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An experimental study on quasi-CW fibre laser drilling of nickel superalloy

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ABSTRACT

Laser drilling of metals and alloys is extensively used in modern manufacturing industries to produce holes of various size and shape. Currently, most laser drilling of aerospace nickel superalloys is performed using Nd:YAG laser. Over the years, many attempts were made to increase the productivity of Nd:YAG lasers drilling process, but with little success. This paper investigates the fundamental aspects of millisecond-pulsed-Quasi-CW-fibre laser drilling of aerospace nickel superalloy. The main investigation concentrates on understanding the Quasi-CW-fibre laser parameters on trepanning laser drilled hole quality and speed. The principal findings are based on controlling the recast layer, oxide layer, hole surface characteristic and fatigue performance of the laser drilled samples. The results showed that the high average power of the quasi-CW-fibre lasers can be effectively used to achieve increased trepanning drilling speed without undermining the drilling quality, which is not feasible with a free-space Nd:YAG laser. Also, low peak power and high frequency (of quasi-CW-fibre laser) can be effectively used to produce better laser drilled holes than the high peak power and low frequency, which is common with the traditional millisecond Nd:YAG drilling processes. Recast layer thickness of around 30 μm can be achieved with a trepanning speed of up to 500 mm/min with single orbit Quasi-CW fibre laser drilling of 0.75 mm hole over 5 mm thick material.

1. Introduction

Millisecond pulse laser drilling of metals and alloys is used extensively in high value manufacturing to produce holes of size ranging from 0.25 to 1 mm, and is a well-established technology for manufacturing various components in aero-engines due to its capability to drill difficult materials at acute angles [1–6]. A key trend in turbine design is to use increased number of holes to maximise cooling and subsequently fuel efficiency [7], for example, a gas turbine afterburner has around 40,000 holes each with a diameter of 0.5 mm [8]. Over the years, the number of cooling holes in gas turbines (and aero-engines) is increasing exponentially, which highlights the need for a high speed-high quality laser drilling process.

Most industrial laser drilling is performed using a percussion or trepan laser drilling process, in which a millisecond laser pulse with a power density of 10^6–10^9 W/cm^2 is used to produce holes by combination of melting, vaporisation and melt ejection. Trepanning drilling process is most often used in high value manufacturing industries due to its ability to produce holes of high quality, and is accomplished by an initial percussion drilling (repeated pulse at single point) followed by a laser cut initiated by moving the work piece (or moving the laser beam). The high quality of the trepanning drilling process is attributed to the fact that the melt is mostly flushed downwards through the hole exit, however, the trepanning drilling process is significantly slower than the percussion drilling; typically by a factor of 4–10 [9]. Generally, millisecond laser drilling process is associated with a number of undesirable defects including recast layer, heat affected zone, oxide layer and spatter. Recast layer formation is considered very critical for rotating components like turbine blades, as it can lead to initiation of fatigue cracks and subsequent failure of the laser drilled components.

The majority of previous studies aimed at optimizing the laser process parameters, such as pulse duration, pulse energy, average power, peak power, focal position, etc., so as to achieve high speed and minimal recast layer. Chien and Hou [10] investigated recast layer formation during the Nd:YAG laser trepan drilling of Inconel 718 and showed that gas pressure, peak power and focal position had significant influence on the recast layer thickness. They also showed that increasing the pulse energy and reducing the speed can result in reduced recast layer. Wang et al. [11] used electrochemical polarisation test, to study the effect of assist gas

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composition on the corrosion performance of laser drilling stainless steel samples. The result showed that the use of nitrogen as the assist gas provide better corrosion resistance performance followed by argon and oxygen. Bandyopadhyay et al. [12] demonstrated that the laser drilling defects including recast layer can be minimised by optimising the laser parameters such as average power, pulse energy, pulse duration, pulse frequency and focal positions. Also, Bandyopadhyay et al. [12], concluded that Nd:YAG laser drilling with high peak power result in efficient melt removal and thus less recast layer on the side walls. Noddin [13] proposed a new drilling method to achieve good quality with two different lasers and trepanned motions, in which the second trepanned motion increased the laser drilled quality. Lozier and Kelley [14] suggested a laser drilling technique, in which the second trepanning orbit was performed in opposite direction to the first one. Yilbas et al. [15,16] reported that the laser drilled hole diameter can be controlled by controlling the position of the laser focus point. This was also in agreement with the results by Bandyopadhyay et al. [12] who reported that the hole size decreases with increasing substrate thickness. Jacobs [17] studied the effect of number of trepanning orbit and reported that an increase in the number of orbits results in increased hole quality.

As reported, most previous works on drilling focused on understanding the performance of Nd:YAG laser drilling process. Over the last decades, fibre lasers have shown its potential in various applications including welding, cladding and cutting. This paper, for the first time, investigates the potential of Quasi-CW fibre laser for the trepanning drilling process. The Nd:YAG and fibre lasers are inherently different not only in the design, but also the fact that fibre lasers operate at high average power of few kW compared to few hundred watts in Nd:YAG laser, and the beam profile of a fibre lasers is a top-hat, whereas the Nd:YAG laser has Gaussian beam profile.

2. Experimentation

The base material used in this study is 5 mm thick Nimonic alloy [17] supplied by All Metal Services Ltd, UK. The chemical composition of the nickel superalloy used in this investigation is shown in Table 1. The laser trepanning drilling of 0.75 mm diameter hole was performed using a 5-axis DMG LT50 CNC laser system, fitted with a quasi-CW IPG Photonics laser source. The fibre laser is capable of operating at a maximum peak power of 20 kW, maximum average power of 2000 W, maximum duty cycle of 10% and pulse duration from 0.2 to 10 ms. A schematic of the laser drilling experimental set-up and the trepanning hole drilling process is shown in Fig. 1(a) and (b) respectively.

A co-axial laser drilling nozzle assembly with a 120 mm collimator lens and 170 mm focal length lens was used to focus the beam on to the work piece surface. The nozzle to work-piece stand-off distance, initial piercing time and number of trepanning orbit were kept constant at 10 mm, 0.1 s and 1 respectively. The stand-off distance was chosen on basis of best gas-dynamic performance, so as to avoid Mach shock disk at the surface. The initial piercing time was chosen based on trial experiments and the number of orbit was kept at one, to increase the productivity.

The laser power was measured using an Ophir power meter and the laser beam profile was obtained using a Primes laser beam monitor. The typical beam profile of the laser beam for various average laser powers is shown in Fig. 1(c). The quasi-CW fibre laser beam is typically a multimode beam, but the beam profile gets homogenised within the fibre and comes out as a predominantly uniform top-hat profile. As can be seen from the Fig. 1(c), the shape of the beam is predominantly top-hat and the beam profile is independent of the laser parameters. The size of the laser beam was experimentally found using the Primes laser beam monitor to be ~0.2 mm.

Initial experimental trials were carried out to identify the feasible processing parameters for laser drilling of 5 mm thick material and the final laser parameters used for this investigation are shown in Table 2. Average and peak power were calculated using Eqs. (1) and (2) respectively:

$$Average\ power = Pulse\ energy \times Frequency \quad (1)$$

$$Peak\ power = Pulse\ energy / Pulse\ width \quad (2)$$

The experimental table was designed to investigate some of the unique features of Quasi-CW fibre lasers including the effect of laser drilling at high frequency and the performance of fibre laser drilling at high trepanning speed.

To confirm the repeatability and reliability of the experiments, five holes were drilled for each parameter set. The laser drilled metallurgical samples were prepared according to ASTM E3-11 [19]. The top and bottom hole diameter were measured using a Keyence digital microscope. All laser drilled samples were mounted, ground and polished to analyse the recast and oxide layer along the mid-cross section of the hole. Kalling's No 2 etchant was used to reveal the recast layer and oxide layer which then was measured using an optical microscope. The surface morphology and roughness of the laser drilled hole surface were analysed using Alicona infinite focus microscope. Prior to Alicona measurement, the mounting materials were removed from the laser drilled hole using a CO_2 laser engraving machine, to reveal the internal surface of the laser drilled hole.

Fatigue performance of the laser drilled sample was analysed using RUMUL Testronic Fatigue testing machine. As shown in Fig. 2a, each fatigue sample (50 mm × 10 mm) was drilled with one 0.75 mm hole, perpendicular to the plate thickness. Specimens were tested at ambient temperature using a three-point bending arrangement as shown in Fig. 2b, with an oscillating frequency of 87 Hz.

3. Results

Fig. 3a shows the effect of laser pulse energy on the recast and oxide layer thickness. All other parameters including pulse width, frequency, and trepanning speed were kept constant at 0.5 ms, 75 Hz and 150 mm/min respectively. The values represents the recast layer thickness noticed over five holes of same parameter. As can be seen from the figure, with the increase in energy, the recast layer initially decreases and then it increases. The same trend was noticed for oxide layer. Best recast layer of ~25 μm was observed for a laser pulse energy of 6 J. The best recast layer thickness should be attributed to the fact that the peak power of 12 kW produced an optimal melting and melt ejection phenomena. The peak power of 12 kW corresponds to a power density of 38 MW/cm^2. Further increase in pulse energy (or peak power) should have increased the vapour/recoil pressure [20,21] and

Table 1
Chemical composition of parent metals in wt% [18].

Element	Ni	Cr	Mn	Si	C	Al	Fe	Mo	Co	Ti
wt%	Bal	19–21	0.60 max	0.40 max	0.04–0.08	0.60 max	0.07 max	5.6–6.1	19–21	1.9–2.4