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Experimental characterization of laser trepanning performance enhanced by water-based ultrasonic assistance

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HIGHLIGHTS

- Water-based ultrasonic assistance increased laser trepanning efficiency.
- Laser trepanning quality was improved using water-based ultrasonic assistance.
- Ultrasonic vibration reduced residual stress induced by laser trepanning.

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ABSTRACT

Laser trepanning is becoming more popular as compared with percussion laser drilling especially in aerospace industry. However, the high-efficiency and high-quality hole drilling using conventional laser drilling/trepanning has always been a challenging task. In this work, a millisecond pulsed Nd:YAG laser trepanning technique enhanced by water-based ultrasonic assistance was proposed for improving trepanning performance with much higher efficiency. The assistance method of ultrasonic vibration for laser trepanning was improved by uniformly vibrating the whole workpiece with a 25 kHz frequency in the water medium, instead of directly loading ultrasonic impact onto workpiece or vibrating optical objective lens. Effects of ultrasonic vibration on millisecond pulsed laser trepanning performance were investigated by changing laser pulse width, trepanning speed, and number of trepanning passes. Compared with laser trepanning without ultrasonic assistance, it was found that both hole diameter and hole depth were increased leading to an effective enhancement of trepanning efficiency if using ultrasonic assistance, reducing hole entrance circularity deviation and hole taper. Compared with normally trepanned holes, the hole cross-section geometry and hole sidewall quality/morphology were improved by using ultrasonic assistance, in terms of a cleaner hole sidewall with smaller arithmetical average roughness height, better hole profile, less spattering/defects, and smaller recast layer thickness. Moreover, micro hardness values for zones surrounding the trepanned hole were improved by using ultrasonic assistance, mainly resulting from the microstructure alteration due to strengthening phase/particle precipitation and grain refinement enhanced/induced by ultrasonic assistance. It was also found that residual stress caused by laser trepanning was effectively reduced by using ultrasonic assistance. The ultrasonic assistance was helpful to reduce recast layer thickness for both normal trepanning and helical drilling. For the hole helically drilled with/without ultrasonic assistance, the recast layer was thinnest near hole entrance while thickest near hole bottom. Compared with holes normally trepanned, much less strengthening phases/particles precipitated due to a much shorter duration used for helical drilling, but the grain refinement in the HAZs was not obviously influenced.

1. Introduction

High quality microhole drilling has always been a challenging task [1]. Electro-discharge machining (EDM) or pulsed laser drilling is the technique commonly used for cooling hole drilling. The EDM drilling is very slow, and its tooling cost is high although it produces high quality holes [2]. Laser drilling has accordingly become an alternative for high-efficiency precise hole drilling in spite of the normally encountered recast layer formation, especially in the aerospace industry [3]. It was reported that the machining speed of EDM for drilling holes (0.8 mm diameter) in stainless steels was around 10 mm/min [4]. However, it was shown that the drilling speed of EDM for machining straight holes

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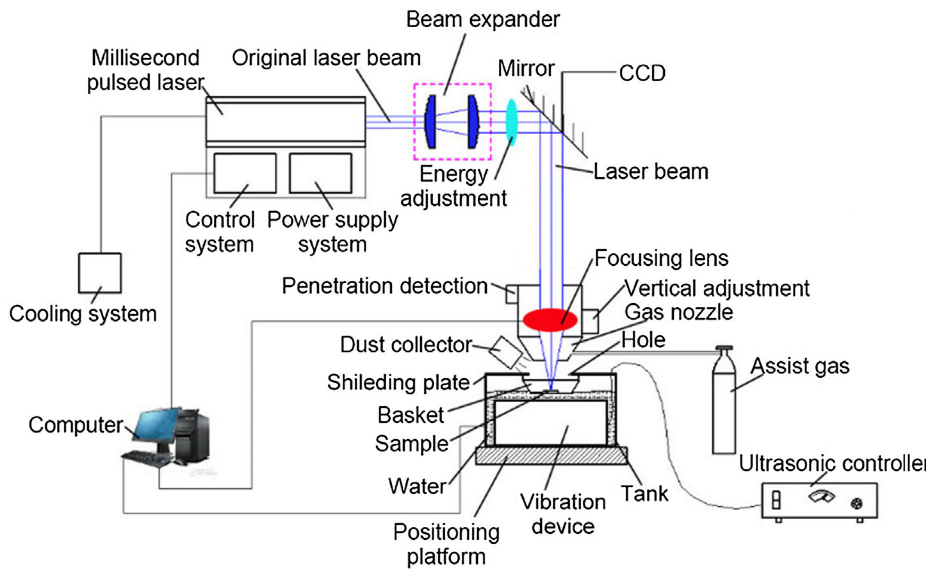

Fig. 1. Illustration for millisecond pulsed Nd:YAG laser trepanning system enhanced by water-based ultrasonic assistance.

Table 1
Operating parameters used for laser trepanning.

Case	Pulse repetition rate (Hz)	Pulse energy (J)	Defocus distance (mm)	Beam expanding ratio	Ultrasonic power (W)	Pulse width (ms)	Number of passes	Trepanning speed (mm/min)
A	55	2.2	−1	3.8	606.6	1.0	1	/
B	50	2.5	0	3.6	544.4	/	2	20
C	45	2.5	0	4.3	575.5	0.8	/	25
D	50	1.0	0	4	622.2	0.6	1	40
E	55	2.2	/	3.8	606.6	1.0	3	50

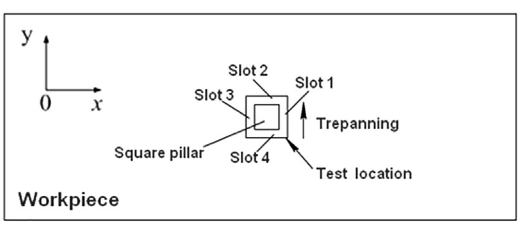

Fig. 2. Schematic for laser trepanning and stress measurement of square-slotted holes.

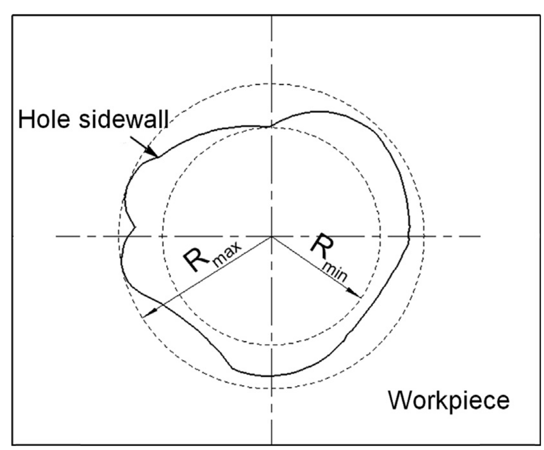

Fig. 3. Hole entrance radii used for characterizing the trepanned hole circularity deviation.

in aluminum alloy with and without workpiece vibration ranged from around 0.15–0.35 mm/min when using a suspended ball electrode of 5.5 mm in diameter [5]. Comparing to laser drilling, Antar et al. studied the high-speed hole drilling (0.8 mm diameter) of nickel-based aerospace alloy (5–10 mm thick) using the state-of-the-art EDM machine. They found that the EDM showed significantly better results in terms of recast layer and geometric accuracy/taper, especially for thicker workpieces. Laser drilling, however, was far superior in terms of drilling speed with less than 3 s drilling time for 10-mm-thick samples, compared to the best recorded drilling time of 48 s using the state-of-the-art EDM machine [2].

Percussion laser drilling, helical laser drilling and laser trepanning are the commonly-used laser drilling methods [6–8]. Laser trepanning, a combined drilling carried out with percussion drilling followed by a relative movement between workpiece and laser irradiation, is becoming more popular as compared with percussion laser drilling as a result of better hole quality and capability to generate macro-size holes. Compared with percussion laser drilling and helical laser drilling, laser trepanning can be used for drilling free-form holes with different shapes and contours on the hole entrance/exit. Besides, compared with percussion laser drilling, laser trepanning provides better control over the drilled hole geometry to fulfill higher dimensional accuracy requirement [1,3].

So far, many investigations with respect to laser trepanning have been reported [1,3,8–15]. Ashkenasi and Jahns et al. [9,10] developed a versatile laser trepanning system, which could adjust circular beam displacement and inclination via rotating the optics. They discussed the feasibility of their self-designed laser trepanning system for drilling different tapered through holes with an entrance diameter in the range of 65–1000 μm. Dhaker et al. [8] investigated the effects of different process parameters on the drilled hole diameter in laser trepanning of Inconel718 sheet. They also used the experimental data to develop a multi regression model for predicting the hole diameter in laser trepan drilling. Goyal et al. [1,3] studied the laser trepanning performance in