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Procedia CIRP 137 (2025) 211–216

www.elsevier.com/locate/procedia

CIRP Conference on Electro Physical and Chemical Engineering

Characteristics of Millisecond Fibre Laser Drilling of Alumina Ceramics

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Abstract

Laser drilling of metals and alloys is a well-established process widely utilised in industries such as aerospace, medical, and automotive. However, the laser drilling of ceramics, particularly alumina of thickness greater than 5 mm, remains a significant challenge. This difficulty arises from alumina's high melting temperature, brittleness that leads to cracking, and its low absorption of standard fibre laser wavelength. This study investigates laser trepanning drilling of 6 mm thick alumina, focusing on understanding the material removal characteristics and the influence of key process parameters on hole geometry and thermal damages. The effects of pulse energy, frequency, assist gas composition, and trepanning speed were systematically examined. A minimum specific energy requirement of 80 J/mm was established for through-hole formation, while crack initiation occurred beyond 640 J/mm. Among various assist gases tested, oxygen demonstrated superior performance with minimal taper despite no reactive fusion. Optimal drilling performance can be achieved by balancing pulse energy (for hole geometry stability and minimal thermal affected zone), frequency (for controlled thermal effects), and trepanning speed (for minimal taper and reduced thermal affected zone).

Keywords: Alumina; Drilling; Fibre; Laser; Oxide; Pulse

1. Introduction

Alumina or Alumina Oxide (Al_2O_3) is a widely used ceramic material [1] renowned for its exceptional thermal, mechanical, and chemical properties. Its high hardness, wear resistance, low thermal conductivity, and ability to endure extreme environments make it indispensable across various industries, including aerospace, automotive, medical, and electronics. Recently, alumina has gained attention for its potential use in high-temperature applications such as space rocket engines, where its thermal stability and resistance to environmental degradation are critical. Components for these applications require dense arrays of cooling holes to optimise thermal management and performance. However, the inherent brittleness, high hardness, and low machinability of alumina present challenges [2] for drilling such features without compromising structural integrity.

Conventional processing methods, such as mechanical routing or diamond tool drilling, are inadequate for alumina ceramics [3] due to their brittle nature. These processes lead to excessive tool wear, material cracking, and poor hole quality, particularly when drilling multiple holes in thick materials (i.e., > 5 mm). Non-conventional methods, including abrasive waterjet [4], electrical discharge machining [5], and laser machining, have been explored to address these limitations.

Laser processing is considered an efficient method for producing holes due to its capability to drill at steep angle [6], and at higher productivity. This makes laser drilling particularly well-suited for challenging materials like alumina ceramics, where conventional techniques face limitations due to the material's high hardness, brittleness, and non-conductivity. The non-contact nature of laser processing significantly reduces mechanical stress [7]. However, drilling thick alumina components (>5 mm), which are common in space engine components, presents unique challenges. The high hardness and brittleness of alumina, coupled with its low conductivity, increase the risk of thermal damage, cracking, and residual stress formation during the drilling process.

Laser drilling of alumina ceramics can be achieved using various drilling techniques, including single-pulse, percussion,

10.1016/j.procir.2025.01.108

trepanning, and helical drilling. Single-pulse and percussion drilling are suitable for high-speed applications [8] but may compromise hole quality due to excessive spatter and recast layers. Trepanning is widely regarded as the optimal technique for drilling high-value components because it balances acceptable speed with superior hole quality [9]. Helical drilling, commonly used with ultrashort pulsed lasers, can produce holes with minimal thermal damage but is slow for thick materials due to its limited removal rate.

The material removal mechanisms in laser drilling are influenced by the thermal properties of the material and the laser-material interaction characteristics. Common mechanisms include vaporisation, fusion, reactive fusion, and cold ablation. Alumina ceramics primarily rely on the fusion mechanism, where high-temperature melting occurs, and molten material is expelled by an assist gas. Unlike reactive metals, alumina does not chemically react with assist gases, such as oxygen [10], eliminating reactive fusion as a viable mechanism. Additionally, while cold ablation using ultrashort-pulse lasers minimises thermal damage, it is unsuitable for thick alumina ceramics due to its low material removal rate.

The choice of laser source plays a pivotal role in determining the quality and efficiency of the drilling process. Continuous wave (CW) lasers are effective for cutting but not ideal for drilling deep holes, as they produce excessive melting, thermal stress, and cracking. Ultrashort-pulse (USP) lasers, operating in the femtosecond to picosecond range, deliver energy rapidly, preventing significant heat diffusion and reducing thermal damage. Rung [11] reported laser micromachining of alumina using a 150 W ultrashort pulsed laser, achieving ablation efficiencies of 0.7–0.76 $\text{mm}^3/(\text{W}\cdot\text{min})$, with ablation rates up to 57 mm^3/min. Similarly, Andriukaitis [12] demonstrated GHz burst mode with a 30 W femtosecond laser (FemtoLux 30), achieving a material removal rate of 10.38 mm^3/min, corresponding to an efficiency of 0.877 $\text{mm}^3/(\text{W}\cdot\text{min})$. Despite advancements in USP laser, their application for drilling thick alumina remains limited due to challenges such as edge wall taper [13], self-limiting effects, and low material removal rates.

Nanosecond lasers, with power densities ranging from 10^9 to 10^{10} W/cm^2, have become increasingly popular for processing metals and composites [14] due to their fair material removal rates (1–10 µm/pulse). However, their application is limited to thin materials (≤1 mm) or surface engineering tasks. Research on using nanosecond lasers for drilling of alumina ceramics remains sparse. Demarbaix [15] and Xu [16] both employed a 100 W IPG nanosecond laser for blind machining of alumina ceramics, with depths of only a few hundred microns.

Millisecond pulsed lasers provide an optimal balance of speed, quality, and removal rate for thick ceramics like alumina. Operating at moderate power densities (10^6–10^9 W/cm^2), they use melting and vaporisation mechanisms to remove material efficiently. Unlike CW lasers, millisecond lasers reduce thermal damage by delivering high peak power pulses with adequate intervals between pulses, promoting vaporisation-based melt ejection while achieving higher productivity compared to ultrashort and nanosecond lasers. Most studies on millisecond laser drilling have focused on metals and alloys. Marimuthu [6, 9] demonstrated trepanning of 2-10 mm thick nickel alloy at 500 mm/min with minimal recast layer (~80 µm). Researchers [17] have recently proposed a hybrid laser drilling method combining nanosecond and millisecond pulse lasers for 1 mm thick alumina ceramics. However, very limited research exists on millisecond laser trepanning drilling of alumina ceramics thicker than 5 mm.

Given this knowledge gap, the present study aims to investigate material removal and hole formation characteristics during millisecond laser drilling of 6 mm thick alumina ceramics. By understanding the interplay between key laser process variables, and process mechanisms, this research seeks to advance the development of efficient and reliable laser drilling techniques for high-performance ceramic components in advanced engineering applications.

2. Materials and Methodology

A 99.99% pure alumina (Al_2O_3) sheet with a thickness of 6 mm was used as the base material. Laser trepanning drilling was conducted using an IPG quasi continuous wave (QCW) pulsed fibre laser. Table 1 provides detailed specifications of the laser source's operating characteristics.

Table 1: Quasi-CW laser beam characteristics

Parameter	Unit	Value
Wavelength	nm	1070
Maximum frequency	Hz	200
Maximum average power	W	2000
Maximum peak power	W	20000
Maximum pulse energy	J	200
Beam parameter product	mm x mrad	4.2
Focus beam size	mm	0.142

The schematic representation of the experimental setup is shown in Figure 1. The optical setup included a 120 mm collimator and a 170 mm focusing lens, which directed the laser beam from the 100 µm fibre-end onto the workpiece surface. Prior to the drilling experiments, the gas jet's pressure exerted on the workpiece was measured using a manometer. For a nozzle with a diameter of 2.5 mm and a nozzle-to-workpiece distance of 6 mm, a gas pressure of 7 bar was found to yield optimal gas dynamic performance. Further insights into the effects of gas pressure and nozzle-to-workpiece distance on gas jet characteristics can be found in various literature [6].

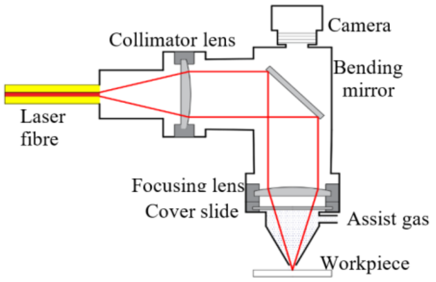


Figure 1: Schematic of the optical set-up with co-axial nozzle

Preliminary experimental trials were conducted to identify key process variables and determine the feasible range of laser parameters for trepanning a 1.4 mm diameter hole over 6 mm thick alumina. The laser parameters selected for experimental investigation are detailed in Table 2. The parameters varied in this study included energy, frequency, trepanning speed, and gas composition. All experiments were conducted using two trepanning orbits, with the initial piercing time set to one second. A systematic investigation was carried out by varying one parameter at a time while keeping the others constant. This approach ensured quantifiable evidence of the influence of each individual laser parameter on the drilling outcomes, providing a clear understanding of their respective effects.

Table 2: Laser process parameters and the range used for this investigation

Energy	Frequency	Speed	Gas Composition
J	Hz	mm/min	
5 - 25	20 - 50	30 - 150	Oxygen, Argon, Nitrogen, Air

To ensure the reliability and repeatability of the results, five holes were drilled and analysed for each set of parameters. Post-drilling, the hole entrance and exit were examined using an optical microscope. The drilled alumina samples were sectioned to analyse the thermal affected zone (TAZ). The TAZ was defined as the combined region of the recast layer and the heat-affected zone along the hole walls.

3. Results and Discussions

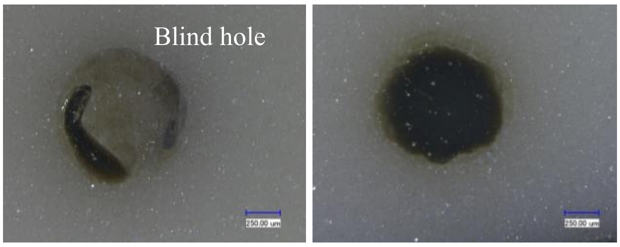
Key requirements for laser drilling alumina ceramics include minimising the thermal affected zone (TAZ), hole taper, and ensuring crack-free holes. This section explores the impact of laser parameters—gas composition, energy, frequency, and trepanning speed—on crack formation, geometric characteristics, and TAZ, providing insights for achieving high-quality holes with minimal thermal damage.

3.1. Crack generation during drilling of alumina

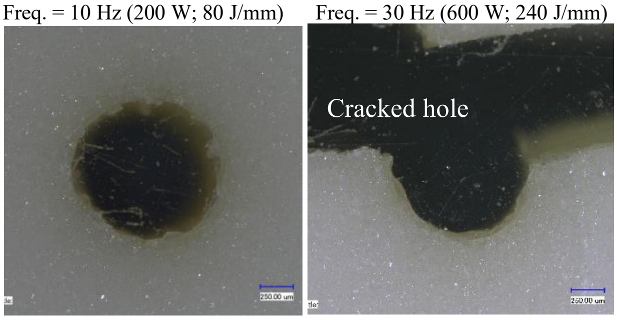
One of the key challenges in laser drilling of brittle materials such as alumina is the formation of cracks [18] due to thermal stresses [19] generated during the rapid heating and cooling cycles inherent to the laser drilling process. Initial experiments focused on identifying the processing window that enables through-hole drilling without crack formation. Figure 2 presents optical microscopic images of hole exits produced under varying laser frequency. The investigation covered the full operational range of the laser system (average power from 200 W to 2000 W) while maintaining constant pulse energy of 20 J, trepanning speed of 150 mm/min, pulse duration of 2 ms, and oxygen assist gas pressure of 7 bar.

The results presented in Figure 2 reveal three distinct processing regimes. At lower energy inputs (20 J, 10 Hz, corresponding to 200 W average power), only blind holes were produced, indicating insufficient energy for complete penetration. This establishes a minimum threshold of specific energy requirement of ~80 J/mm (calculated as (average power (W) ÷ trepanning speed (mm/s))) for drilling through-holes in 6 mm thick alumina. Within the intermediate power range (300-1500 W average power; 15 Hz < frequency < 75 Hz), through-holes without cracks were consistently achieved, demonstrating a stable processing window. However, when the average power exceeds 1600 W (or 80 Hz; equivalent to 640 J/mm specific energy), crack formation becomes evident around the hole periphery. This cracking phenomenon is attributed to several mechanisms. The rapid temperature changes during laser irradiation generate steep thermal gradients in the material, causing thermal shock. The cyclic heating and cooling induced by the pulsed laser beam leads to the accumulation of residual stress. There may also be possible localised phase changes in the alumina structure due to extreme temperatures. Additionally, different expansion rates between the heated and surrounding material create internal stresses due to thermal expansion mismatch.

Crack-free drilling of alumina ceramics can be achieved, bounded by the minimum energy requirement for through-hole formation (>80 J/mm) and the maximum energy threshold before crack initiation (<640 J/mm), and further experiments were conducted within this process window.



Freq. = 10 Hz (200 W; 80 J/mm) Freq. = 30 Hz (600 W; 240 J/mm)



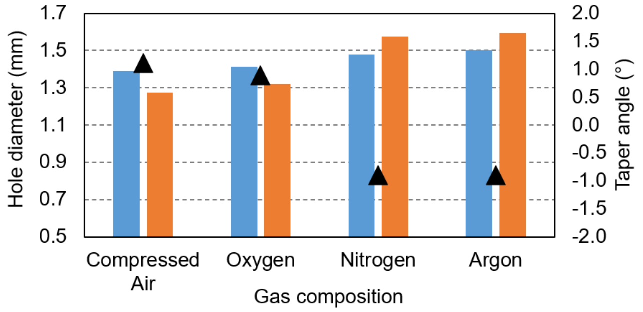
Freq. = 60 Hz (1200 W; 480 J/mm) Freq. = 80 Hz (1600 W; 640 J/mm)

Figure 2: Images of hole exits produced at different laser frequencies Effect of gas composition on drilling characteristics (scale bar = 250 µm)

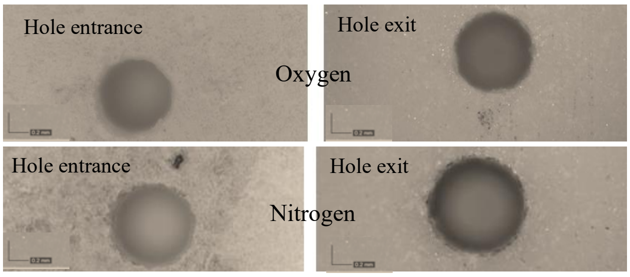
Laser drilling can be performed using various assist gases [9]; the selection typically depends on the material's reactivity with the chosen gas and the required drilling mechanism, i.e., fusion or reactive fusion. The influence of assist gas composition on the laser drilling characteristics of 6 mm thick alumina ceramics was investigated. Alumina, being an inert [20] ceramic material, does not undergo exothermic reactions [8] with reactive gases such as oxygen, making the gas selection primarily dependent on its thermal and fluid dynamic properties rather than chemical reactivity. Figure 3 presents the effect of different assist gases (compressed air, oxygen, nitrogen, and argon) on the drilling characteristics at constant laser parameters (pulse energy of 20 J, frequency of 40 Hz, pulse width of 2 ms, trepanning speed of 150 mm/min and gas pressure of 7 bar).

As noticed from Figure 3a, holes produced using air and oxygen exhibited positive taper angles (entrance diameter larger than exit), while those created with nitrogen and argon demonstrated negative taper characteristics (entrance smaller than exit). The optical microscope images in Figure 3b also show these contrasting hole geometries.

The variation in taper characteristics can be attributed to several mechanisms. The positive taper observed with oxygen and air suggests material melting based on the laser energy/ peak power density throughout the material thickness, with the gas primarily serving to eject melt from the laser interaction zone. Despite oxygen not participating in exothermic reactions with alumina, it produced the most stable hole formation with minimal taper (~0.9°). This can be attributed to oxygen's higher molecular mass and conductivity, which facilitate more efficient heat dissipation and melt ejection, compared to gases like nitrogen or argon, which have lower thermal conductivity.



(a) Effect of gas composition on hole diameter and taper



(b) Optical microscopic image of laser drilled hole

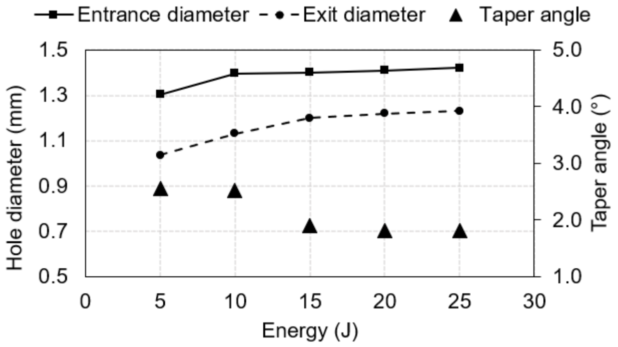
Figure 3: Effect of gas composition on drilling characteristics (all scale bars are at 200 µm)

Conversely, the negative taper observed with nitrogen and argon indicates enhanced material removal at the hole exit. This phenomenon could be explained by the thermal properties of these inert gases. Their lower thermal conductivity should have led to heat accumulation at the bottom of the hole, resulting in wider exit diameters. Additionally, the gas dynamics of nitrogen and argon, particularly their lower viscosity, might affect the melt ejection pattern, contributing to the observed negative taper. Based on these findings, oxygen was identified as the optimal assist gas for laser drilling of alumina ceramics, demonstrating superior hole quality with minimal taper. Consequently, oxygen was selected as the assist gas for all subsequent experiments in this study.

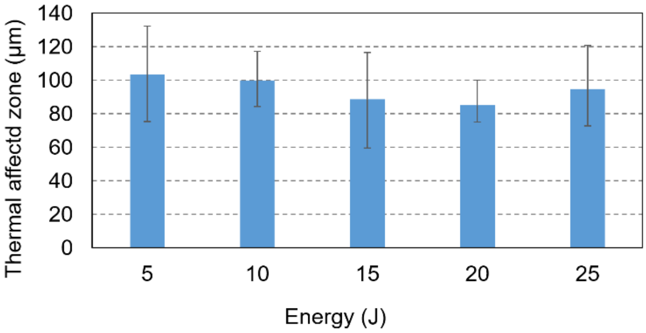
3.2. Effect of pulse energy on drilling characteristics

Figure 4 illustrates the effect of laser pulse energy (5 J to 25 J) on key drilling characteristics during the trepanning of 6 mm thick alumina ceramics, conducted at a constant frequency of 40 Hz, a pulse duration of 2 ms, a trepanning speed of 150 mm/min, and with oxygen assist gas pressure of 7 bar. The entrance hole diameter shows a distinct increase from 5 J to 10 J, after which it stabilises at ~1.4 mm with minimal fluctuations. Similarly, the exit hole diameter shows a gradual increase up to 15 J before maintaining a relatively constant diameter of ~1.2 mm through to 25 J, while consistently remaining smaller than the entrance diameter. The hole taper improves with pulse energy, decreasing steadily from 5 J to 20 J before stabilising at ~1.7° beyond 20 J. The TAZ shows a beneficial reduction from ~105 µm at 5 J to ~85 µm at 20 J, reaching its minimum value in the 15-20 J range, though it begins to increase beyond 20 J.

These trends can be attributed to several key mechanisms. The initial increase in hole diameter (5-15 J) results from enhanced material removal due to increased peak power density [21], improved energy coupling, and more efficient melt pool formation and ejection dynamics. The subsequent diameter stabilisation beyond 15 J suggests a thermal equilibrium between energy input and material removal, limited by the focused beam diameter and thermal diffusion characteristics, with possible plasma shielding effects at higher energies preventing further diameter increase. The reduction in taper with increasing energy is due to enhanced energy delivery to the bottom surface through multiple reflections [22] and improved melt ejection, driven by stronger vapor pressure. The TAZ behaviour reflects the efficiency of the material removal process, with its initial decrease (5 J-20 J) indicating optimal balance between melting and ejection, while the increase beyond 20 J suggests excessive heat input leading to broader thermal diffusion and enhanced lateral heat conduction. The findings indicate that 20 J represents an optimal pulse energy level, where hole geometry stabilises with minimal taper, TAZ remains minimal, and material removal efficiency reaches its maximum, achieving an ideal balance between energy input and material removal mechanics.



(a) Effect of laser pulse energy on hole diameter and taper

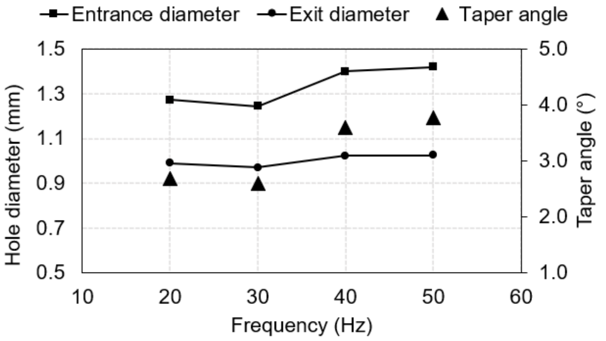


(b) Effect of laser pulse energy on thermal affected zone

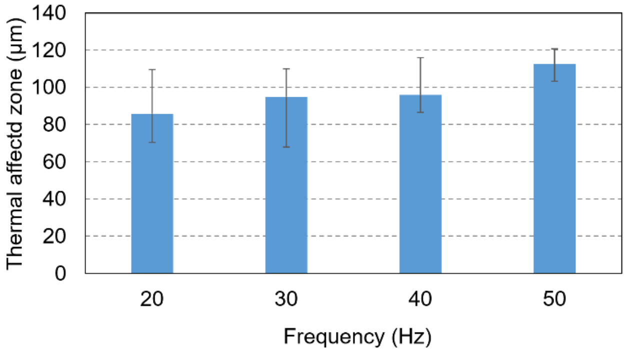
Figure 4: Effect of laser pulse energy on drilling characteristics

3.3. Effect of laser pulse frequency on drilling characteristics

Figure 5 shows the effect of laser pulse frequency (20 Hz to 50 Hz) at a constant pulse energy of 20 J, pulse duration of 2 ms, trepanning speed of 150 mm/min, and oxygen assist gas pressure of 7 bar on the drilling characteristics of 6 mm thick alumina ceramics. The entrance hole diameter exhibits a distinct two-phase behaviour: initially maintaining a relatively constant diameter of ~1.27 mm between 20 Hz and 30 Hz, followed by a steady increase reaching 1.45 mm at 50 Hz. In contrast, the exit diameter shows minimal variation, fluctuating around 1.05 mm across the entire frequency range, consistently remaining smaller than the entrance diameter and indicating a positive taper profile. The hole taper angle demonstrates a complex relationship with frequency, initially decreasing between 20 Hz and 30 Hz, before increasing significantly beyond 35 Hz to reach ~3.5° at 50 Hz.



(a) Effect of laser pulse frequency on hole diameter and taper



(b) Effect of laser pulse frequency on thermal affected zone

Figure 5: Effect of laser pulse frequency on drilling characteristics

The observed trends can be attributed to several key mechanisms. The increase in entrance diameter at higher frequencies results from two primary factors: enhanced energy input and cumulative thermal effects. At higher frequencies, the time interval between successive pulses decreases, leading to reduced cooling between pulses [22]. This results in residual heat accumulation in the material, effectively lowering the energy threshold for material removal in subsequent pulses. Additionally, the increased pulse overlap at higher frequencies leads to more uniform and higher energy distribution around the hole circumference, contributing to the enlarged entrance diameter. The relatively constant exit diameter across the frequency range suggests that the frequency-dependent thermal effects are more pronounced near the surface than at depth. This behaviour can be explained by energy attenuation through the material thickness and the role of assist gas in heat dissipation. Despite the increased thermal accumulation at higher frequencies, the energy available at the exit remains primarily dependent on the pulse energy rather than the pulse frequency, resulting in minimal variation in exit diameter.

The TAZ, as shown in Figure 5b, demonstrates a clear correlation with pulse frequency, showing a significant increase particularly beyond 40 Hz. This expansion of the TAZ can be attributed to three mechanisms: firstly, the reduced cooling time between pulses at higher frequencies leads to heat accumulation in the surrounding material; secondly, the increased average power input enhances lateral heat conduction; and thirdly, the multiple reflections of the laser beam within the hole create additional heat affected regions. At 50 Hz, the combination of these effects results in the largest observed TAZ values, indicating significant thermal impact on the surrounding material. The findings suggest that while higher frequencies can enhance material removal rates through improved energy coupling and thermal accumulation, they also lead to less controlled hole formation with increased taper and thermal effects. The optimal frequency range appears to be between 25-35 Hz, where a balance is achieved between processing efficiency and hole quality, maintaining reasonable taper angles and controlled thermal effects. This understanding is crucial for controlling the laser drilling process for specific applications where either processing speed or hole quality is prioritised.

3.4. Effect of trepanning speed on drilling characteristics

Figure 6 illustrates the influence of trepanning speed (60-150 mm/min) on the drilling characteristics at constant laser parameters (energy: 25 J, pulse duration: 2 ms, frequency: 20 Hz) and oxygen assist gas pressure of 7 bar during the drilling of 6 mm thick alumina ceramics. The results demonstrate that trepanning speed significantly affects both the hole geometry and thermal characteristics of the drilling process.

The entrance hole diameter shows a marked decrease with increasing speed, while the exit diameter remains relatively constant at ~1.1 mm across the speed range. This variation in entrance diameter leads to a corresponding reduction in hole taper angle, decreasing from ~3.0° at 60 mm/min to 1.5° at 150 mm/min. The TAZ also exhibits a clear dependence on trepanning speed, reducing from over 100 μm at lower speeds (60 mm/min) to ~75 μm at 150 mm/min.

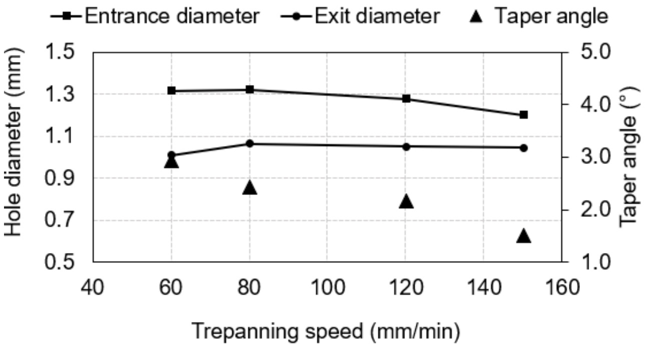
These trends can be attributed to several basic mechanisms. The reduction in entrance hole diameter with increasing speed is primarily due to reduced laser-material interaction time per unit area. At lower speeds, prolonged exposure to laser radiation leads to excessive material heating and melting around the entrance region, resulting in larger hole diameters. As the speed increases, the energy deposition becomes more localised and controlled, leading to more precise material removal and smaller entrance diameters.

The consistency in exit diameter across different speeds suggests that the material removal at hole bottom is predominantly governed by the energy rather than the speed. This behaviour can be explained by the multiple reflection effects within the hole and the focusing of energy at the bottom of the hole, which maintains relatively constant conditions for material removal regardless of the trepanning speed.

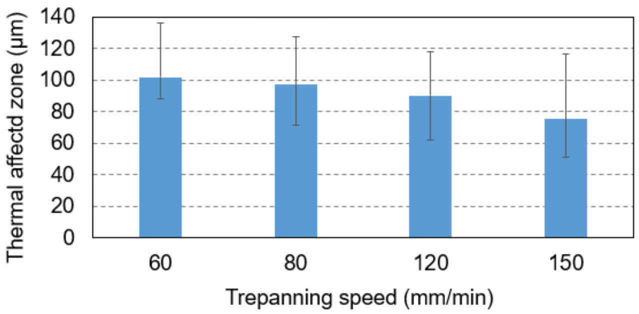
The improvement in hole taper at higher speeds can be attributed to two factors: firstly, more controlled material removal due to the optimal amount of input-specific energy at the entrance, which results in smaller entrance diameters and reduced taper; secondly, the higher speeds reduce laser-material interaction time, leading to more localised material removal and a more uniform energy distribution throughout the hole depth, resulting in consistent material removal and reduced taper.

The reduction in TAZ with increasing speed is particularly significant from a quality perspective. This improvement can be explained by several factors: reduced heat accumulation due to shorter interaction times, more efficient melt ejection due to the dynamic nature of the process at higher speeds, and better utilisation of the assist gas flow for cooling and debris removal. The larger TAZ observed at lower speeds (~60-80 mm/min) results from excessive heat accumulation and lateral thermal conduction due to prolonged laser-material interaction.

These findings indicate that higher trepanning speeds (~150 mm/min) produce superior hole quality with minimal taper and reduced thermal damage. However, it's important to note that excessively high speeds might lead to reduced input-specific energy and subsequently incomplete material removal or inconsistent hole formation. The results suggest that 150 mm/min (corresponding to input-specific energy of 200 J/mm) represents an optimal balance between processing efficiency and hole quality for the given laser parameters.



(a) Effect of trepanning speed on hole diameter and taper



(b) Effect of trepanning speed on thermal affected zone

Figure 6: Effect of trepanning speed on drilling characteristics

4. Conclusions

This study investigated millisecond laser trepanning of 6 mm thick alumina, examining the effects of energy, frequency, trepanning speed, and assist gas composition on the drilling process. The research identified a specific energy window between 80 J/mm and 640 J/mm for successful through-hole drilling without crack initiation. Assist gas composition significantly influences hole characteristics through thermal and fluid dynamic properties rather than chemical reactivity, with oxygen and air producing positive taper profiles while nitrogen and argon result in negative taper profiles. Oxygen assist gas provides better hole quality compared to air or inert gases, achieving minimal taper (~0.9°) through enhanced melt ejection and heat dissipation. Lower frequencies enabled controlled hole formation, while higher frequencies caused residual heating, leading to increased thermal damage, taper, and cracking. The study established optimal processing window, including input-specific energy of 200 J/mm for balanced processing efficiency, corresponding to an energy of 25 J, frequency of 20 Hz and trepanning speed of 150 mm/min yielding superior hole quality with minimal taper (1.5°) and reduced thermal affected zone (75 µm). These findings advance the understanding of laser drilling in thick alumina ceramics for high-value manufacturing applications.

Acknowledgements

This work was supported by UKRI Future Leaders Fellowship under grant number MR/V02180X/1 and benefited from the collaboration and learning from Horizon Europe project FLASH under grant number 101138380.

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