam, i.e., without any control of the inclination or shape of the walls. In order to overcome this, a 20 µm side flat top triangular laser spot has been used with the aim of controlling the inclination of both walls. The results confirm the possibility to generate trenches with wall inclinations from 12° to more than 50°, variating both the orientation of the triangular spot with respect to the scanning direction and the number of scans per trench.

Keywords: ultrafast lasers; beam shaping; top-hat; micro-structuring

1. Introduction

Ultrafast lasers have been extensively used to microstructure materials due to their high accuracy and flexibility. Because of this, there's a constant effort in improving its efficiency (Neuenschwander et. al., 2015; Gafner et. al.,2021) in view of closing the gap between the lab and the industrial scale. To this end, several beam shaping approaches have gained plenty of interest as of late, most of them attempting to shorten processing times (Möhl et. al.,2019; Hauschwitz et. al.,2021).

In this work, we propose the use of a triangular-shaped beam to produce grooves on stainless steel with different degrees of tilt. The advantage of this polygonal form is that the pulses overlap unevenly depending on the processing direction, leading to an asymmetric energy deposition along the raster of a line and thus to an asymmetric V-trench. With a circular or square beam, this kind of profile is typically replicated by programming the stacking of partially overlapped lines in two different processing planes (e.g., Y and Z), which is both time consuming and inconvenient.

2. Materials and Methods

The trenches were fabricated on the surface of 1mm stainless steel (*AISI 304L*) polished samples using a 1030nm Yb-doped fiber laser with a pulse duration of 280 fs (*Satsuma HP*). To achieve the triangular shape, the diameter of the Gaussian beam was tuned before entering a Multi-Plane Light Conversion (MPLC) module provided by Cailabs. The now triangular beam was relayed using two telescopes to the 20x microscope objective (MO) used for the engravings, which had a NA of 0.4 and a focal length of 10 mm. The intensity distribution of the beam at the processing plane was then recorded using a beam profiler, which showed that the flat-top (FT) profile was maintained throughout the triangle, as can be seen in Fig. 1, and that its side length was of 20 µm FWHM. The figure also contains a sketch of the processing direction based on the triangle shown.

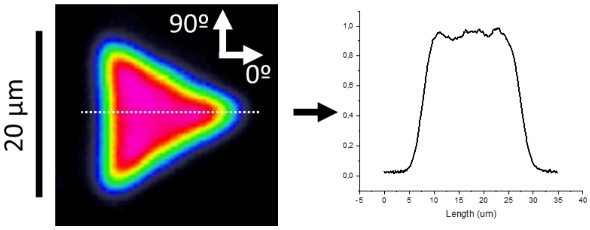

Fig. 1. Image of the generated triangular flat-top beam in false color (left) and intensity profile along the white dotted line (right).

Fixing the repetition rate at 10 kHz, four experimental parameters were altered in order to fabricate a matrix of trenches of different morphologies: orientation of the processing direction, pulse energy, scanning repetitions and speed of the motorized linear translation stage. The range of tested parameters can be seen in Table 1. For each fabrication condition, three identical trenches were engraved to evaluate the replicability of the procedure. For reference, the 0º processing orientation corresponds to the overlap of the beam in Fig.1.left from left to right, whereas the 90º stands for translation of the stage from down to

Table 1. Range of experimental parameters tested.

Orientation [°]	Pulse energy [µJ]	Repetitions	Speed [mm/s]
0, 90	2.5 — 12.5	1 — 5	3 — 20

Lastly, the morphological analysis was carried out by means of a 3D Optical profiler (*S neox Five Axis* from SENSOFAR), which enabled the swift recording of the topography of the fabricated trenches. Four results were drawn from each measurement, namely: the depth of the grooves, their width, and the angles between the surface of the sample and the left (θ_{left}) and right (θ_{right}) walls of the trenches.

3. Results and discussion

Each parameter tested had quite a different effect on the topography of the trenches. The width of the grooves was kept almost constant between 20 and 25 µm for most of the experimental conditions: However, using a pulse energy of 12.5 µJ resulted in widths of up to 30 µm. As the amount of energy greatly exceeded the ablation threshold, the “tail” of the beam (i.e. the edges of the profile shown in Fig.1.right) ended up contributing to this effect, thus the increase in width.

Both the increase of the number of repetitions and a decrease in the processing speed led to trenches of higher depth, reaching values over 15 µm. This also entailed, by default, a rise in both θ_{left} and θ_{right}, as the width of the grooves remained constant.

The consequence of the change in the processing directions from 0º to 90º was a drastic shift in the morphology of the trenches, which can be quantified as the ratio between θ_{left} and θ_{right}: for 0º, it was in the order of 0.9 to 1.0 and for 90º between 2 and 3. In Fig.2 one can see how this variation affects two groups of grooves in the same order of depth.

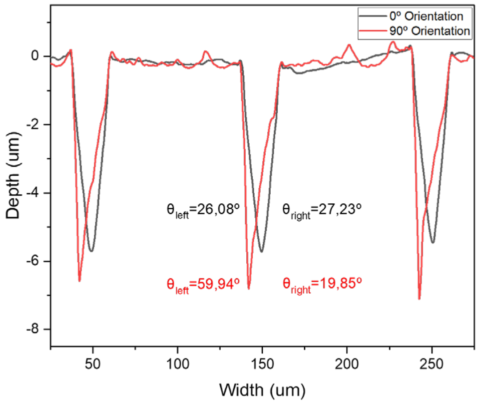

Fig. 2. Profile of three trenches fabricated at different processing orientations along with their respective trench wall angles.

4. Conclusions

We have combined ultrafast lasers with a triangular beam-shaping technique to grooves with tilted walls in stainless steel. We have verified how the change of the experimental parameters affects the morphology of the trenches, identifying the processing direction as the one with highest influence. An expansion of the range of conditions tested is necessary in order to broaden the tunability of the morphology of the grooves.

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