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Helical drilling of three-dimensional conical converging-diverging nozzle in steel using ultrashort laser pulses

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Abstract

Three-dimensional conical converging-diverging nozzle typically a de Laval nozzle can be used for micropropulsion of microsatellites. The profile control, surface roughness and symmetry of the nozzle are key parameters to determine its performance. In this paper, we focus on the fabrication of a three-dimensional conical converging-diverging nozzle using helical drilling optics and ultrashort laser pulses. The helical optics makes it possible to dynamically control the profile of a hole by adapting the helical path during drilling process. An opening angle up to 18.6° on the converging part and 6.6° on the diverging part are achievable in 1 mm thick stainless steel by means of classic helical drilling. By introducing a dynamic helical process, the opening angle of converging part with straight profile can be extended to more than 90°. Moreover, the employment of an ultrashort pulsed laser has contributed to a high quality surface on the hole-wall having an average roughness less than 0.4 µm.

Keywords: Helical drilling optics; ultrashort laser pulse; shaped holes; helical path; nozzle fabrication

1. Introduction

Three-dimensional conical converging-diverging nozzle typically a de Laval nozzle can be used to increase the velocity of exhaust in micropropulsion of microsatellites [1,2]. Depending on the material applied, such nozzle can be fabricated by several conventional micro technologies such as deep reactive ion etching (DRIE)[3], powder blasting process, electric discharge machining (EDM)[1, 4]. These technologies are either material selective, or not able to shape a negative conical hole profile. Moreover, holes fabricated by powder blasting demonstrated poor quality on side wall [1]. The former two approaches are applicable merely for semiconductors like silicon and germanium. Whereas the EDM works exclusively in metallic materials. Comparing with them, laser processing is characterized as non-contact and non-selective processing and qualifies unique advantages in terms of quality and flexibility. By taking advantage of ultrashort laser pulses with pulse duration less than 10 picosecond, an extraordinary geometrical precision of drilling with minimized thermal effect can be achieved in a variety of materials owing to a vaporization dominated process [4-6]. The state-of-the-art technology of laser microdrilling can achieve a 2/2.5 dimensional hole with a drilling optic which enables a relative movement of laser beam on the workpiece [7-9]. In order to achieve a three-dimensional converging-diverging hole, the sample must be treated from two side. This strategy provides a high flexibility in shaping the hole profile. However, it lead to a high requirements on the alignment of coaxial structuring by laser beam [1].

In this work, we present a one-side drilling strategy to fabricate conical converging–diverging holes by utilizing a helical optic and an ultrashort pulsed laser. Factors, which determine the nozzle profile including the angles of converging and diverging parts and the position of throat, as well as the diameters of entrance and exit, are investigated.

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Furthermore, the productivity and hole quality using static and dynamic helical drilling strategies are comparatively studied.

2. Experimental setup and approach

The helical drilling system for three-dimensional conical converging-diverging nozzle is schematically shown in Fig. 1. It consists of an ultrashort pulse laser source, helical drilling optics and CNC linear motor stages. The ultrashort pulse laser source delivers a second harmonic generation of 515 nm wavelength and a maximum average output power of 75 W at the maximal repetition rate 600 kHz. The pulse duration τp is 900 fs. The maximal single pulse energy is 125 µJ. The Dove prism locates in the hollow shaft motor. Passing through the spinning Dove prism with a maximum rotation speed of 10000 rpm, the linear polarized laser beam rotates with doubled speed along an optical axis and is focused on the surface of sample to a spot diameter of 15 µm by an objective having a 60 mm focal length.

In the helical drilling process, the bore diameter and taper are controlled by a motorized wedge prism and a linear table separately. More precisely, the rotation diameter of focused laser beam is determined by the tilt angle of wedge prism Δβ, which alters the incident angle of the incoming raw laser beam in front of focusing lens, while the linear table regulates a defined parallel offset, which determines the inclined angle of focused laser beam on workpiece. With the rotation of the inclined laser beam, a hole with a certain taper angle can be achieved. The helical path on a z-plane is recorded by a high-resolution CMOS camera having a pixel size of 1.67 µm, and then a three-dimensional helical path is visualized by using a CAD software. The holes are fabricated in 1 mm thick stainless steel X5CrNi18-10. The holes are analyzed by a confocal laser scanning microscope (LSM) and a scanning electron microscope (SEM).

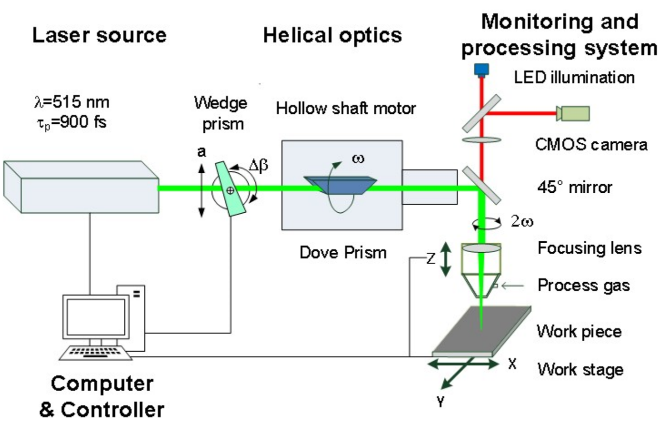

Fig. 1. Schematic of the helical drilling systems

The first step to achieve a conical converging–diverging hole, is drilling of a negative conical hole (diverging hole) with the linear table set at the negative position. Following that, a positive conical hole with converging angle is concentrically superposed on the diverging hole with linear table position. In order to achieve a convergent entrance, both static and dynamic helical drilling strategy are applicable and investigated in this work. The static strategy means the fixed processing parameters especially the positions of wedge prism and linear table. While in the dynamic strategy, at least one parameter dynamically varied during the helical drilling process. By means of the dynamic helical drilling strategy, different entrance profile with designated hole diameter can be shaped. In this work, varied focal position and pulse energy of laser beam are investigated to define the dependence of the throat position of the conical converging-diverging hole on process parameter.

3. Results and discussion

3.1. Helical path in helical drilling process

In the helical drilling process, besides the laser parameters applied, the hole geometry is determined primarily by the caustic of the three-dimensional (3D) helical path. The 3D helical path describes the trajectory of the laser pulse positions in revolutions along the hole depth. Rephrased, by plotting the positions of laser pulses sequentially deposited, the spatial path of laser pulses in the whole drilling channel can be represented approximately as a 3D helix curve - the 3D helical path. Fig. 2 illustrates the 3D helical paths for three typical hole profiles: positive and negative conical as well as cylindrical hole geometry. A 3D helical path of laser beam in the borehole is determined by the positions of wedge prism and linear table.

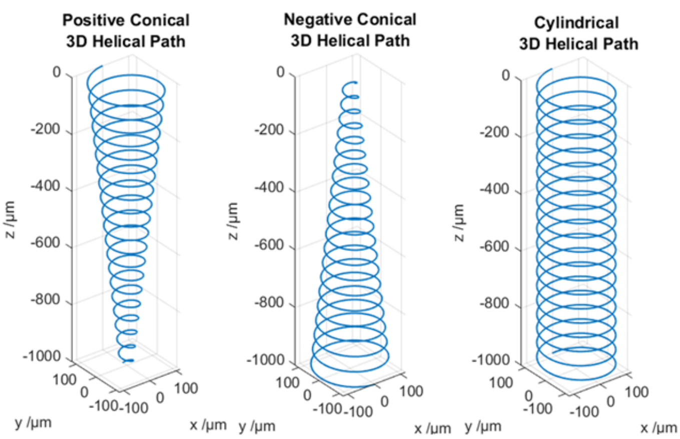

Fig. 2. Simplified three-dimensional helical path in positive, negative conical and cylindrical profiles

The 3D helical path is adjusted for designated hole profile. As aforementioned, the 3D helical path is determined by the position of wedge prism and parallel offset in the helical drilling optics. Fig. 3 shows the caustic of the helical path with varied parallel offset from a=-5 mm to +5 mm with an interval of 1 mm at the position of wedge prism Δβ=4°, which corresponds to a helical diameter 60 µm.

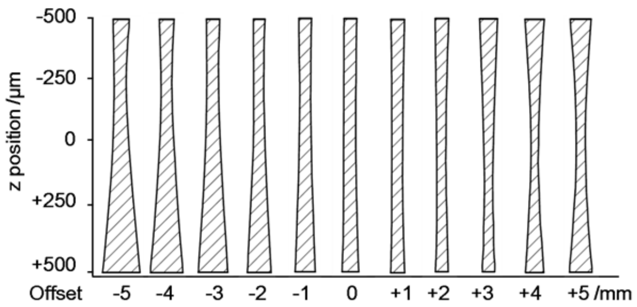

Fig. 3. Two-dimensional caustic of helical path with varied parallel offset

The z position z=0 in Fig. 3 denotes the focal position of single laser beam, and positive z position is in the direction of laser propagation. An intuitive development of the profiles displays in the Fig. 3, that the caustic of helical path is cylindrical when the offset a=0 mm, whereas the profile evolves to negative conical at negative positions a<0 mm and positive conical at positive positions a>0 mm. Noteworthy is that, the positions of caustic waist in helical path are not always overlapped with the position of laser beam focus z=0. At the negative parallel offset, the positions of caustic waist locate upper the focal position, whereas at the positive parallel position, they locate under z=0.

3.2. Analysis on hole geometry and morphology

By using the parameter setting for the helical path displayed in Fig. 3, holes are fabricated in 1 mm thick stainless steel with the focus of the laser beam at the 0.25 mm and 0.5 mm under the top side of material, where the inlets of laser beam. As can be seen from the cross-sections of the bore-holes in Fig 4, the focal position plays an important role in the hole profile. Compared with the hole profile bored with the focal position at z=0.5 mm, the entrances of holes bored with the focal position at z=0.25 mm are sharper. In addition, a more distinct evolution of hole profile from negative conical over cylindrical to positive conical is shown in the drilling results at z=0.25 mm. The main part of the bore-hole at this z position is generally dominated by a single art of taper, i. e. negative, positive or zero taper.

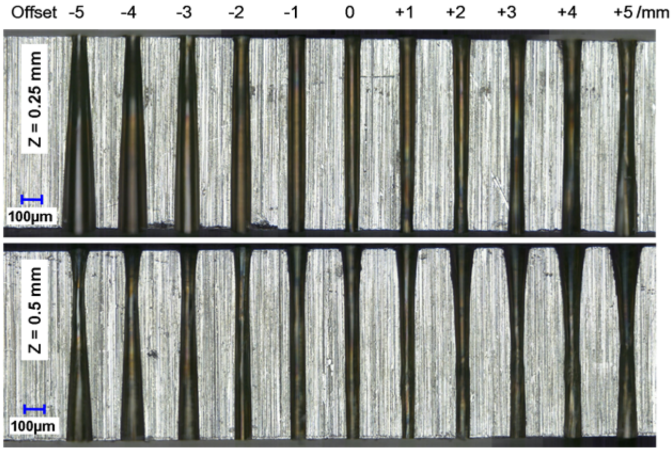

Fig. 4. Cross-section of bore-holes at focal positions of z = 0.25 mm and 0.5 mm in material with varied parallel offset, applied laser single pulse energy 125 µJ, pulse repetition rate 60 kHz, drilling time 10 seconds, helical rotating speed 3600 rpm

Due to the strong defocusing of laser beam t z=0.5 mm, converging-diverging holes can be fabricated with a larger parallel offset in both plus and minus direction especially at offset a=≥+4 mm and a≤ -4 mm as shown in Fig. 4. The hole profile bored at z=0.5 mm in material are in an excellent agreement with the 2D caustic of helical path displayed in Fig. 3. The full opening angle of the main part of the bore-holes are plotted by the parallel offset in Fig. 5. Greater positive taper can be obtained by focusing the laser at deeper position in material. An opening angle of 18.6° can be achieved at offset +5 mm and z=0.5 mm, while the opening angle is about 6.6° at z=0.25 mm. However, the achievable negative taper stays approximately the same (6.5°) at both z positions. The achievable maximum negative taper in 1 mm stainless steel is limited by the aperture of the Dove prism and the maximum single pulse energy of the laser beam.

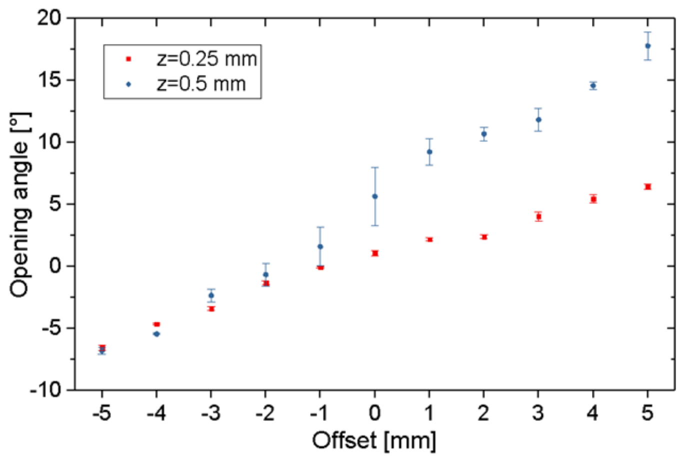

Fig. 5. Opening angle of the main part of holes at varied parallel offsets in helical drilling process with focal plane at z=0.25 mm and 0.5 mm

The morphology of the bore-holes is analyzed by examination on the hole-wall under a scanning electron microscope and laser scanning microscope. As the SEM image in Fig. 6 depicted, neither recast layer nor heat affect zone (HAZ) can be detected on the hole-wall. Furthermore, the root mean squared (RMS) roughness R_q on the hole-wall is measured to be 0.35 µm, which gives evidence to a very smooth hole-wall. On the one hand, the application of an ultrashort pulsed laser having a pulse duration 900 femtoseconds contributes to the high-precision ablation and minimized HAZ [10], on the other hand, as a result of the helix revolution of laser pulses, the local thermal accumulation is weakened [11, 12]. Both the two factors are essential for a high-quality drilling process.

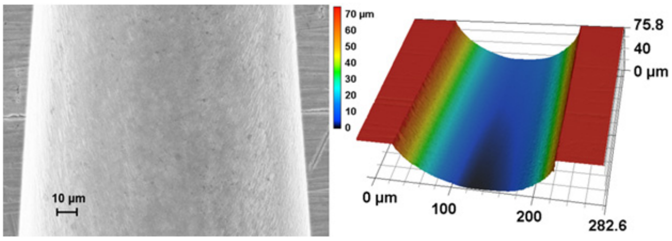

Fig. 6. SEM image (left) and confocal laser scanning microscopy (right) of the cross-section of the diverging part in a converging-diverging hole

3.3. Fabrication of converging-diverging holes

With the parameters for negative and positive conical holes and the static strategy, a converging-diverging hole can be fabricated by concentrically superposing a positive conical hole upon a pre-bored negative conical hole, as shown in Fig. 7a. The drilling time is about 15 seconds. The position of throat lies at z=170 µm beneath the surface (approximately 1/6 of the material thickness) and its diameter is 120 µm. The diameter of hole entrance and exit are both 180 µm. In order to improve the controllability on the shaping of converging hole and the depth of throat positon, a dynamic drilling strategy is chosen for the converging part.

The dynamic strategy is characterized by an increasing helical diameter and dynamically adapted laser parameters during the drilling process. By means of that, a hole entrance with designated profile is feasible. Fig. 7b and 7c show the converging-diverging holes with entrance of a funnel and trophy form - different curvature of entrance. For the funnel-like hole depicted in Fig. 7(b), the helical diameter increases from 40 µm to 570 µm within 30 seconds. Accompany with that, the laser pulse energy decreases from 12.5 µJ to 2.5 µJ with a decrement of 2.5 µJ and duration of 6 seconds at each pulse energy. Whereas the single pulse energy stays the same (12.5 µJ) during this process for the hole in Fig. 7(c). The total bore time is 40 seconds. The throat positions of the both converging-diverging holes locate at z=330 µm, about 1/3 of the material thickness under the top surface. The opening angle of the converging parts are 91° and 58° respectively. The diverging part of the holes are of the same geometry: hole-exit diameter 180 µm, divergence angle 6.6°. Compared with static strategy, the dynamic drilling approach is less productive, however, it manifests a higher flexibility in shaping the entrance part of a converging-diverging hole.

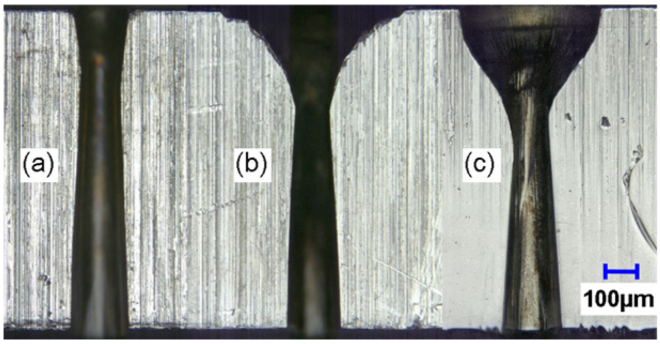

Fig. 7. Converging-diverging holes fabricated by static (a) and dynamic (b and c) helical drilling strategies

The converging-diverging holes in Fig.7 demonstrate an excellent symmetry of hole profile owing to helical path with a fairly good circularity achieved by using the helical drilling optics. By varying the pulse energy and increasing rate of helical diameter for the converging part, the position of throat can be adjusted in the z direction [13].

4. Conclusion

The helical drilling system based on a rotating Dove prism can manufacture micro holes with high precision in the aspects of hole symmetry and controllability of hole taper. Additionally, it enables the fabrication of three-dimensional conical converging-diverging holes by means of shaping the entrance of a diverging hole concentrically into a converging form. Different opening angle of the converging and diverging parts can be achieved at varied parallel offsets of incident laser beam. However, the maximal opening angle is limited by the factors such as available laser pulse energy and offset in the helical drilling optics. Nevertheless, by using a dynamic drilling strategy, in which the helical diameter and laser pulse energy dynamically adapted, the opening angle of converging part can be extended to more than 90°. Moreover, this part can be shaped in different profiles. As a final remark, the application of ultrashort laser pulses contributes to minimized heat affect zone and recast layer on the hole-wall. The analysis on the morphology of the hole-wall gives evidence of a smooth surface with R_q=0.35 µm. As a promising technique for drilling of 3D converging-diverging microholes, the helical drilling optics could be used for manufacturing complex nozzles like de Laval nozzle for micropropulsion.

Acknowledgements

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