Optics and Laser Technology 106 (2018) 451–460

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Effects of ultrasonic assistance on microhole drilling based on Nd:YAG laser trepanning

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ARTICLE INFO

Article history:
Received 14 November 2017
Received in revised form 26 April 2018
Accepted 5 May 2018

Keywords:
Nd:YAG laser
Laser trepanning
Ultrasonic assistance
Microhole
Nickel super-alloy

ABSTRACT

The ultrasonic vibration was introduced to assist the Nd:YAG laser trepan drilling for improving drilling quality/performance. Effects of ultrasonic power and pulse energy on geometrical and/or metallurgical quality were deciphered for the ultrasonic-assisted Nd:YAG laser trepanning. The energy dispersive spectroscopy analysis was also carried out to reveal the influence of ultrasonic vibration on the elemental compositions of the areas surrounding the drilled microhole entrance. It was shown that the axial ultrasonic vibration coupled into the Nd:YAG laser trepanning process could effectively improve the hole entrance profile/morphology with less metallurgical defects such as microcracks. Moreover, relatively high ultrasonic power was more beneficial to the improvement of laser trepan drilling quality in terms of smaller hole taper angle, thinner recast layer, and less cracks, etc. However, the oxidation of the microhole sidewall could not be effectively improved by using the ultrasonic assistance.

1. Introduction

Laser drilling has become an alternative for drilling precise holes in advanced difficult-to-cut super alloys, especially in the aerospace industry [1]. Microhole drilling of superalloys meeting high-quality standards has always been a challenging task for widespread applications in aero engine component manufacturing [2]. The normally-used laser drilling methods consist of single pulse laser drilling, percussion laser drilling, laser trepanning, and helical laser drilling [3–5]. Laser trepanning, a combined process of drilling and cutting typically applied with pulsed laser radiation, is actually the hole machining with a single pulse laser drilling or percussion laser drilling followed by a relative movement between laser radiation and workpiece. It is possible to machine free-form holes with different shapes and contours on the hole entrance/exit using laser trepanning. Due to better hole quality and capability to generate macro-size holes, laser trepanning is becoming more popular as compared with percussion laser drilling. Compared with percussion laser drilling, however, laser trepanning provides better control over the drilled hole geometry to fulfill the higher dimensional accuracy requirement [1,2].

So far, many studies regarding laser trepan drilling have been carried out. Goyal et al. [1,2] studied the laser trepanning performance in terms of geometrical quality characteristics such as hole taper and circularity for drilling small-diameter hole in difficult-to-cut titanium alloy sheets. They discussed the influence of significant process parameters on hole characteristics based on the data obtained through a well-designed orthogonal-array experimental matrix, and they developed reliable empirical models for different quality characteristics. Moreover, they also demonstrated that higher values of laser pulse frequency and trepanning speed in the present range might result in more circular holes with reduced taper. Dhaker et al. [5] 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 the multi regression model for predicting the hole diameter in laser trepan drilling. Ashkenasi and Jahns et al. [6,7] 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. Fan et al. [8] proposed to use the trepanning method to solve the problem of microcracks encountered for high pulse energy femtosecond laser drilling of 0.5-mm-thick 304 stainless steel (pulse width of the femtosecond laser was 120 fs). Compared with the microholes drilled using percussion drilling, they found that the microcracks could be effectively reduced through using femtosecond laser trepanning despite some nanometer periodic stripes found on the trepanned microhole side walls. Zhang et al. [9] demonstrated to use femtosecond laser for trepanning the super alloy with thermal barrier coating to drill

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https://doi.org/10.1016/j.optlastec.2018.05.003

the holes without crack extension, attached debris, and recast layer. Zhang et al. [10] developed a quantitative method for characterizing the hole quality during laser trepan drilling of high-temperature alloy. They obtained the optimal drilling parameters including laser power and beam expanding ratio according to the calculation of the hole taper and circularity. Choudhury et al. [11] conducted laser trepanning of 5-mm-thick polymer sheets for fabricating different holes with diameters of 2 mm, 4 mm and 6 mm, and they optimized the combination parameters for producing the minimum taper in the drilled through hole.

The metallurgical defects such as microcrack, recast layer, and heat affected zone (HAZ) normally occur during the laser (especially the millisecond/nanosecond pulsed laser) drilling process. Moreover, when the laser beam irradiates onto the material surface, the oxide layer also easily occurs on the recast layer surface around the drilling microhole sidewall. These defects will obviously reduce the morphological/geometrical quality and mechanical performance for the laser-drilled microholes. However, the laser alone normally cannot drill high-quality microholes. Because the ultrasonic vibration can reduce defects, make grains finer, relieve stress, and improve mechanical properties [12–15], the idea of developing a combined laser-ultrasonic technique was accordingly developed [16,17].

The previous work has indicated that deeper and better-quality laser drilled holes can be obtained by using ultrasonic assistance [12–26]. Lau and Yue et al. [16,17] explored this technique in the 1990s, and they found that the ultrasonic-assisted laser drilling technique might increase the depth-of-drill and also improve the hole quality for aluminum-based metal matrix composites. Zheng et al. [18] reported that the high-frequency ultrasonic vibration-assisted femtosecond laser might improve the aspect ratio and the wall surface finish of the drilled microholes. Alavi et al. [20–22] investigated the geometry/quality features during ultrasonic vibration-assisted continuous wave laser surface drilling. They found the interaction between the ultrasonic vibration-assisted continuous wave CO_2 laser and the austenite stainless steel might be used for laser surface drilling (the ultrasonic frequency used was 20 kHz) because the ultrasonic vibration might help the melted material expel from the molten pool. Considering the observations of melt expulsion from high speed photography, they also carried out a multi-step finite element analysis for ultrasonic vibration-assisted continuous wave laser drilling process to predict the hole volume. It was found that the melt expulsion under the influence of ultrasonic vibration initiated after the laser melted pool reached a critical size/volume, and the depth of the laser-drilled holes increased almost linearly in the early stages, afterwards, the drilling rate progressively decreased. Park et al. [23,24] demonstrated to improve the laser machining quality on metals by vibrating optical objective lens with a frequency (500 Hz) and various displacements (0–16.5 mm) during a femtosecond laser machining process. They found that the wall surface finish of machined structures and the aspect ratio obtained using low-frequency vibration-assisted laser machining were improved, compared to those derived via laser machining without vibration assistance. Wu et al. [26] tried the experimental study for the underwater ultrasonic-aided nanosecond laser drilling of stainless steel. They reported that the ultrasonic vibration might improve the hole morphology. However, during underwater laser drilling, the water medium could unavoidably influence the interaction between the laser beam and the workpiece due to the absorption and reflection of the incident laser beam, without mentioning water surface fluctuation/instability resulting from the assist gas flow.

Different from the previous work other researchers reported, in the present work, an ultrasonic-assisted millisecond pulsed laser trepanning technique is reported to drill holes in GH4037 nickel super-alloy sheets of 2.75-mm-thickness, increasing trepanning quality through improving the assistance method of ultrasonic vibration with a 25 kHz frequency by uniformly vibrating the whole workpiece in the water medium, instead of using direct ultrasonic impact onto optical objective lens or some locations of the workpiece. Accordingly, the influence of ultrasonic power and pulse energy on geometrical and/or metallurgical quality of the holes drilled using ultrasonic-assisted laser trepanning was analyzed. The energy dispersive spectroscopy (EDS) analysis was also carried out to investigate the effect of ultrasonic vibration on the elemental compositions of the areas surrounding the trepanned hole entrance.

2. Materials and methods

A water-based ultrasonic-assisted Nd:YAG laser trepanning system (Fig. 1), mainly consisting of a pulsed Nd:YAG laser (the laser operating parameters are listed in Table 1), a five-axis high-precision computerized numerical control positioning stage, and an ultrasonic-assisted system (voltage is 220 V), was utilized for carrying out the laser trepanning experiments with/without ultrasonic assistance. As shown in Fig. 1, the ultrasonic vibration device with a 25 kHz frequency is controlled by an ultrasonic controller, through which the current (ultrasonic power) can be altered. When the ultrasonic controller is on, the ultrasonic vibration device will work, and the ultrasonic wave will propagate to the sample in the water, instead of directly loading ultrasonic impact onto the workpiece or the optical objective lens using a transducer. Consequently, high-frequency uniform mechanical vibration occurs on the whole workpiece through ultrasonic wave propagation in the water medium, greatly increasing the operating life length of the ultrasonic assisted system, obviously decreasing the piercing noise induced by the direct ultrasonic impact onto the workpiece, with effective reduction of energy loss normally resulting from the ultrasonic wave propagation in the air.

The material used is nickel super-alloy GH4037, which consists of Cr (13–16%), W (5–7%), Mo (2–4%), Ti (1.8–2.3%), Al (1.7–2.3%), V (0.1–0.5%), C (0.03–0.1%), Fe ($\leq$5%), Mn ($\leq$0.5%), Si ($\leq$0.4%), B ($\leq$0.02%), Ce ($\leq$0.02%), P ($\leq$0.015%), S ($\leq$0.01%), and Cu ($\leq$0.07%). Nickel super-alloy GH4037 is widely used for manufacturing aero-engine components with drilled cooling holes for long-time applications at high temperature working conditions below 850 °C, due to its good microstructural stability, good weldability, and good mechanical performances such as excellent high-temperature strength, high fatigue strength, good fracture toughness, and good oxidation-resist and corrosion-resist properties at high temperature below 850 °C.

Table 2 containing the experimental plan lists the ultrasonic-laser operating parameters used. The 2.75-mm-thick nickel super-alloy GH4037 sheets were drilled using the ultrasonic-assisted Nd:YAG laser trepanning system. The assist gas argon with 0.05 MPa pressure flowing through a gas nozzle, whose axis was the same as the laser beam, was also used to assist the laser trepanning process.

The hole cross sections were prepared through grinding, polishing, and etching (chemical etchant mixed by hydrochloric acid, ethanol, and blue vitriol). The morphology for hole entrance and cross section was observed and imaged by using scanning electron microscopy (SEM). The elemental compositions of the domains surrounding the drilled microhole entrance were measured using the EDS analysis. The hole diameters and hole depths were measured using confocal laser scanning microscopy (CLSM). As shown in Fig. 2 (*a*), the recast layer thickness is normally used to evaluate the drilled microhole quality (thinner recast layer represents better drilled quality in terms of less metallurgical or morphological