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Zero taper, fast drilling of high thickness metal parts

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Abstract

For material thickness up to nearly 1 mm, use of high average power, high repetition rate, ultrashort lasers jointly with trepanning head (enabling both beam rotation and inclination) has been shown to be an effective tool to obtain holes with high machining quality, zero or even negative taper, aspect ratio as high as > 10 and high throughput. Nevertheless, this technological approach shows its limitations when material thickness higher than nearly 1 mm is considered. Here a novel approach is proposed consisting of a top-down, hybrid (sequence of trepanning, drilling and trepanning) drilling process. By systematic variation of process parameters (beam inclination angle, focus re-positioning, etc.) this approach has been optimized to drill zero tapering holes in stainless steel 316 L having a thickness varying from 0.9 mm to 2 mm. Importantly, a zero-tapering hole with aspect ratio of 10 was obtained in a 2-mm thick sample with a processing time which has been reduced to 32 s. We believe these results not only show the full potential of the technological approach we utilised but can open the way for high power high repetition rate ultrashort laser to gain an ever-ubiquitous diffusion into an increasing number of industrial fields.

Keywords: trepanning head, drilling, zero taper, high aspect ratio, femtosecond laser

1. Introduction

Laser drilling has been observed to replace conventional drilling strategies in an ever-increasing number of applications and industrial fields such as aerospace [1,2], power plant components [3], photovoltaics [4], jewelry and watch [5], precision micromachining [6], etc. Use of lasers systems enables the drilling of holes with a remarkable accuracy and repeatability, high throughput, negligible debris and characteristics features of few hundreds of microns [7]. In particular, use of laser sources with ultrashort duration, has been shown to progressively reduce the heat affected zone. For a number of applications like automotive, microfluidics, highly precise micromechanics, and electronics, it is also crucial the possibility to obtain an adequate control

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of the hole geometry parameters like the aspect ratio AR (i.e. the ratio between the material thickness and the hole diameter) and the hole conicity or taper. In fact, due to the grazing incidence of the beam on the internal hole surface, drilling with a Gaussian beam perpendicular to the workpiece surface will always induce a positive taper (hole diameter at the entrance larger than at the exit surface). In this case, the most suitable approach consists in adopting the laser trepanning technique with rotating optics [8]. A suitable trepanning head is required which not only enables a fast rotation of the beam around a circular path but also allows the inclination of the beam with respect to the material surface with an angle β avoiding grazing incidence on side walls. Differently from more conventional drilling approaches, the latter enables a beam guiding mechanism permitting the control of the conicity and, according to β is possible to pass from positive taper to cylindrical or even negative taper. Nevertheless, in standard operating conditions, this technological approach shows its limitations when samples thicker than nearly 1 mm are considered. It is in fact well known that during the process, the more the laser goes deep inside the material the lower the ablation rate and a maximum depth is reached which depends amongst others on the pulse energy [9]. Here a novel approach is proposed consisting of a top-down, hybrid (sequence of trepanning, drilling and trepanning) drilling process. By systematic variation of process parameters (beam inclination angle, focus re-positioning, etc.) this approach has been optimized to drill zero tapering holes in stainless steel 316 L having a thickness varying from 0.9 mm to 2 mm. Importantly, for the first time a zero-tapering hole with aspect ratio of 10 was obtained in a 2 mm thick sample with a processing time which has been reduced to 32 s.

2. Experimental

We carried out laser drilling tests in stainless steel (SUS) 316 L with thicknesses of 900 µm, 1.2 mm, 1.5 mm and 2 mm. The laser utilised (Tangerine by Amplitude) is an IR (emission wavelength λ = 1030 nm) pulsed (up to 2 MHz) laser with pulse duration of 350 fs. The maximum average power is 20 W. During the tests, we fixed the repetition rate to 200 kHz and the pulse energy to 65 µJ. The beam delivered by the source was expanded (×1.5) and injected into a trepanning head (GF provided by GFH) enabling the beam rotation (20000 rpm, maximum 30000 rpm) and inclination of an angle between – 200 mrad and 200 mrad. The beam was finally focalized (focal length = 54 mm) through a process head allowing the ejection of a high pressure (4 atm) gas stream (Nitrogen) coaxially to the optical axis.,. The beam size in correspondence of the focus was estimated to be between 25 µm and 28 µm.

3. Results

Different drilling approaches and strategies have been introduced according to the material property, and the desired hole geometry and process throughput. We mention for instance, percussion, spiralling, trepanning, etc. In the specific case of high aspect ratio and zero tapering holes with diameter up to d ≈ 100 µm, a multi-step approach has been proposed consisting of a sequence of percussion, spiralling from initial diameter $d_s = 0$ to a final diameter value d_f and trepanning around a circle with $d = d_f$ [10].

In our study, we target a higher diameter value of d ≈ 200 µm with the consequence that a larger amount of material has to be ablated to complete the hole. This has been taken into account adding two more steps in the drilling sequence as described in Tab. 1. The overall processing time is 13 s. In Fig.1(a) are shown the values of hole diameter d_{in} at the entrance (red circles) and d_{out} (black square) at exit surface versus the laser beam inclination angle β obtained utilising the above mentioned sequence. It can be clearly observed that varying β from 0 to 150 mrad whilst d_{in} is relatively stable (varying between a minimum value of d_{in} = 208 µm and a maximum d_{in} = 235 µm i.e. a relative variation of 16%) d_{out} increases monotonically from d_{out} = 98 µm to d_{out} = 228 µm.

Table 1. Composition of the drilling sequence utilised during the tests

Drilling Step	d_s (µm)	d_f (µm)
Trepanning	0	0
Spiralling	0	250
Spiralling	250	130
Spiralling	130	250
Trepanning	250	250

Consequently (see Fig. 1b) the tapering angle decreases from θ = 3.4° to θ = - 0.1° reaching zero in correspondence of β* = 135 mrad. Finally, Fig. 1(c) shows the internal hole profile obtained in correspondence of β* value which is clearly cylindrical.

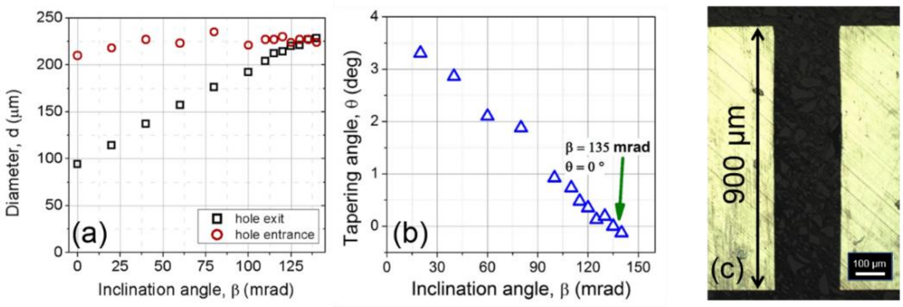

Fig. 1. Drilling of 900 µm thick SUS 316L: in (a) are plotted the values of hole diameter at entrance (red circle) and exit (black square) surface versus the beam inclination angle β and (b) the consequent values of tapering angle θ. In (c) the hole internal profile obtained for β = 135 mrad

Nevertheless, the same set of process parameters (drilling sequence and inclination angle θ*) yields quite different results when applied to thicker samples. Fig.2 shows the visual appearance of the hole entrance and exit obtained repeating the drilling sequence N times. For N = 1 although the entrance is perfectly circular, the exit has an irregular, barely circular shape with a diameter d_{out} ≈ 89 µm and a circularity defect Δ = 28 µm. Increasing N = 2, 3,4 and 5 induces substantial improving but still, in the case of N = 5 is θ = 2.2° and Δ = 9 µm. Besides, the processing time increases from 13 s to more than a minute.

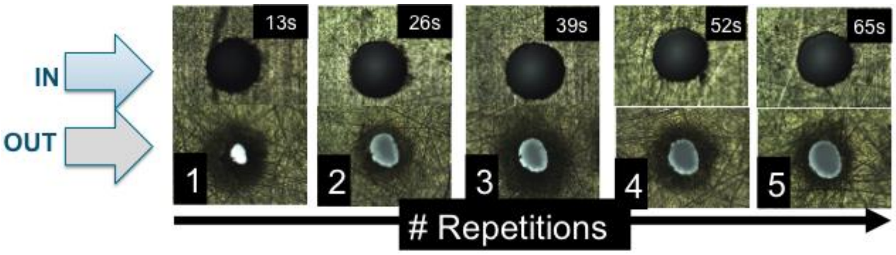

Fig. 2. Drilling of 1.2 mm thick SUS 316 L: visual appearance of the entrance (up) and exit (bottom) hole surfaces versus the number of repetitions of the drilling sequence

More interesting results are obtained with an top-down approach i.e. accomplishing a second drilling sequence after moving the laser focus position from the surface inside the material for 400 µm.

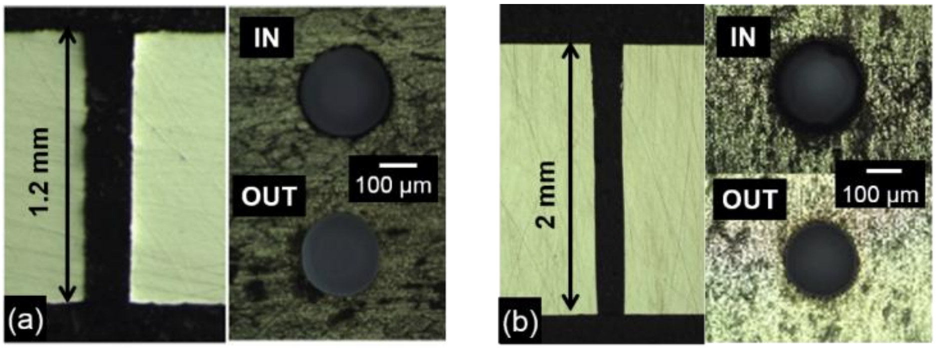

Fig. 3. Drilling of SUS 316 L with top-down. The hole profile (left) and the visual appearance of the entrance (IN, up right) and exit (OUT, bottom right) surfaces are shown for thickness 1.2 mm (a) and 2 mm (b)

As shown in Fig. 3 (a) not only the hole at the exit surface is much more regular but the tapering is drastically reduced to a value of nearly 0.6°. The processing time is 26 s.

The same top-down approach has been utilised for samples both 1.5 mm thick (with two focus replacement at 400 µm and 800 µm below the surface) and 2 mm thick. In the last case, the focus has been moved below the surface at 400 µm, 800 µm and 1200 µm. As shown in fig. 3(b) we obtained a cylindrical hole with a regular circular shape both at the entrance (d_{in} = 259 µm) and the exit (d_{out} = 221 µm) and a tapering θ = 0.5°. The processing time is 52 s and AR = 8.

Finally, in Fig. 4 is shown the profile of the hole obtained in case of d_f = 200 µm and reducing the overall length of each drilling sequence to 8s.

Although a slight reduction of the diameter is observed nearly 100 µm below the surface, the hole shows a quite cylindrical profile with a tapering of 0.4°, an overall processing time of 32 s and a diameter at the entrance of nearly 200 µm corresponding to AR = 10.

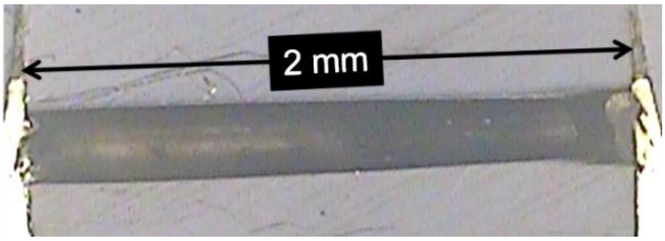

Fig. 4. Drilling of SUS 316 L with top-down approach of 2 mm thick samples.
The final tapering is 0.4°, aspect ratio 10 and drilling time 32 s

4. Conclusion

We carried out drilling tests on SUS 316L parts having a thickness comprised between 900 µm and 2 mm. A hybrid drilling sequence (percussion, spiraling and trepanning) repeated with a top-down approach has been introduced and successfully tested. Holes with a good machining quality and tapering of nearly 0.5° have been shown for all the thickness values considered confirming the high potential of our technological approach. Finally, a hole with aspect ratio 10 and tapering 0.4° drilled in 32 s has been obtained and reported in a 2 mm thick sample.

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