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Taper Angle Correction in Cutting of Complex Micro-mechanical Contours with Ultra-Short Pulse Laser

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Abstract: The objective of this work was to investigate the possibility of taper angle correction in cutting of complex micro-mechanical contours using a TruMicro ultra-short pulse laser in combination with the SCANLAB precSYS micro machining sub system. In a first step, the influence of the process parameters on the kerf taper angle of metallic alloys was systematically investigated without beam inclination. A set of base parameters was derived for the subsequent investigations. In a second step, the kerf taper angle was controlled by static beam inclination. In a third step, the same optics was used in its dynamic precession mode to fabricate micro-mechanical components of complex contours with perpendicular 0° taper angles. It was found that taper angle adjustments of up to 7.5° are possible with the used setup for cutting applications. Taper angle control is possible both in the static beam inclination mode and in the dynamic precession mode. The static mode could be interesting for contours with sharp inner radii and for achieving faster cutting times similar to results with fixed optics, but would require excellent synchronization of beam inclination and axis motion. The dynamic precession mode would allow an easier integration of the optics into a laser machine but will result in longer cutting times and limitations with respect to achievable inner radii.

Key words: Ultra-short pulse laser cutting, kerf taper angle, zero taper, 5-axis micro machining.

1. Introduction

Many industries—from electronics, medical technology to watch industry—require precise cutting edges in the micrometer range. Due to the natural divergence of a focused laser beam, deep cutting kerfs with zero tapered (perpendicular) walls are a challenge with conventional perpendicular laser beam incidences. It is state of the art that a suitable choice of process parameters [1-4] and choice of the irradiation angle of the laser beam with respect to the inclined sample surface [5] highly influences the kerf taper. Helical laser drilling allows machining of holes with 0° or even a negative kerf taper with an inclined laser beam [6-10]. Due to the dynamic ability to precisely position the laser beam in 5 axes with the new micromachining subsystem precSYS from SCANLAB, it can be effectively combined with an USP (ultra-short pulsed) laser TruMicro 5050 from TRUMPF to meet the demands of high precision cutting applications of complex contours at acceptable process times.

The kerf shape depends on the laser and process parameters. The material ablation depth z_{abl} in ultra-short pulse laser micromachining can be described as a function of the fluence Φ, with Φ_{th} being the ablation threshold fluence and the energy penetration depth [11, 12]. The Gaussian fluence profile of the laser beam results therefore in a wall angle γ (i.e. the complementary angle of the kerf taper) of the ablated area which is not 90° anymore, but slightly inclined. This inclination of the wall leads to a larger area under the laser spot. Assuming a homogeneous fluence distribution over an infinitesimal area element of inclined wall and within infinitesimal area element of the laser spot perpendicular to the optical axis, the effective fluence $\Phi_{eff,i}$ on the inclined wall can be calculated from the fluence Φ_i of the Gaussian beam [13]:

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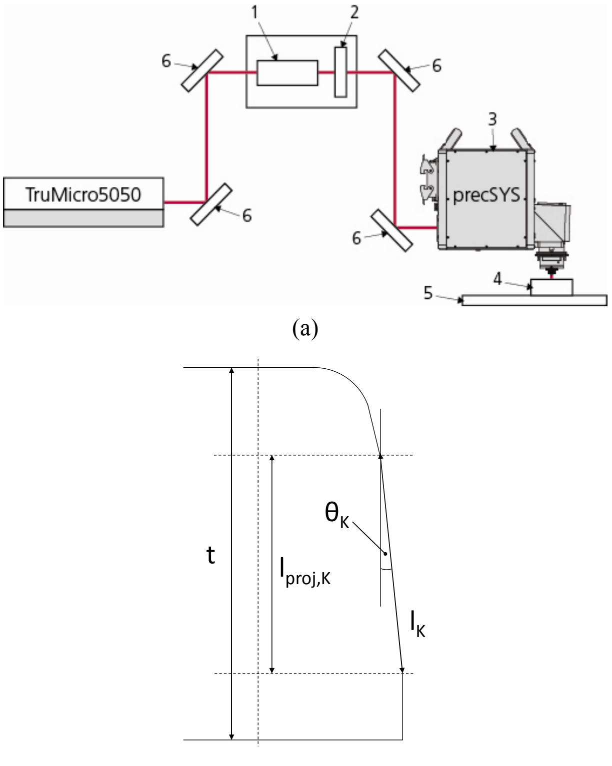
$$z_{abl} = \partial \ln\left(\frac{\Phi}{\Phi_{th}}\right) \qquad \Phi_{eff,i} = \Phi_i \cos\gamma \qquad (1,\ 2)$$

2. Experimental Apparatus

The experimental setup for laser cutting of perpendicular kerfs comprises a TruMicro 5050 ultra-short pulsed laser and the highly integrated 5-axis micromachining subsystem precSYS. A scheme of the experimental setup is shown in Fig. 1a. precSYS positions the focal spot in 5 axis (x, y, z, α, β) onto workpieces with precise AOI tracking (angle of incidence) in a range of ±7.5° in a precision processing image field of 2.5 mm and a z range of ±1 mm (more product information in Ref. [14]). The TruMicro 5050 laser provides a wavelength of 1,030 nm, a 6 ps pulse duration, 50 W average power and 250 µJ maximum pulse energy. Furthermore, the optical path comprised mirrors and a beam conditioning unit containing a beam expander and wave plates for adjustment of circular polarization in the process area. The resulting focal spot had a diameter of 15.5 µm, measured with a Metrolux FM 100 beam camera. The sample holder was mounted on an x-y-z-stage with one micrometer positioning precision. Nitrogen was used as process gas at 4 bar using a nozzle of 1 mm in diameter. The test material was 0.2 mm thick brass sheet (37% zinc content). A rectangular kerf taper is defined to have a kerf taper angle Θ_k value of 0° (Fig. 1b). A cutting kerf with increasing kerf width towards the upper surface is considered to be a positive kerf taper and vice versa.

In a first step, the influence of the process parameters on the kerf taper angle of metallic alloys was systematically investigated working with a perpendicular beam incidence (Fig. 2a-I.). In a second step, the SCANLAB precSYS was used to control the kerf taper angle by static beam inclination (Fig. 2b-II.). In a third step, precSYS was used in its dynamic precession mode (Fig. 2c-III.) to fabricate micro-mechanical components of complex contours with perpendicular 0° taper angles. In the last processing mode the laser beam is moved on a circular path with a superimposed angle of incidence as known from trepanning and drilling applications. precSYS high-end scan technology and low moving masses ensure highly dynamic processing with precession frequencies up to 500 Hz (30,000 rpm). For cutting of the contours, the workpiece is moved with an x-y translation stage underneath the inclined laser beam.



(a)

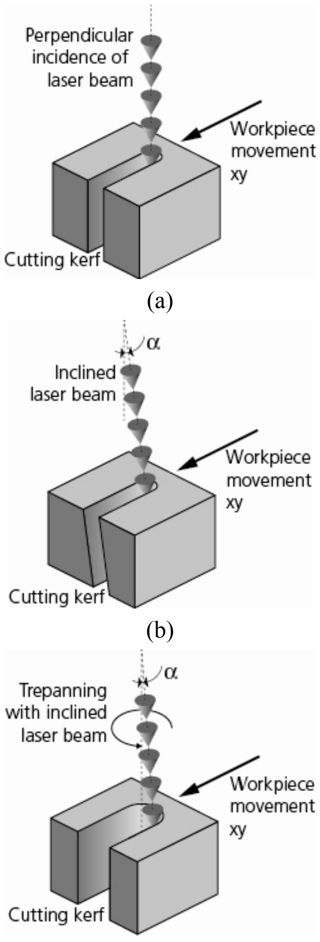
(b)

Fig. 1 (a) Scheme of experimental setup (1-beam reducer, 2-circular polarizer, 3-precSYS 5-axis sub system, 4-sample fixation, 5-x-y-z-stage, 6-mirror). (b) Definition of the kerf taper Θ_k (t-material thickness, l_k-length of a kerf segment, $l_{proj,k}$-length of the projection of l_k).

3. Experimental Results

3.1 Perpendicular Beam Incidence

In the first approach with perpendicular beam incidence, the laser fluence showed the most significant impact on the taper angle. Low pulse energy resulted in positive kerf taper values. Towards higher pulse energy, the kerf taper decreased (the cutting kerf became more perpendicular) (Fig. 3a). At 90 µJ and



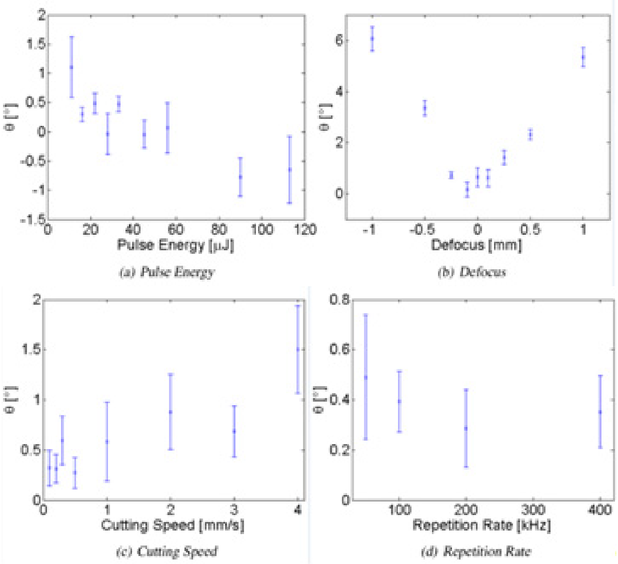
(c)

Fig. 2 Scheme of the three processing strategies investigated in this paper. (a) Perpendicular beam incidence, (b) Static beam inclination, and (c) Beam inclination on a circular path.

113 µJ the cutting kerf showed a slight curvature inwards extending over the middle and lower part of the kerf. Increasing defocus led to positive kerf tapers (Fig. 3b). The effect of cutting speed and repetition rate was less pronounced. High repetition rate and low cutting speed result in larger pulse overlap leading to slightly steeper kerf tapers (Figs. 3c and 3d).

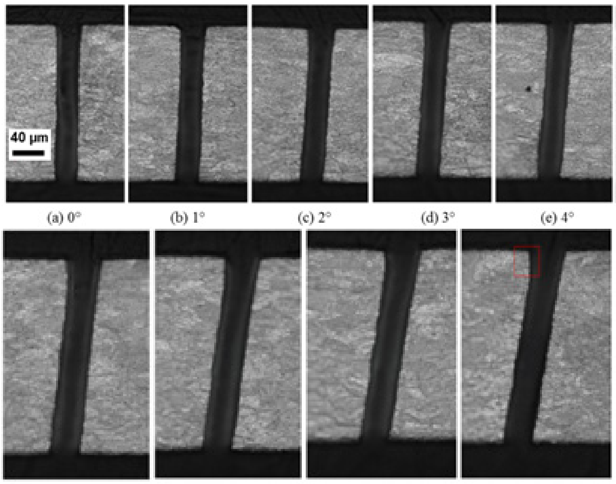
3.2 Static Beam Inclination

Static beam inclination was used to control the resulting kerf taper for the base parameter setting (straightest kerf) of the previous section. The static beam inclination was varied in steps between 0 and +7.5°. The kerf taper Θ_k scaled linearly with the static beam inclination angle α (Fig. 4). The cutting kerf width amounted to 28 µm for the base parameters. The measured surface roughness R_a amounted to 0.35 ± 0.05 µm.



(a) Pulse Energy (b) Defocus (c) Cutting Speed (d) Repetition Rate

Fig. 3 (a) Influence of pulse energy, (b) focus position, (c) cutting speed and (d) repetition rate on kerf taper.



(a) 0° (b) 1° (c) 2° (d) 3° (e) 4° (f) 5° (g) 6° (h) 7° (i) 7.5°

Fig. 4 Control of cutting kerf taper of the base parameterby static beam inclination between 0° and +7.5°.

3.3 Beam Inclination on a Circular Path (Dynamic Precession Mode)

The precSYS optics was used at a frequency of 8.3 Hz (500 rpm), at a beam inclination angle of +2° and a resulting precession radius of 9.2 µm (without z-axis movement). With this strategy the angle of incidence α

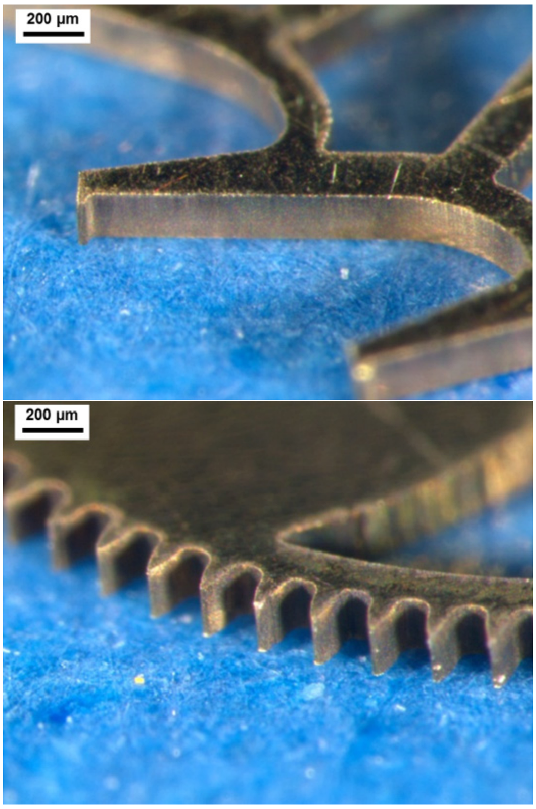


Fig. 5 Micro-mechanical demonstrator with complex contour cut using precSYS dynamic precession mode.

of the laser (AOI) and the resulting kerf taper Θ_k is unequal.

The most advantageous process strategy is to machine with a positioned laser beam defocused 75 µm above the work piece surface resulting in a spot diameter of 17.3 µm on the surface. An optimum result was achieved using 33 µJ laser pulse energy, 400 kHz laser repetition rate and a xy translation stage speed of 1 mm/s. The path was processed with 5 passages. In just 8 minutes a complex micro-mechanical geometry was cut out with a zero taper kerf through the entire length of the structure in a 0.2 mm thick brass sheet (Fig. 5). The cutting kerf width amounted to 40 µm for the process parameters given above. The measured surface roughness R_a amounted to (0.36 ± 0.04) µm, i.e. similar to the static beam inclination.

4. Conclusions

Working with a perpendicular beam incidence, a base parameter setting was found which led to straight kerfs with a slight kerf taper of less than 0.5°. Due to the linear correlation of the static beam inclination angle and the resulting kerf taper a defined cutting kerf taper can be reproducibly processed. Furthermore, static beam inclination could be an interesting option for kerf taper correction because it would allow maintaining established fixed optics cutting process parameters and process times and achieving very small inner radii in complex contours. The precession radius (in combination with the spot diameter) is the limiting scale for sharp inner radii of complex contours. The dynamic precession mode resulted in straight kerfs with 0° taper. It could be shown that complex contours can be cut at longer process times than with fixed optics with further potential for improvement by higher rotation rates.

The precSYS micromachining sub system provides much more possibilities for future investigations. It is easily possible to superimpose a z-axis movement of 2 mm while using very high precession frequencies up to 30,000 rpm. Thereby the potential of cutting thick work pieces in the millimeter region is given. In a circular processing area with a diameter of less than or equal to 2.5 mm no xyz-translation stage is needed for cutting depths up to a few millimeters. precSYS enables laser cutting, structuring and drilling applications on the same machine with the same work piece clamping. The combination of the TruMicro 5050 ultra-sort pulse laser with the precSYS enables laser micro processing of precise flexibly variable kerf geometries, e.g. fabrication of positive/negative (even negative/negative or positive/positive) or ideal zero taper cutting kerfs with high aspect ratios.

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