12th CIRP Conference on
Photonic Technologies [LANE 2022]

Industrial Paper

Laser Drilling of Cooling Holes in Thick-Section Nickel Superalloy

Sundar Marimuthu[a]*, Helen Elkington[a], Yijun Liu[a], Bethan Smith[a]

[a]*The Manufacturing Technology Centre, Ansty Business Park, Coventry, CV7 9JU, UK*

Abstract

The millisecond pulse trepanning laser drilling process is state-of-the-art for producing cooling holes in aero-engines. However, the current understanding of millisecond laser drilling is limited to shallow holes, of length less than 10 mm, possibly due to the lack of process knowledge. This paper investigates the fundamental characteristics of millisecond laser drilling of thick materials (10-20 mm). The effect of laser parameters on the piercing and trepanning process were discretely investigated. High-speed and thermal imaging cameras were used to aid understanding of the drilling process. Most defects in the thick section drilling process are associated with the piercing process rather than the trepanning. High-quality and high-speed drilling are demonstrated for hole lengths of 20 mm with an aspect ratio of 20. It takes 13 s to drill a 0.8 mm diameter hole with a length of 20 mm, which is significantly faster than the current state-of-the-art thick-section drilling processes.

Keywords: Laser; Millisecond; Drilling; Fibre; Trepanning; Thick-section

---

1. Introduction

Higher engine temperature is associated with higher fuel efficiency, so the hot sections of aero-engines operate at temperatures close to the melting point of aerospace alloys. Hence, cooling of such aero-engine parts is essential to avoid damage under the temperatures and forces encountered in these environments. Film cooling generated by the cooling holes plays a critical role in protecting the critical components. Of all the manufacturing processes, drilling using electrical discharge machining (EDM) and millisecond (ms) pulsed laser are two of the most well-established methods, Antar (2016). Irrespective of the fact that ms laser drilling is faster than other technologies, lasers are currently used only for holes with lengths less than 10 mm (Gautam, 2018), which is likely due to the lack of process knowledge.

Of all laser-drilling techniques, the trepanning process is widely used for high-value components including aerospace components due to its ability to produce high-quality holes. The trepanning process involves initial piercing to produce the pilot hole and one or more trepanning orbit to achieve the required diameter and quality.

Most industrial laser drilling is currently performed using a high peak power millisecond (ms) pulse laser due to its capability to efficiently remove material and achieve high aspect ratio holes with a minimal thermal load. Millisecond pulse laser drilling is a thermal process where the material removal mechanism is significantly influenced by melt ejection (Marimuthu, 2017) along with slight vaporization. When the ms laser pulse hits the material, the beam is absorbed by the top surface, resulting in melt-pool formation, followed by surface boiling and ejection of the molten materials. During the initial percussion/piercing process, 60-80% of the melt is ejected through the hole entrance. The trepanning motion commences after piercing. During trepanning, most of the melt is ejected through the exit of the hole. Being a thermal process, ms laser drilling is associated with several thermal defects including recast, oxide, crack, taper and barrelling. As discussed in the review paper, written by Gautam (2018), most researchers used process control and optimisation as a means to limit the damages in thin section (2-6 mm) laser drilling, but no such information exists for thick section (10-20 mm) laser drilling. Few innovative techniques like hybrid laser-mechanical drilling or hybrid millisecond-nanosecond laser drilling were proposed in the past. However, industrial laser drilling is still performed with traditional gas-assisted millisecond laser, due to its cost-effectiveness, reliability and efficacy.

---

* Corresponding author. Tel.: +44 7892 891 997.
E-mail address: Sundar.Marimuthu@the-mtc.org

The current knowledge and understanding of laser drilling (Gautam, 2018) are based on holes with length significantly lower than 10 mm. The only known research output on thick section laser drilling is the work by Tam (1993), who investigated percussion drilling of 25 mm thick Inconel using an Nd:YAG laser and reported a cycle time of 30-148 s/hole. Irrespective of the advancement in laser technology over the last few decades, including the introduction of millisecond fibre lasers, the work by Tam (1993) still acts as a benchmarking quality for thick section drilling. To address this knowledge deficit, this paper investigates the basic characteristics of ms pulsed fibre laser trepanning drilling of holes with a length ranging from 10-20 mm in aerospace nickel superalloy (C263).

2. Materials and Methods

A Nimonic C263 alloy with dimensions of 100 mm x 50 mm and 10 mm thickness was used for the laser drilling experiments. The laser drilling of holes was performed at various angles (90°, 47.9°, 42.1° and 30° to the surface; corresponding to a hole length of 10 mm, 13.5 mm, 15 mm and 20 mm respectively) using an IPG quasi-continuous wave (QCW) fibre laser, which has a BPP of 4.2. The laser can operate at a peak power of 20 kW, average power of 2 kW and pulse duration of 0.2 ms to 10 ms. The were performed using a conical nozzle of exit diameter 1.5 mm. The optical set-up consisted of a 300 mm focusing lens and a 120 mm collimating lens, imaging the fibre (100 µm) over the laser irradiation zone. Based on the results from a manometer, gas pressure of six bar was use in all experiments, to achieve the best gas dynamic performance.

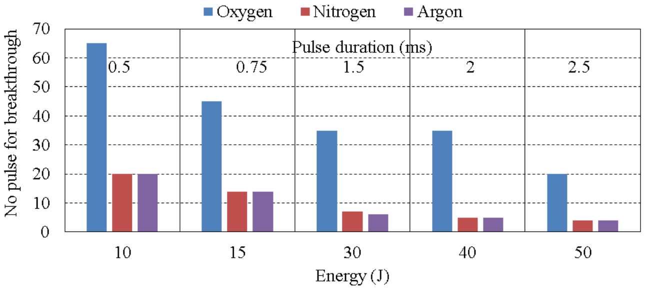


Fig. 1. Effect of gas composition on the number of pulses required for breakthrough (13.5 mm, 10 Hz, 6 bar, 20 kW)

3. Results

Most published research on trepanning laser drilling focused specifically on the trepanning part of the drilling, without any consideration of the initial piercing process. This approach may be acceptable for thin section drilling (<10 mm), where the drilling quality is predominantly based on the physical process that occurs during the trepanning stage, however, this is not the case with thick section drilling of high aspect ratio holes. To systematically understand the thick section drilling process, this research concentrates on the fundamentals of the thick section piercing process followed by the investigation of the thick section trepanning process.

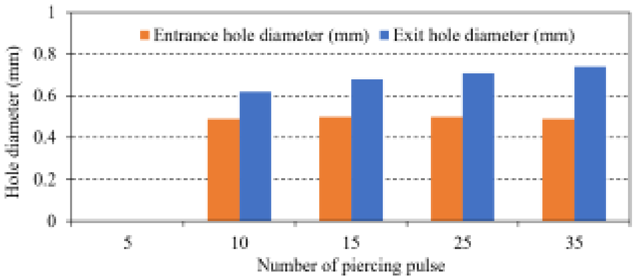


Fig. 2. Effect of number of pulses on diameter (13.5 mm; focus 4 mm above surface ~0.52 mm beam size, 30 J, 1.5 ms, 10 Hz, 6 bar argon)

3.1. Piercing drilling process

Piercing involves generating a through-hole in the component to be drilled to establish a cut front, which will allow laser energy to enter at the top of the cut zone, and molten materials to flow from the bottom. During the piercing process, most molten materials are ejected from the top of the workpiece (Pocorni, 2017). Melt ejection from the top surface is complex and is prone to thermal defects compared to the trepanning, in which all the melt is ejected through the bottom surface.

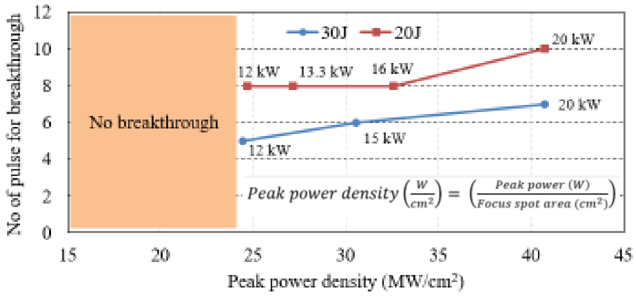
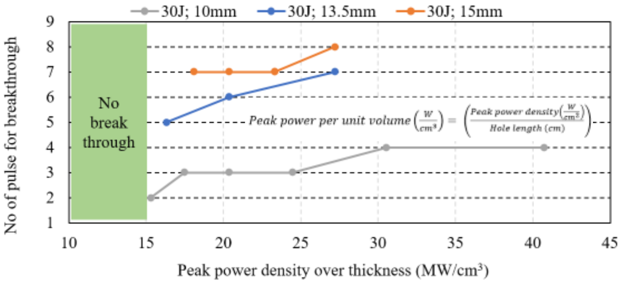


Fig. 3. Effect of peak power (or peak power density) on breakthrough (13.5 mm, 10 Hz, 6 bar, argon)

Fig. 1 shows the effect of gas composition on the number of pulses required for the breakthrough. As noticed from this figure, the use of oxygen assist gas is very inefficient for the piercing process. Inert gas (argon and nitrogen) resulted in a faster and more efficient piercing process, with argon showing better performance than other gas types. Currently, laser drilling (both percussion and trepanning) of nickel superalloy is mostly performed using oxygen as a assist gas; however, as noticed Fig. 1, oxygen gas is not ideal for the thick section piercing process. This should be



attributed to the exothermic reaction and subsequent oxide formation, which hampers the melt ejection from the top of the hole.

Fig. 2 shows the influence of the number of piercing pulses on the diameter. The entrance hole diameter was almost constant at 0.5 mm whereas the exit hole diameter increases with increases in the number of piercing pulses. In general, it can be concluded that the number of piercing pulses has an insignificant effect on the piercing process, and it cannot be used to control the hole diameter. This is attributed to the fact that once the breakthrough is been achieved, a significant proportion of the laser energy passes through the hole without interacting with the hole surface. Any additional hole wall heating (by the laser through direct irradiation or by multiple reflections) is likely countered by the cooling effect of the assist gas, resulting in no significant erosion of the wall.

The effect of peak power density on the number of pulses required for breakthrough is shown in Fig. 3. The minimum power density required for breakthrough seems to the optimal. Contrary to the conventional wisdom, increases in peak power density reduced the drilling efficiency, however, no breakthrough was observed for peak power densities lower than 25 MW/cm^2 (peak power of 20 kW). The trend was similar for both 30 J and 20 J pulse energies. Fig. 4 shows the effect of peak power per unit volume required for a breakthrough. As noticed from Figure, it requires ~17.5 MW/cm^3 to achieve breakthrough for holes with lengths from 10 to 15 mm. The peak power (or peak power density) has been changed by varying the pulse duration, at constant energy. Low peak power corresponds to long pulse duration and vice versa. Within the operating range (10-20 kW; 1.5-3 ms), piercing with a laser pulse of long pulse duration (or low peak power) results in gentle melt ejection ideal for the percussion process. Increase in peak power change the melt ejection dynamics from gentle to cavitation or phase explosion based melt ejection (Marimuthu, 2017) which is not ideal for thick section piercing process.

The experiments in figure 1-4 were performed with the focus plane (spot size = 0.25 mm) over the workpiece surface. Fig. 5 shows the effect of beam size over the workpiece surface, on the number of pulses required for breakthrough. The increase in beam size from 0.25-0.38 mm (reduction of peak power density from 40.7 MW/cm^2 to 17.6 MW/cm^2) does not affect the number of pulse required for a breakthrough. Moreover, the increase in beam size to 0.72 mm (or reduction of peak power density to 4.9 MW/cm^2) increased the number of pulses required for a breakthrough to 10, which is in contradiction to the effect observed in Fig. 3, (i.e. no breakthrough was observed for peak power densities of less than 25 MW/cm^2). The observations from Fig. 3 and Fig. 5 suggest that the peak power required for piercing is closely related to the beam size and hole aspect ratio (beam size to hole length).

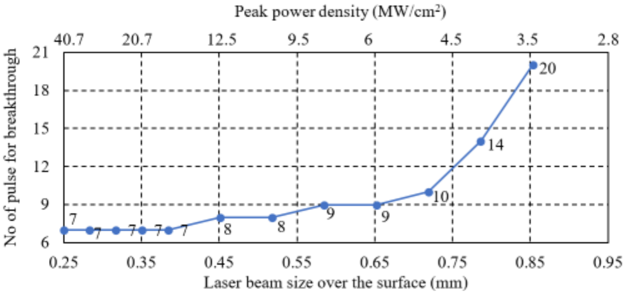


Fig. 5 Effect of beam size (or peak power density) on breakthrough (30 J, 1.5 ms, 10 Hz, 6 bar argon)

3.2. Trepanning drilling process

Hole barrelling is the only issue related to the initial piercing process, with all other quality parameters dependent on the trepanning drilling process. Fig. 6 shows typical results of a hole with a length of 20 mm, with an average recast layer thickness of ~60 µm. The piercing was performed with argon gas followed by trepanning with 50 J, 2.5 ms, 20 Hz, 2 orbits, 30 mm/min and with oxygen assist gas. By using argon for piercing and oxygen for trepanning, high-quality laser-drilled holes can be achieved at a speed significantly higher than the current state-of-the-art electrical discharge drilling. For example, the drilling time for the 20 mm holes shown in Fig. 6 was 13 s/hole, which is significantly faster than the drilling time for EDM, reported to be 48 s/hole (Antar, 2016) for a hole with a length of 10 mm. That said, a negative taper of 0.2 degrees was observed in the laser-drilled 20 mm hole. The hole taper can be counteracted by the combination of a beam with a low divergence angle and by shifting the focal position onto the material.

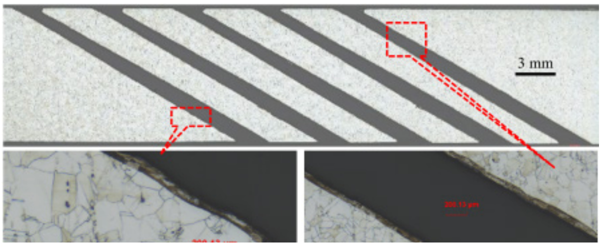


Fig. 6. Typical results of a hole with 20 mm length (2 orbits, argon for percussion and oxygen for trepanning at 20 Hz and 50 J)

4. Discussions

Of all the defects with ms laser drilling, barrelling (around the middle of the hole) is the most critical issue with the thick section drilling processes and is directly associated with the piercing process. Barrelling of holes is associated with the uncontrolled burning of sidewalls, which is attributed to the inefficient melt ejection during the piercing process. The uncontrolled burning of sidewalls cannot be related to the trepanning process. Thick section piercing is more challenging than the trepanning, as most of the melt is being ejected from the top (Pocorni, 2017) and ineffective melt ejection results in significant thermal defects. A high-speed camera operating at 2900 FPS was used to investigate the efficiency of the melt-ejection with various assist gas compositions during the piercing process.

Fig. 7 shows the melt ejection characteristics obtained using a high-speed camera for one to eight laser pulses. During the first three/four laser pulse, a high volume of material is ejected with oxygen assist gas compared to the argon assist gas. This should be due to the fact that the laser-irradiated zone resulting from the use of argon gas is predominantly made of molten alloy, which has a high viscosity and thus more vapor pressure is required for melt ejection (Rao, 2005). With oxygen gas, the material is first converted to oxides (which have a relatively lower density than molten metal) due to the exothermic reaction and thus can be ejected at a relatively lower recoil pressure. Moreover, the exothermic reaction generates additional heat and recoil pressure which increases the volume of material being melted and ejected during the first few laser pulses.

With oxygen gas, the melt ejection behavior changes abruptly from the fifth pulse (Fig. 7), whereas the melt ejection process with argon gas seems to be consistent (between 1-7 pulses) and achieves a breakthrough at the seventh pulse. This is in line with the observations made on the thin-section laser drilling process, in which oxygen performs well for both piercing and trepanning. In general, the melt ejection efficiency reduces as the laser irradiation zone propagates deeper into the material, but this is more pronounced with oxygen assist gas.

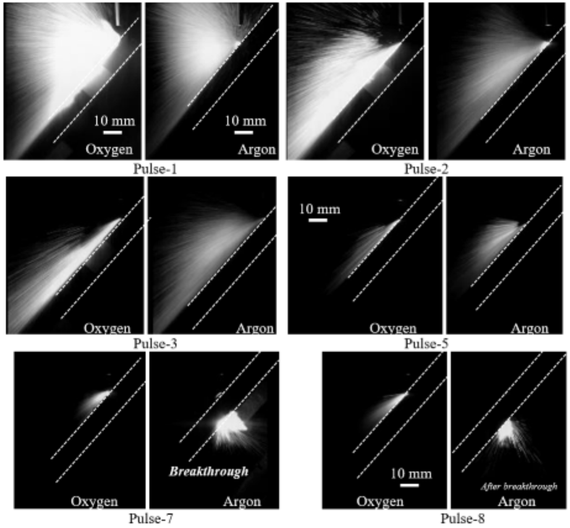


Fig. 7. Melt ejection with argon and oxygen assist gas for various number of pulses (1-8) (hole length of 15 mm, 30 J, 1.5 ms, 10 Hz, 6 bar)

To further understand the reason for reduced efficiency with oxygen gas, after the first few pulses, the transient temperature profile of the laser piercing process has been investigated using a Flir A320 thermal camera. Direct measurement of the temperature within the laser irradiation zone may not be practical; hence the piercing process was performed at the centre of a 2 mm wide material at 42.1° (i.e. hole length of 15 mm) to the top surface and the thermal profile over the sidewall was observed using a thermal camera. Fig. 8 shows the transient thermal characteristics observed in the sidewalls of a 2 mm wide nickel alloy during the laser piercing process for various number of laser pulses (2 to 15). With an increase in the number of laser pulses, the laser irradiation zone moves deeper and subsequently the hole depth increases. With both argon and oxygen, increases in the number of pulses increased the temperature of the laser irradiation zone until a breakthrough was observed and then a quasi-steady state temperature prevailed (from 8 pulses with argon). In line with the observation from Fig. 7 and Fig. 8, the use of oxygen gas results in higher penetration (or material removal) compared to argon for the first few pulses (up to 4 pulses) and then the width of the laser irradiation zone and temperature keeps increasing (from 6 pulses). This may be related to the barrelling effect with oxygen gas, in which excessive heating and melting occur without sufficient melt ejection. With argon as the assist gas, the laser irradiation zone propagates uniformly into the material and achieves breakthrough without any side burning or heat accumulation.

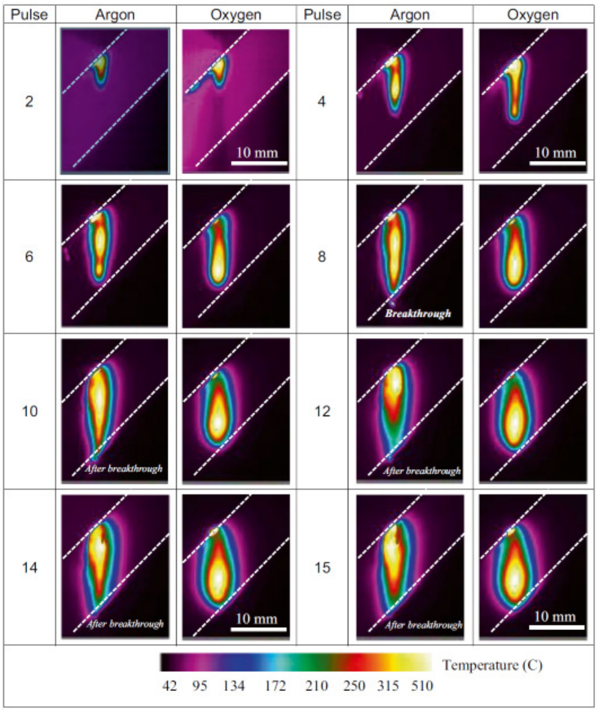


Fig. 8. Thermal profile observed during the laser piercing process (hole length of 15 mm, 30 J, 1.5 ms, 10 Hz, 6 bar)

5. Summary

Millisecond laser can be used for high-speed trepanning drilling of aerospace nickel alloy, with hole lengths of up to 20 mm with an aspect ratio of ~20. With optimal parameters, it takes ~13 s to drill a 0.8 mm diameter hole in a 10 mm thick material with a hole length of 20 mm (hole drilled at 30° to the surface), which represents a significant increase in productivity when compared to the current state-of-the-art drilling technologies. The average recast layer is around 60 µm, which is well within the limits required for industrial laser drilling processes. The selection of appropriate gas is key for the thick section laser drilling process. The use of argon gas for piercing and oxygen for trepanning produced holes with the required quality. The use of oxygen gas for piercing thick materials results in high temperature, inefficient melt ejection and barrelling.

Acknowledgement

This research work was supported by MTC IMP research funding under grant number 33770-22, and UKRI Future Leaders Fellowship under grant number MR/V02180X/1.

References

Antar, M., et al., 2016. High speed EDM and laser drilling of aerospace alloys. Procedia CIRP 42,526-531.
Gautam, G.D., A.K. Pandey., 2018. Pulsed Nd: YAG laser beam drilling: A review. Optics & Laser Technology 100, 183-215.
Marimuthu, S., et al., 2017. An experimental study on quasi-CW fibre laser drilling of nickel superalloy. Optics & Laser Tech. 94, 119-127.
Pocorni, J., et al., 2017. Investigation of the piercing process in laser cutting of stainless steel. Journal of laser applications 29(2), 22201.
Rao, B.T., et al., 2005. Inert gas cutting of titanium sheet with pulsed mode CO2 laser. Optics and Lasers in Engineering 43, 1330-1348.
Tam, S., et al., 1993. Optimization of laser deep-hole drilling of Inconel718 using the Taguchi method. J. Mater. Process. Techno. 37, 741-57.