The International Journal of Advanced Manufacturing Technology (2019) 102:2833–2843
https://doi.org/10.1007/s00170-019-03389-8

ORIGINAL ARTICLE

Millisecond fibre laser trepanning drilling of angular holes

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Received: 5 November 2018 / Accepted: 22 January 2019 / Published online: 7 February 2019

Abstract

This paper aims to investigate the basic characteristics of millisecond (ms) pulsed fibre laser drilling of 0.8 mm diameter angular holes (30° to the surface) in a 2 mm thick aerospace nickel superalloy (resultant hole length of 4 mm). Experiments have been conducted to understand the influence of various process parameters on the hole quality, including gas pressure, nozzle-workpiece distance, laser beam focus position, trepanning speed, number of trepanning orbits, pulse energy, pulse duration and pulse frequency. The results suggest that high quality and high productivity can be achieved with millisecond fibre laser drilling, especially when compared to traditional Nd:YAG laser drilling. A new trepanning drilling method for achieving high-quality laser drilling was proposed and evaluated.

Keywords Drilling · Laser · Angular hole · Fibre · Trepanning · Millisecond

1 Introduction

The hot section of modern aero engines is mostly made up of nickel-based superalloys such as N738, C263, Rene80, or CMSX-4 [1]. These materials are used due to their high-temperature fatigue and creep properties. Generally, higher temperatures are associated with higher fuel efficiency in aero engines, so the hot section of aero engines operates at temperatures near to the melting point of the constituent components in order to achieve peak engine efficiency. Hence, cooling of the aero-engine components such as turbine blades and vanes is paramount to avoid destruction under the forces and temperatures of modern aero-engines. Film cooling using angular cooling holes plays an important role in protecting the hot section of the aero-engine components from overheating [2]. Over the last 50 years, advances have led to an overall increase in aero-engine cooling effectiveness from 0.1 to 0.7 [2].

Of all the machining processes available for the production of cooling holes, laser processing is considered to be the preferred technique due to its high productivity [3] and its unique capability to drill at an acute angle [4]. In aero-engine industries, millisecond pulsed Nd:YAG lasers are commonly used to produce holes of various shapes and sizes. Due to the relationship between the required hole diameters and the average laser spot size (~ 100 μm), the majority of industrial millisecond pulsed laser drilling is accomplished using a trepanning method. In addition to productivity and accuracy, a key factor for drilling in high-value manufacturing industries is the hole quality. Compared to percussion laser drilling, the trepanning technique is mostly used in industries due to its ability to meet these quality levels at reasonable output rates.

Being a thermal process, the millisecond laser drilling process often results in undesirable defects such as recast layer formation, oxide layers, heat-affected/thermomechanical-affected zones and spatter. Recast layer in particular is a critical consideration for rotating components such as turbines, as it can lead to the initiation of fatigue cracks in the components [5]. Morar [6] studied the effect of laser trepanning drilling parameters on recast-related crack formation during Nd:YAG laser drilling of angular holes in single-crystal nickel superalloy. Morar [6] concluded that the recast layer thickness increases with increases in peak power and trepanning speed whereas the crack density decreases with the increase of peak power only. Frequency has no significant effect on either output response. The low responsiveness of the material to changes in frequency observed by Morar [6] may be due to the low-frequency range available with the Nd:YAG lasers. Low [7] studied the phenomena of melt spatter during laser drilling of 90° holes in Nimonic 263 alloy sheets using a

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millisecond pulsed Nd:YAG laser and suggested the use of anti-spatter composite coatings to address the spatter deposition over the top surface of the laser-drilled parts. Wang [8] investigated the effect of assist gas composition on hole quality during laser drilling of a nickel-based superalloy. He concluded that use of oxygen gas results in higher oxidation, the formation of microscale depressions and incidences of crack instigations around the hole surface. Conversely, the use of argon was seen to reduce such defects. Despite this, most industrial laser drilling is performed with oxygen as the assist gas due to its contribution to increased productivity [3]. A number of researchers have investigated the effect of laser parameters on the trepanned hole shape achieved with Nd:YAG lasers. Goyal [9] studied the use of artificial neural networks and genetic algorithms for optimising Nd:YAG laser drilling processes and demonstrated considerable improvements in hole taper circularity. He concluded that the use of high laser frequency and high transverse speeds can result in holes with better circularity and taper. Dhaker [10] studied the effect of laser processing parameters including gas pressure, lamp current, stand-off distance and trepanning speed on the drilled hole diameter in the laser trepanning drilling of Inconel718 sheets. He concluded that higher gas pressure results in reduced hole diameter due to the resultant decrease in heat accumulation. To address the issue of typical defects in laser drilling, Okasha [11] proposed a hybrid drilling technique in which tool-based drilling was used to remove the defects produced during the laser drilling of 90° holes in Inconel 718. He concluded that the hybrid method produced holes with reduced burr size and no recast layer.

Most of the previously published work on millisecond laser drilling focused on optimising the process parameters using Nd:YAG lasers for the production of holes perpendicular to the workpiece surface, rather than for acutely angled holes. This paper investigates the characteristics of millisecond pulsed fibre lasers for high-speed trepanning drilling of angular holes at 30° to the surface in a 2 mm thick nickel superalloy. One of the main objectives is to give a clear indication of the influence of various laser processing parameters on drilling quality and to establish a strategy to achieve high-speed laser drilling.

2 Materials and methods

A Nimonic C263 alloy with dimensions of 100 mm × 50 mm and 2 mm thickness was used for the laser drilling experiments. The laser drilling of 0.8 mm diameter holes at 30° to the surface (total hole length of 4 mm) was performed by trepanning drilling using a five-axis CNC machine, fitted with a millisecond pulsed IPG fibre laser source. The fibre laser can operate at a peak power of 20 kW, with an average power of 2 kW with pulsed width ranging from 0.1 to 10 ms. The beam distribution is a typical top-hat profile with a beam parameter product of ~ 5 mm-mrad. Fibre lasers offer a significantly higher average power and uniform beam profile compared to traditional lamp-pumped Nd:YAG lasers [3]. Schematics of the experimental set-up with a co-axial nozzle assembly and a trepanning drilling methodology are shown in Fig. 1a and b respectively. The nozzle exit diameter was 1.5 mm. The optical set-up consisted of a 170 mm focusing lens and a 120 mm collimating lens, imaging the end-of-the-fibre to the workpiece surface. Prior to the laser drilling experiment, the pressure exerted by the gas jet (from the laser drilling nozzle) over the workpiece surface was experimentally measured using a manometer. A manometer connected to a small chamber with a hole of diameter 0.4 mm was used to study the gas pressure over the workpiece surface [12].

The effect of various process parameters including gas pressure, nozzle-workpiece distance, laser beam focus position, trepanning speed, number of trepanning orbits, pulse energy, pulse duration and pulse frequency were investigated. The initial piercing/percussion time was kept constant at 0.5 s. One of the objectives of this study is to understand the effect of laser parameters on drilling quality, so a one-factor-at-a-time experimental method was used instead of the standard multi-factor analysis. Moreover, the laser drilling process is complex (not very repeatable) and the results of a small multi-factor analysis may not be statistically significant. Initial experimental trials were performed to identify the range of laser parameters that can be used for laser trepanning drilling of 2-mm-thick Nimonic alloy at 30° to the surface. The derived parameters including average and peak laser power can be found using the following equations:

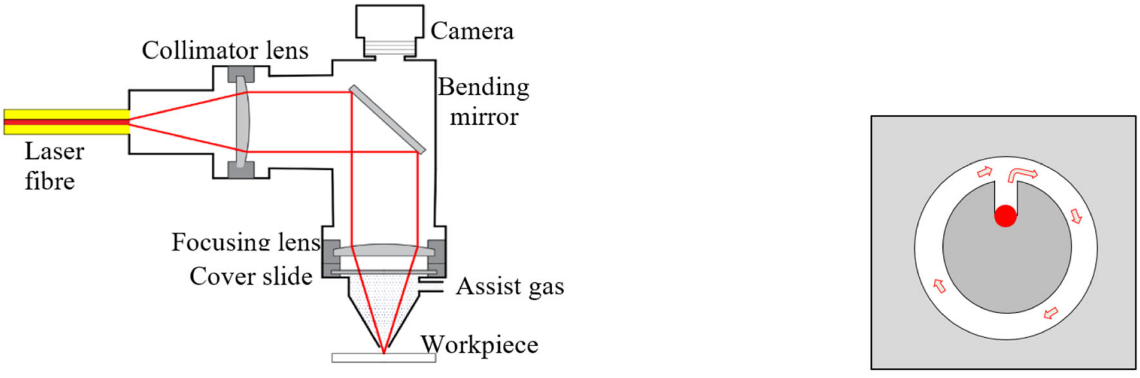
$$\text{Average power} = \text{pulse energy} \times \text{Frequency} \tag{1}$$

$$\text{Peak power} = \text{pulse energy}/\text{pulse width} \tag{2}$$

Three holes were produced for each set of laser parameters in order to ensure the reliability and repeatability of the experimental process. The hole diameter at the entrance and exit was analysed using an optical microscope. The laser-drilled samples were sectioned, polished and etched as per ASTM-E3-11 for examination of the recast and oxide layer thickness along the central plane of the hole. A Keyence microscope was used to observe and measure the thickness of the oxide layer and of the recast layer.

3 Results and discussions

The main objective of this study is to understand the quality characteristics during quasi-CW fibre laser drilling of angular



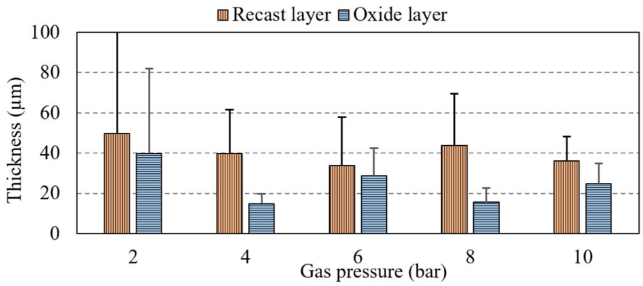
(a) (b)

Fig. 1 Schematic diagram illustrating the laser trepanning drilling. **a** Experimental set-up. **b** Laser trepanning drilling method

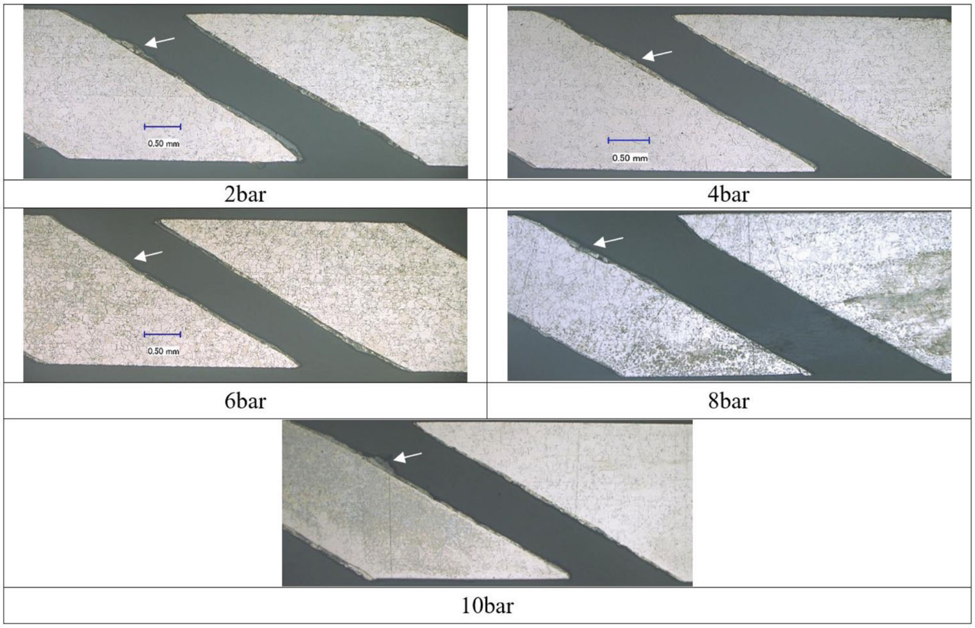
holes. The quality requirements of laser-drilled holes include minimal recast layer, minimal oxide layer and accurate hole diameter. However, recast layer is considered the most critical quality factor, as it is directly related to the fatigue life of laser-drilled aerospace components [6].

Figure 2 shows the effect of gas pressure on the laser-drilled hole quality. The number of trepanning orbits (NOR) was kept constant at two revolutions. As can be seen from the figures, no clear trend was observed. However, the samples drilled at 6 bar show better performance in terms of recast

Fig. 2 Effect of gas pressure on hole quality characteristic (trepanning speed = 400 mm/min; frequency = 100 Hz; pulse duration = 0.5 ms; energy = 5 J; NOR = 2)

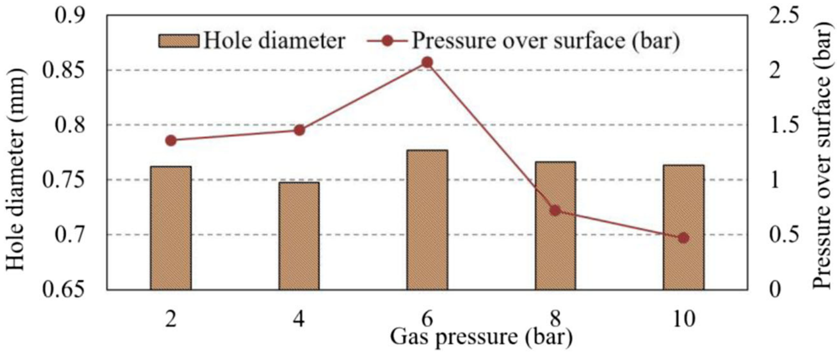


(a) Effect of gas pressure on average recast and oxide layer thickness



(b) Optical microscopic images showing the effect of gas pressure

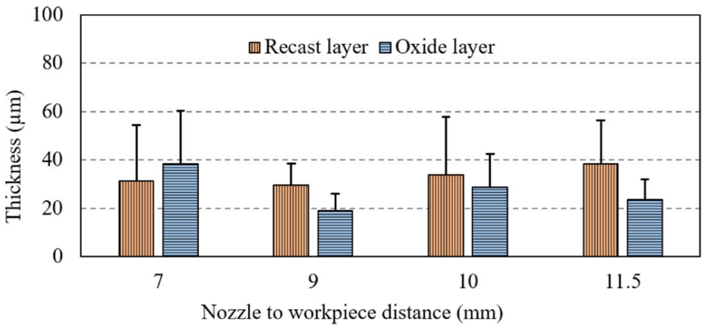
Fig. 3 Effect of gas pressure on average hole diameter and pressure observed over the workpiece surface (speed = 400 mm/min; frequency = 100 Hz; pulse duration = 0.5 ms; energy = 5 J; NOR = 2)



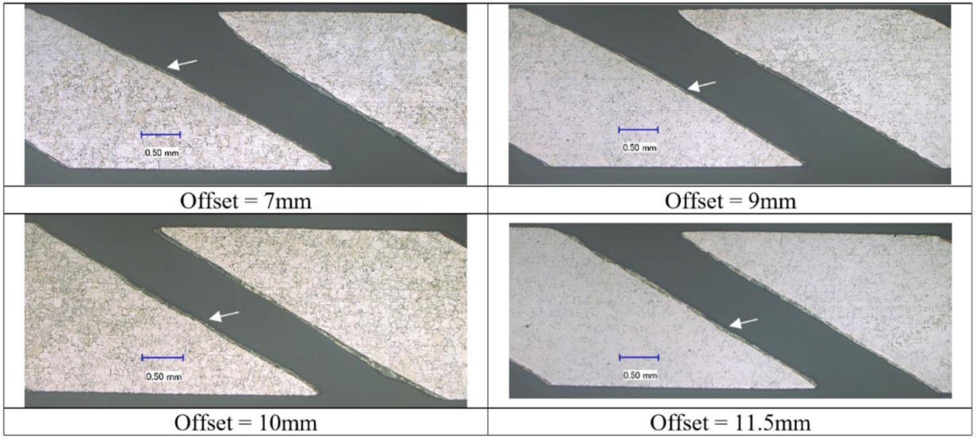
layer thickness. Figure 3 shows the effect of inlet stagnation pressure on hole diameter and the measured pressure over the workpiece surface. The pressure over the workpiece was measured prior to the laser drilling process using a manometer. Increases in stagnation gas pressure did not actually increase the gas pressure over the laser irradiation zone. Though the trepanning orbit position was kept constant, the hole diameter varies according to the laser drilling parameters due to the change in the heating and melting characteristics. As seen from Figs. 2 and 3, the use of gas at a pressure of 6 bar resulted in holes of low recast layer thickness and marginally higher diameter. This should be due to the gas dynamic characteristic, which can be explained on the basis of the pressure over the workpiece surface. The assist gas pressure of 6 bar produced better gas flow characteristics, which resulted in a high pressure and mass flow rate over the laser irradiation zone. The high-pressure assist gas jet produced a higher shear force along the hole walls and consequently higher diameter and less recast layer thickness. All results reported from this point forward were performed using 6-bar gas pressure.

Figure 4 shows the effect of nozzle to workpiece stand-off distance on laser-drilled hole quality. Figure 5 shows the effect of nozzle to workpiece stand-off distance on hole diameter and pressure over the workpiece surface. In both cases, the focal point of the laser was maintained at the workpiece surface irrespective of the nozzle to workpiece distance. As can be seen from Fig. 4, the effect of the nozzle to workpiece distance on hole quality seems minimal. A slight increase in

Fig. 4 Effect of nozzle to workpiece distance on hole quality characteristic (speed = 400 mm/min; frequency = 100 Hz; pulse duration = 0.5 ms; energy = 5 J; pressure = 6 bar; NOR = 2; focus position = workpiece surface)

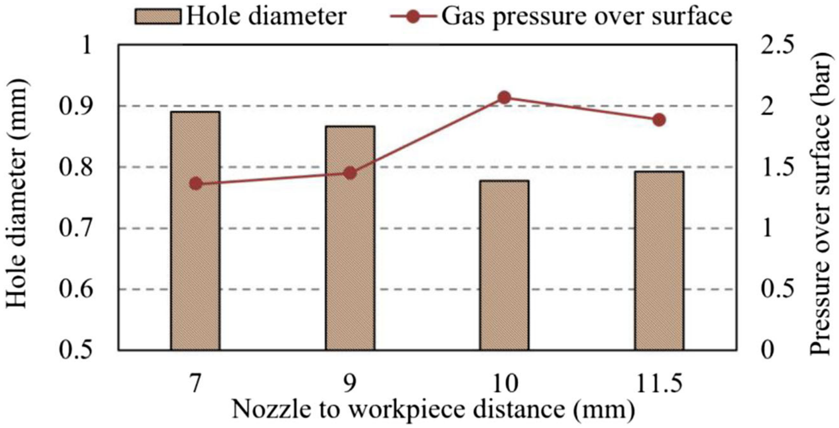


(a) Effect of nozzle to workpiece distance on average recast and oxide layer thickness



(b) Optical microscopic images showing the effect of nozzle to workpiece distance

Fig. 5 Effect of nozzle to workpiece distance on average hole diameter and pressure observed over the workpiece surface (speed = 400 mm/min; frequency = 100 Hz; pulse duration = 0.5 ms; energy = 5 J; pressure = 6 bar; NOR = 2)



recast layer thickness was observed for nozzle to workpiece distances higher than 10 mm. As noticed from Fig. 5, the nozzle to workpiece distance has a major influence on the gas jet dynamics, and subsequently the hole diameter. The nozzle to workpiece distance of 10 mm seems to produce the best gas dynamic characteristic (Fig. 5) and was taken as the optimal parameter for the rest of the experiments. It is important to note that the gas pressure observed in Figs. 3 and 5 is specific to the nozzle used in this research. Even a slight variation in nozzle dimension or nozzle inner wall profile will produce a different gas jet characteristic.

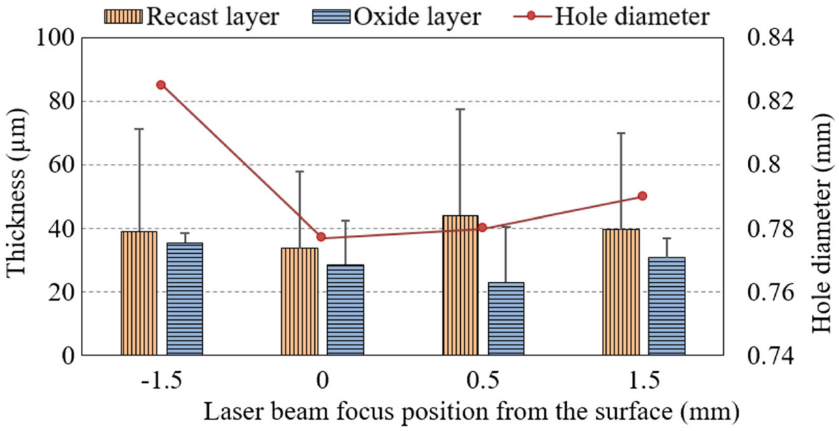
Figure 6 shows the effect of the laser beam focus position relative to the workpiece on average recast layer thickness, oxide layer thickness and average hole diameter. Negative values refer to a focal position within the workpiece, while positive values refer to a focal position above the workpiece surface. In these trials, the nozzle-workpiece distance was maintained at 10 mm. Minimal recast and oxide layer thickness was observed when the focal position was maintained at the workpiece surface (0 mm). Smaller hole diameters were also observed when the focal position was maintained at the workpiece surface. This is due to the high power density and smaller laser beam spot size when the focal position was concentrated on the workpiece surface.

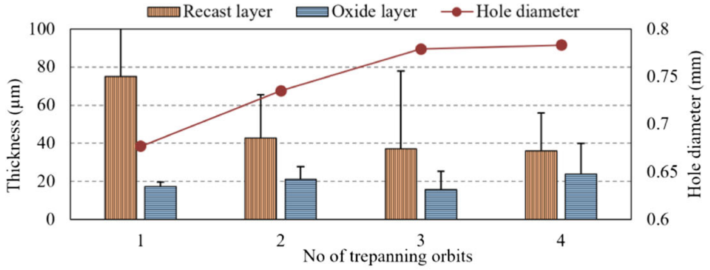
Figure 7 shows the effect of the number of laser trepanning orbits (NOR) (Fig. 1b) on the hole quality and diameter. In the laser trepanning drilling process, fewer trepanning orbits are preferred, as this leads to higher productivity. As can be seen from Fig. 7, the number of trepanning orbits has a major effect on the laser-drilled hole quality. There is a huge improvement in hole quality when increasing from one to two orbits. It seems that the second trepanning orbit effectively removes the excessive recast layer at the inner walls of the laser-drilled hole, especially around the hole exit region. No major improvement in recast layer thickness was observed beyond two orbits, as most of the laser beam passes freely without interacting with the walls of the hole.

Further experiments were performed to understand the effect of the position of the second orbit with reference to the first trepanning orbit and the results are shown in Fig. 8. The intention of this investigation is to see if it was possible to efficiently remove the recast layer (which had a thickness of ~ 0.1 mm after one trepanning orbit) using the second trepanning orbit, without inducing any further recast layer with the second orbit.

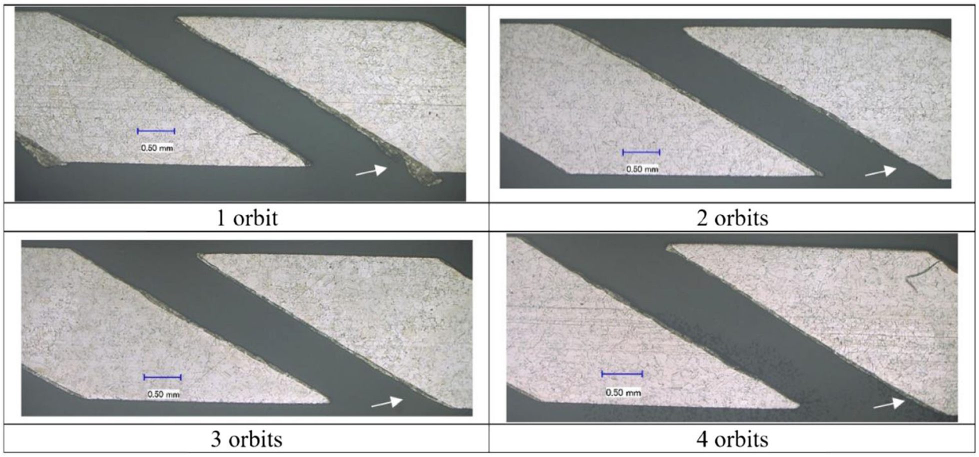
As can be seen in Fig. 8, the position of the second orbit has a noticeable influence on the laser drilling quality, especially

Fig. 6 Effect of laser beam focus position on average recast and oxide and hole diameter (speed = 400 mm/min; frequency = 100 Hz; pulse duration = 0.5 ms; energy = 5 J; pressure = 6 bar; NOR = 2)





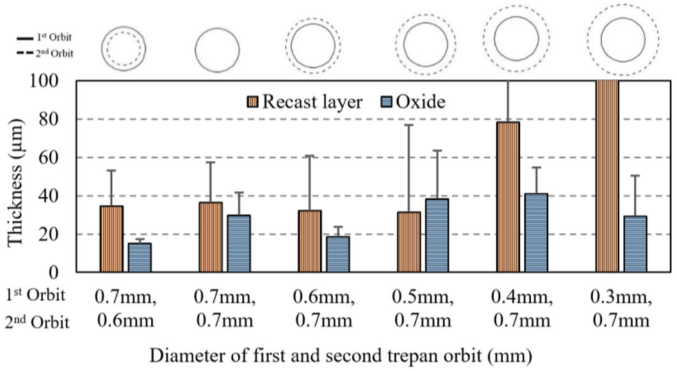
(a) Effect on number of trepanning orbits on average recast layer, oxide layer and hole diameter



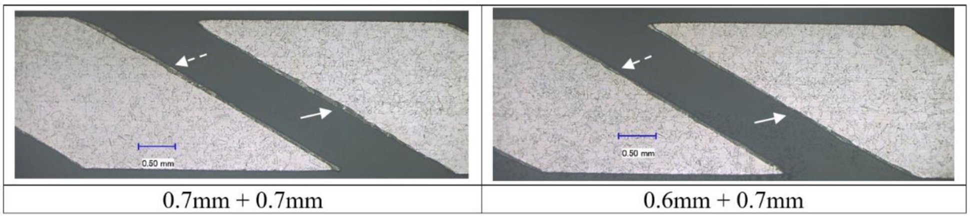
(b) Optical microscopic images showing the effect of trepanning orbit

Fig. 7 Effect of the number of trepanning orbits on hole quality (speed = 400 mm/min; frequency = 100 Hz; pulse duration = 0.5 ms; energy = 5 J; pressure = 6 bar)

when the beam is moved away from the centre. A negative offset of the second orbit (moving the second orbit towards the centre of the hole) fails to change the drilling quality because the laser-material interaction is reduced. However, a positive offset of the second orbit (moving the second orbit away from the hole centre) influences the drilling quality. An offset



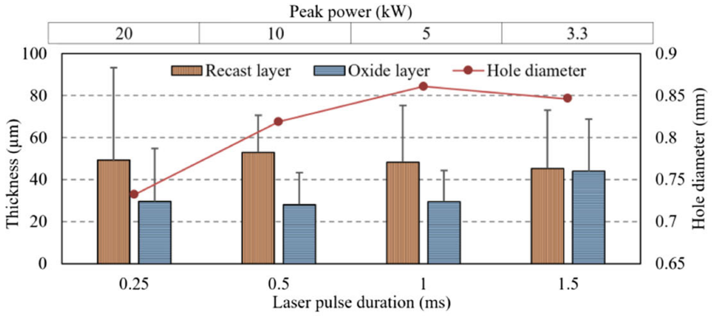
(a) Effect ofposition of the trepanning orbit on recast layer and oxide layer



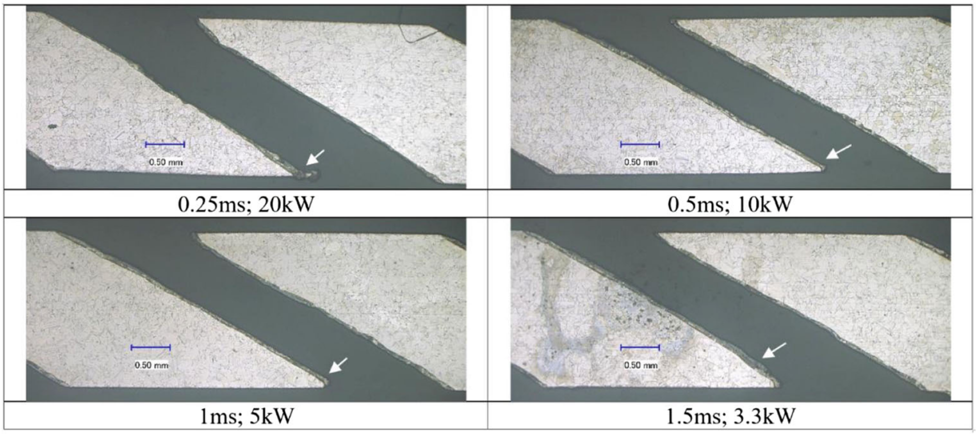
(b) Optical microscopic images showing the effect on positionof the trepanning orbit

Fig. 8 Effect of position of the trepanning orbit on hole quality (speed = 400 mm/min; frequency = 100 Hz; pulse duration = 0.5 ms; energy = 5 J; pressure = 6 bar)

Fig. 9 Effect of laser pulse duration on hole quality characteristic (speed = 400 mm/min; frequency = 100 Hz; pulse energy = 5 J; pressure = 6 bar; NOR = 2)



(a) Effect of laser pulse duration on recast layer, oxide layer and hole diameter



(b) Optical microscopic images showing the effect of laser pulse duration

distance same as the size of the recast layer thickness can produce an ideal condition in which the second trepanning orbit can remove a portion of the recast layer without inducing additional thermal damages.

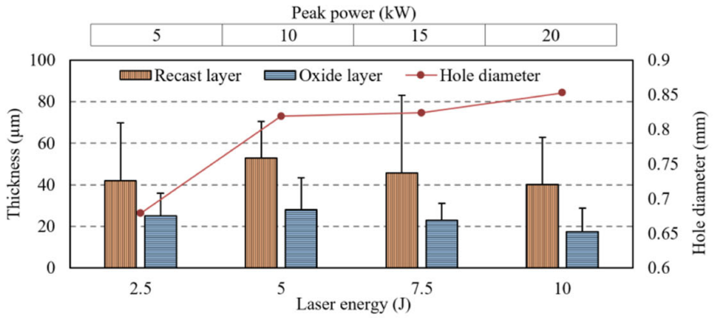
Figure 9 shows the effect of laser pulse duration on hole quality. As can be seen from Fig. 9, the pulse duration has a major impact on the laser-drilled hole quality. Pulse durations in the range of 0.5–1 ms result in better hole drilling characteristics. Laser drilling with a pulse duration of less than 0.5 ms results in excessive recast at the hole exit (Fig. 9; 0.25 ms). Increases in laser peak power increase the temperature of the laser irradiation zone, which results in superheating of the melt-pool and subsequent phase explosion of the melt [13]. This is not desirable for melt-ejection-based laser drilling processes [14]. At the other extreme, laser drilling with a high pulse duration (or low peak power) results in hole formation predominantly by melting with minimal recoil pressure. This reduces the melt-ejection efficiency and is therefore not ideal for melt-ejection-based laser drilling processes [14].

Figure 10 shows the influence of energy on hole quality. As can be seen in Fig. 10, within the investigated range, the average recast and oxide layer thickness shows minimal variation. It appears that high peak power is not always essential to achieve better hole drilling quality. Another important observation is that the samples drilled with low pulse energy show smaller diameters due to the minimal melting and side burning [15], which is not ideal for macro drilling processes.

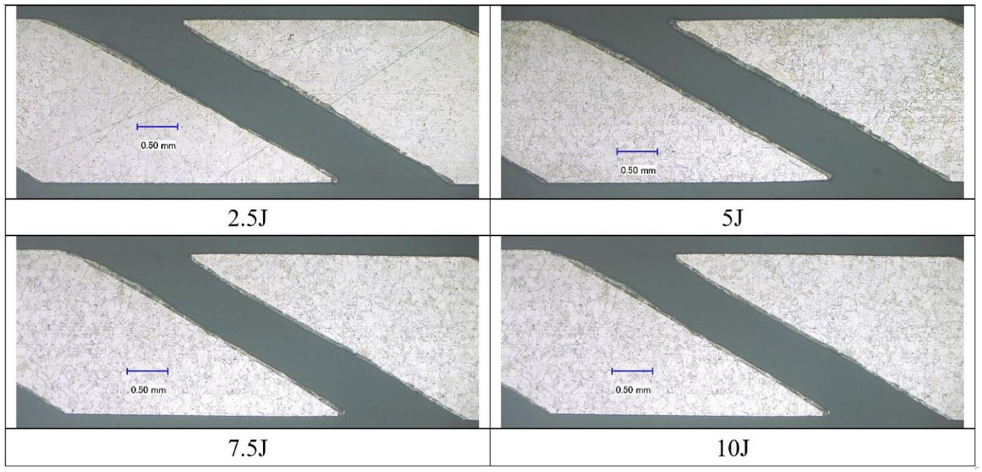
Figure 11 shows the effect of laser pulse frequency on hole quality. Pulse frequency had a major effect on laser-drilled hole quality, which is in contradiction to the results observed with Nd:YAG laser drilling [6]. This is due to the fact that most Nd:YAG laser drilling machines have a low average power (125–250 W) and operate within a narrow range of pulse frequencies. The fibre laser used for this research can operate at a maximum average power of 2000 W and in a wide range of frequencies. As noticed from Fig. 11, for the 0.5 ms–300 mm/min combination, the best drilling was observed at 75 Hz, while for 2 ms–400 mm/min, the best drilling was observed at 50 Hz. It seems that frequency and speed have a combined effect on the laser drilling process.

Figure 12 shows the effect of trepanning speed (or laser beam overlap) at constant pulse frequency on hole quality. As can be seen from these figures, depending on the pulse frequency, the optimal drilling performance was observed at different speeds. However, the best speed always matched to a laser beam overlap of ~ 53%. A laser beam overlap of ~ 50% corresponds to approximately two pulses per position. The first pulse acts as a coarse drilling pulse and the second pulse removes the recast layer

Fig. 10 Effect of laser pulse energy on hole quality characteristic (speed = 400 mm/min; frequency = 100 Hz; pulse duration = 0.5 ms; NOR = 2)



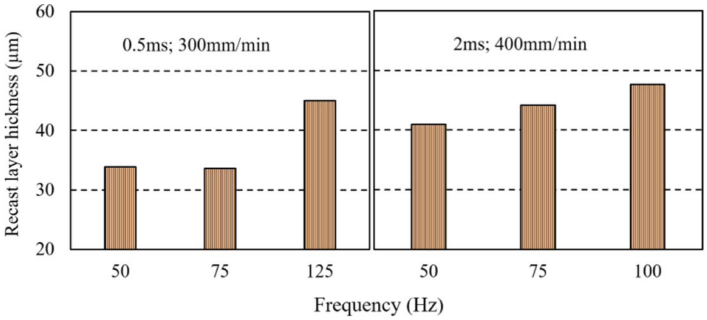
(a) Effect of laser pulse energy on recast layer, oxide layer and hole diameter



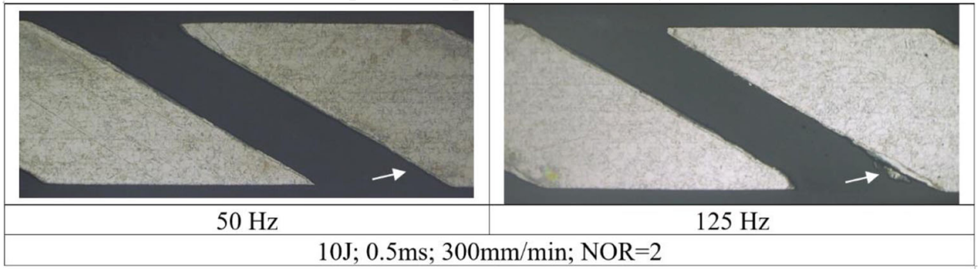
(b) Optical microscopic images showing the effect of laser pulse energy

generated during the first laser pulse. Increasing the laser beam overlap increases the number of pulses per position, which results in excessive heat generation and higher recast layer thickness. When the laser beam overlap decreases, the material is not being removed fully, which subsequently results in more recast generation. This is

Fig. 11 Effect of laser pulse frequency on hole quality characteristic (energy = 10 J; NOR = 2)

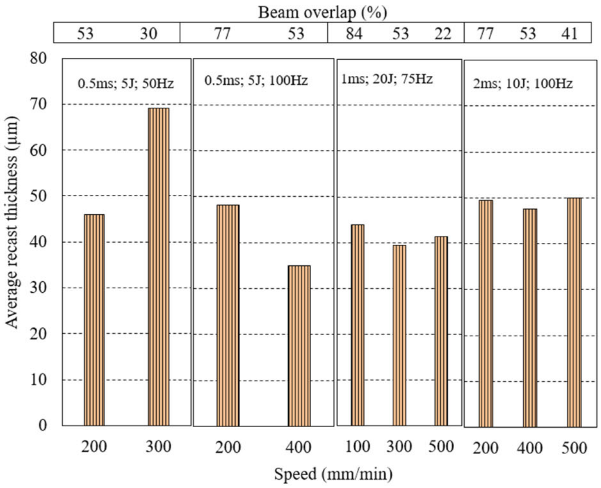


(a) Effect of laser pulse frequency on recast layer thickness

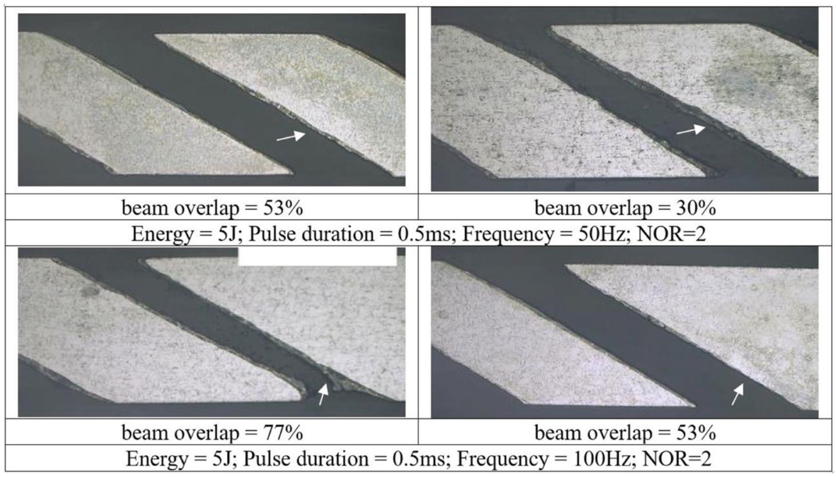


(b) Optical microscopic images showing the effect of laser pulse frequency

Fig. 12 Effect of trepanning speed and beam overlap on hole quality characteristic (NOR = 2)



(a) Effect of trepanning speed on recast layer thickness for various beam overlaps



(b) Optical microscopic images showing the effect of beam overlap

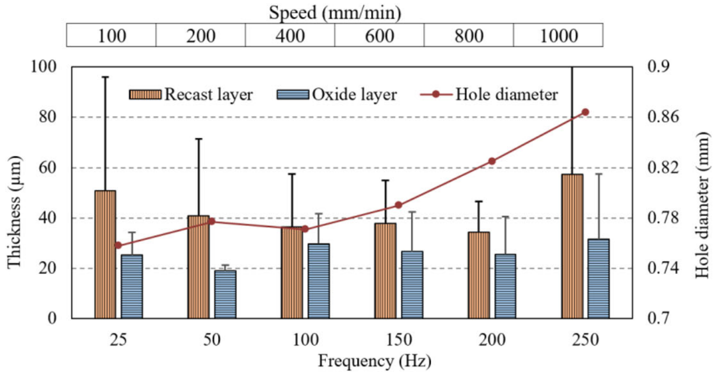
similar to the effect on the number of trepanning orbits shown in Fig. 7 in which the second trepanning orbit removes the excessive recast generated during the first trepanning orbit. The laser beam overlap was calculated using Eq. 3 as:

$$\text{Laser Beam Overlap}(\%) = \left(\frac{\text{Speed (mm/s)}}{\text{Frequency (Hz)} \times \text{Beam size (mm)}}\right) \times 100 \qquad (3)$$

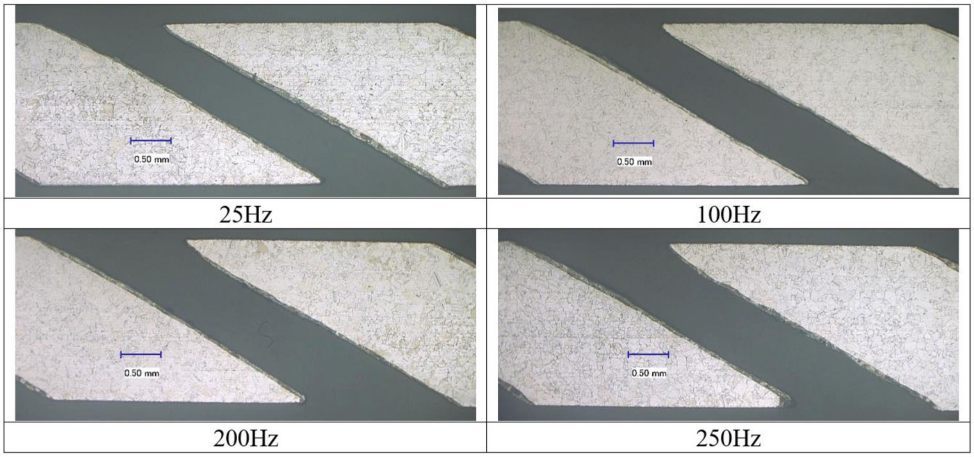
To confirm this observation, further experiments were performed varying the speed and frequency proportionally to maintain a constant beam overlap of ~ 53%, and the results are shown in Fig. 13. As noticed from the figures, irrespective of speed and frequency, a laser beam overlap of 53% produces the best laser drilling performance. No deterioration in hole quality with increased trepanning speeds was observed until speeds of ~ 800 mm/min. Another key observation is that the hole diameter increases with increased speed and frequency. This is attributed to increases in melting volume due to the residual heating effect at higher pulse frequencies. Most of the current aerospace laser drilling processes using Nd:YAG lasers are performed at speeds of ~ 100–200 mm/min [6]. These results represent a step change in laser drilling productivity.

Assist gas composition is expected to have a huge effect on laser-drilled feature characteristics and it also represents a significant proportion of the overall laser drilling cost. In most cases, oxygen assist gas is used for laser drilling of nickel-based aerospace alloys. This is to exploit the energy produced during the exothermic reaction [16] which increases the drilling productivity rate. Figure 14 shows the effect of assist gas composition on hole quality. As noticed from the images, the holes drilled with oxygen as an assist gas have a minimal recast layer. The smaller hole diameters observed with compressed air as an assist gas result from the reduction in the exothermic energy and can be

Fig. 13 Effect of laser pulse frequency on hole quality characteristic (beam overlap = 53%; pulse energy = 5 J; pulse duration = 0.5 ms; pressure = 6 bar; NOR = 2)



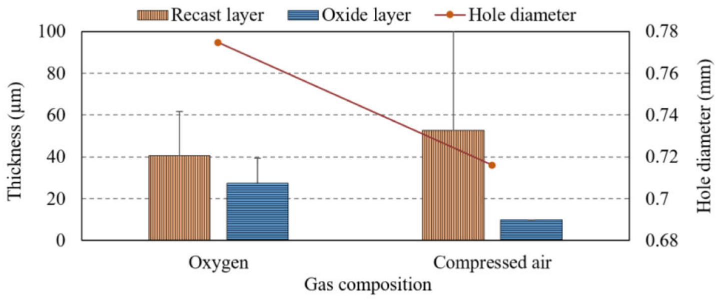
(a) Effect of laser pulse frequency on recast layer, oxide layer and hole diameter



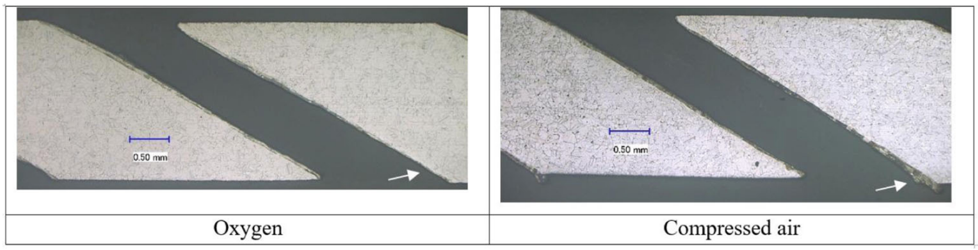
(b) Optical microscopic images showing the effect of laser pulse frequency

addressed by altering the input diameter of the trepanning orbit. The holes drilled with compressed air show a thin oxide layer due to the reduced exothermic reaction. A high recast layer was observed at the egress side of the holes drilled with compressed air as the assist gas, and this can be addressed with further investigations.

Fig. 14 Effect of assist gas composition on hole quality characteristic (beam overlap = 53%; pulse energy = 5 J; pulse duration = 0.5 ms; pressure = 6 bar; NOR = 2)



(a) Effect of assist gas composition on recast layer, oxide layer and hole diameter



(b) Optical microscopic images showing the effect of gas composition on quality

4 Conclusions

An experimental investigation was performed to understand the characteristics of millisecond fibre laser drilling of 30° angular holes in a 2 mm thick Nimonic C263 alloy (resultant hole length of ~ 4 mm). The following conclusions are drawn from this investigation.

1. The results demonstrated the superior performance of a millisecond fibre laser for trepanning drilling. Trepanning speeds of up to 800 mm/min can be achieved without compromising the drilling quality, which represents a huge increase in productivity compared to Nd:YAG laser drilling.
2. All the investigated laser parameters including, gas pressure, nozzle-workpiece distance, laser beam focus position, trepanning speed, number of trepanning orbits, pulse energy, pulse duration and pulse frequency influenced the laser drilling quality.
3. The inlet stagnation gas pressure and the nozzle to workpiece distance should be tuned to achieve a suitable gas dynamic performance at the workpiece surface. Better gas dynamic performance at the workpiece surface produces better hole quality and minimal hole diameter.
4. Maintaining the focal position at the workpiece surface produces better hole quality and minimum hole diameter.
5. The number of trepanning orbits has a huge impact on the laser-drilled hole quality. Two trepanning orbits were seen to result in a good compromise between quality and speed.
6. A new trepanning technique was proposed, in which the position of the second trepanning orbit was moved inwards with reference to the first trepanning orbit, with demonstrated advantages versus a conventional multi-orbit trepanning drilling process. Repositioning the second trepanning orbit away from the hole centre by an offset equal to the recast layer thickness produces better hole quality.
7. Laser pulse durations in the range of 0.5–1 ms resulted in better hole drilling characteristics.
8. Irrespective of the trepanning speed and laser frequency, the best drilling performance was observed with a laser beam overlap of ~ 53%. This opens up an opportunity to proportionally increase the trepanning speed and frequency without any adverse effect on drilling quality.
9. Laser drilling of Nimonic alloy with compressed air can produce acceptable drilling quality.

Funding information The authors acknowledge the financial support from Innovate-UK under the Flexlase project.

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