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Laser and mechanical micro-drilling for aerospace applications

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Abstract

Traditional laser percussion drilling encounters challenges related to poor geometry and thermal defects. At the same time, mechanical micro-drilling while generating high-quality holes, faces issues such as premature drill breakage and difficulty drilling at acute angles. This review paper introduces a novel approach to micro-drilling Inconel 718 alloy sheets at acute angles by combining sequential laser and mechanical drilling. The study showcases the feasibility and fundamental characteristics of this innovative technique. Results indicate that the sequential laser-mechanical micro-drilling approach mitigates the drawbacks associated with laser-drilled holes, leading to reduced burr size, decreased machining time, and increased tool life when compared to conventional mechanical drilling methods. This advancement holds promise for enhancing precision and efficiency in aerospace applications, paving the way for improved manufacturing processes in the aerospace industry.

Keywords: Laser Micro-Drilling; Mechanical Micro-Drilling; Aerospace Applications

1. Introduction

The aerospace sector has traditionally employed electrical discharge machining (EDM) and laser drilling techniques to create effusion cooling holes in components such as nozzle guide vanes, micro-channel heat exchange, and turbine blades as shown in Fig.1. However, EDM drilling is associated with high tooling costs, low drilling speeds, and issues like recast and heat-affected zones [1]. On the other hand, laser drilling faces challenges in controlling drilling quality, specifically minimizing recast layers and heat-affected zones (HAZ) [2]. Furthermore, drilling hollow components, such as aerofoil blades and fuel injector nozzles, poses a challenge in laser drilling, as the laser beam can inadvertently damage the opposite wall after breaking through the front wall. Common mitigation methods include cavity filling with a blocker and in-process breakthrough detection, but these are not always applicable, especially for closed or hard-to-access cavities. Although an alternative, mechanical drilling encounters issues like premature drill breakage due to the delicate nature of micro-drills, particularly when drilling at acute angles. The high lateral force at the contact point with the workpiece surface causes the micro-drill to diverge from the required position, leading to bending and easy tool fracture. Additionally, burr formation in mechanical drilling affects workpiece accuracy and quality [3]. EDM has been reported to have a significantly lower drilling rate (0.0125 mm/s) compared to mechanical (>0.25 mm/s) and laser (>1000 mm/s) drilling [1].

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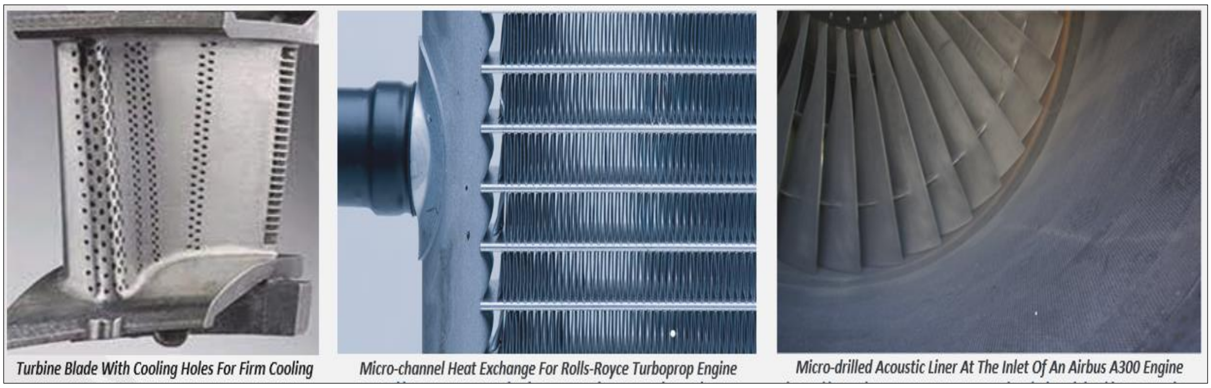

Turbine Blade With Cooling Holes For Firm Cooling

Micro-channel Heat Exchange For Rolls-Royce Turboprop Engine

Micro-drilled Acoustic Liner At The Inlet Of An Airbus A300 Engine

Figure 1 Micro-Drilling in Aerospace Applications.[2]

Recognizing the limitations of individual machining processes, hybrid machining has emerged as a promising technique, especially for superalloys [4]. Theory Studies, such as Brown's exploration of hybrid laser and mechanical machining, and Li's application of laser beam machining and EDM [5], have shown promising results in terms of reduced drilling time and increased production capacity. This reviewed paper introduces a novel approach—sequential laser-mechanical drilling for acute angle drilling (30°) of Inconel 718 alloy in aerospace applications. This innovative process aims to address challenges associated with tip divergence, low tool stiffness in pure mechanical micro-drilling, and issues specific to drilling at acute angles, including poor geometry, heat-affected zones, recast layer formation, and back-wall damage problems in laser micro-drilling. The focus of this investigation is on drilling on an inclined plane, where a pilot hole is initially created by a laser beam, followed using an end mill to machine the diffuser portion of the hole and provide a flat surface for the drill entrance side [2]. The final step involves micro-mechanical drilling to complete the holes. The holes produced using this machining process are compared to those created through traditional mechanical drilling and laser drilling methods.

Aims and Objectives

This reviewed paper aims to study Laser and Mechanical Micro Drilling for Aerospace Applications using pulsed Nd: YAG lasers operating at wavelengths of 1064nm on Inconel 718, under certain experimental conditions.

To achieve this aim, the following objectives were considered:

- Comparative Analysis and Quality Assessment of Laser and Mechanical Micro-Drilling Processes.
- Comprehensive Process Characterization of Laser-Drilled Holes.
- Comparative Analysis of Gas type- Oxygen and Air during Laser Drilling.
- Tool Life Evaluation Assessment for both Laser and Mechanical Micro-Drilling Processes.

2. Literature Review

Auto Cited	**Study Research**	**Gap Identified**	**Knowledge Contribution**
Andreas et al. (2014)	High-speed laser micro drilling for aerospace applications.	Traditional drilling methods are not suitable for producing large areas with small holes (50-100μm) due to limitations in precision, speed, and thermal distortion. Efficient and cost-effective methods for drilling large areas with small holes are crucial for hybrid laminar flow control (HLFC) applications in aerospace.	The paper proposes a system technology that utilizes a short-pulsed fibre laser to drill precise and fast through-going holes (down to 30μm) on large areas (100mm x 100 mm) of titanium sheets. The developed system achieves a drilling rate of more than 400 holes per second, enabling efficient and cost-effective production of HLFC components. This demonstrates the capability of the system to control the drilling sequence and energy input to minimize thermal distortion and ensure high hole quality.
Okasha et al. (2020)	Sequential laser and	Laser percussion drilling produces poor hole geometry	The paper proposes a sequential process of laser and mechanical micro-drilling for Inconel 718 alloy

	mechanical micro-drilling of Ni superalloy for aerospace application.	and thermal defects, while mechanical micro-drilling produces good-quality holes, but suffers from premature drill breakage and difficulty drilling at acute angles.	sheets at an acute angle. The process improves hole quality, reduces burr size and machining time, and increases tool life compared to mechanical drilling alone.
Levent et al. (2023)	A comprehensive study on water jet guided laser micro hole drilling of an aerospace alloy.	Water jet guided laser (WJGL) is a promising method for drilling micro cooling holes in turbine components, but there is limited understanding of the factors that affect machining efficiency, particularly for different hole geometries. Real-time monitoring methods are needed to optimize the WJGL process and ensure consistent hole quality.	The paper explores the process limits and machining efficiency of WJGL drilling for various hole diameters and depths. A novel real-time measurement method based on acoustic signals is proposed to correlate ultrasound emission with material removal, providing valuable insights into the drilling process. The study demonstrates the potential of WJGL drilling for high-precision micro-cooling hole production in aerospace applications.
Marimuthu et al. (2019)	Characteristics of micro-hole formation during fibre laser drilling of aerospace superalloy.	There is a limited understanding of the characteristics of quasi-CW fibre laser micro-hole drilling (~100μm) of nickel superalloy. Existing studies often lack a comprehensive approach that combines experimentation and numerical modelling to provide a holistic understanding of the micro-hole formation process.	The paper investigates the characteristics of micro-hole formation during quasi-CW fibre laser drilling of nickel superalloy using both experimentation and numerical modelling. The study utilizes high-speed imaging and finite element modelling to gain insights into the fundamental mechanisms of melt ejection and micro-hole formation during millisecond laser drilling. The experimental results demonstrate the influence of laser parameters such as pulse duration and pulse energy on melt ejection duration and micro-hole characteristics. The findings provide valuable insights into the optimization of laser drilling parameters for achieving precise and efficient micro-hole drilling in nickel superalloys.

3. Methodology

3.1. Laser Drilling Process with Inconel 718 Alloy

In this experimental phase, the spotlight shines on the laser drilling process, a pivotal aspect of advancing micro-machining capabilities for aerospace applications. Employing Inconel 718 alloy plates of precise dimensions measuring 40mm in length, 25mm in width, and 2.15mm in thickness with an impressive hardness of 225Hv, laid the groundwork for a meticulous exploration of drilling dynamics [2]. The goal transcends mere hole creation; instead, it systematically characterizes holes. This comprehensive investigation adopts a three-factor approach, unravelling the influence of gas type, power, and pulse frequency on the drilling process. Through a robust two-level full factorial experimental design with 8 runs, a nuanced understanding of the interplay between variables is sought [2]. In drilling a blind hole, the material ejection mechanism differs from that of the standard through hole in which all the molten material must leave via the entrance section Fig.2. The primary objective is to generate holes mirroring the chisel edge length of the drill, aligning precisely with the demands of aerospace applications.

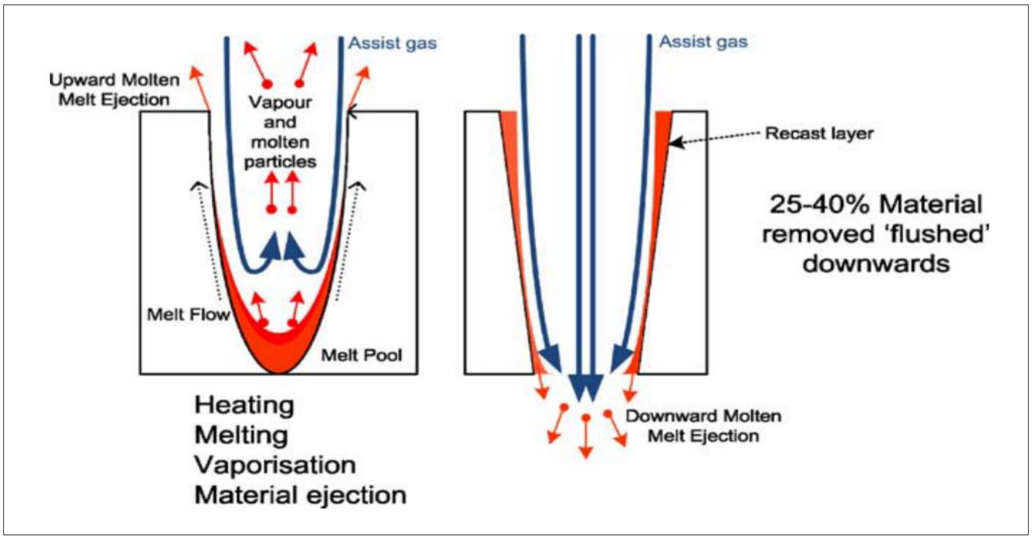

Figure 2 Material ejections in laser percussion drilling before and after the material breakthrough [6].

At the heart of this technological venture is the GSI-JK300D pulsed Nd: YAG laser, operating at a wavelength of 1064nm [2]. The laser beam, a key player in this intricate symphony of precision, is carefully focused to achieve a beam diameter of 240mm at the workpiece surface. The experiment extends its complexity by venturing into the realm of inclined holes. At an inclination angle of 30 degrees to the surface, a scenario often encountered in aerospace configurations, the nozzle and the axis of the laser beam are intentionally inclined. This innovative approach ensures that the workpiece retains a horizontal position, a critical consideration in aerospace machining. To maintain uniformity and draw from prior research findings, the pulse duration is steadfastly maintained at 0.3ms, and the assist gas pressure is held at a consistent 5 bar [6]

3.2. Mechanical Micro-Drilling Process

Transitioning seamlessly from laser drilling, the experimentation advances into the realm of mechanical micro-drilling a critical component in the broader exploration of micro-machining capabilities for aerospace applications. The Mikron HSM-400 machining center takes center stage, orchestrating the mechanical micro-drilling tests precisely. Here, the focus shifts to the intricacies of tool selection and material properties. The choice of TiAlN (titanium aluminium-nitride) coated micro-drills from Rainford Precision UK Ltd, crafted from ultra-fine tungsten carbide, is underpinned by their proven effectiveness in drilling Inconel 718 superalloy [2].

The mechanical drilling parameters are finely tuned to ensure optimal performance. Drills with a diameter of 0.8mm, featuring a point angle of 1508, a helix angle of 3008, a flute length of 10mm, and a chisel edge length of 0.3mm, are selected for uniformity across experiments [7]. Cutting speed, feed rate, pecking depth, and the application of flood coolant are meticulously controlled, reflecting the precision required in aerospace micro-machining. A 1mm diameter 3-flute square end mill is strategically employed as a prelude to the drilling process. This not only facilitates the machining of the diffuser portion of the hole but also provides a flat surface at the hole entry side, setting the stage for subsequent drilling operations.

3.3. Comparative Analysis and Quality Assessment

Beyond the individual intricacies of laser and mechanical micro-drilling, a comprehensive comparative analysis is on the horizon. The acquired data, spanning hole characteristics, surface finish, and structural integrity, will be scrutinized. Advanced metrology techniques, including optical microscopy and scanning electron microscopy (SEM), will be deployed for precise measurements and qualitative assessments. This multifaceted experimental approach aims to unravel the comparative efficacy of laser and mechanical drilling techniques on Inconel 718 alloy. The findings promise to contribute significantly to the evolving landscape of aerospace micro-machining, offering nuanced insights into the capabilities and limitations of each drilling method.

4. Material

Materials chosen for laser micro drilling in aerospace applications undergo careful selection to meet the exacting standards of the aerospace industry, accounting for factors like high-temperature resistance, mechanical strength, and lightweight properties. In aerospace applications, Inconel alloys, particularly Inconel 718 are commonly used materials, and they can be suitable for laser micro-drilling processes. However, the suitability of Inconel 718 for laser micro-drilling depends on several factors, including the specific requirements of the drilling application, the thickness of the material, and the desired hole characteristics. Inconel 718 is a nickel-based superalloy known for its excellent high-temperature resistance, corrosion resistance, and mechanical properties. These properties make it suitable for critical components in aerospace, such as turbine discs, jet engine components, and other high-temperature environments [4].

When considering laser micro-drilling, Inconel 718's properties may present both advantages and challenges. The high-temperature resistance of Inconel 718 is beneficial in aerospace applications where components experience elevated temperatures. Additionally, the material's strength and oxidation resistance contribute to its suitability for drilling processes. However, Inconel 718 is known for its toughness and hardness, which can pose challenges during machining processes, including laser drilling. Laser drilling involves precise material removal through the application of focused laser beams. The hardness of Inconel 718 may require a careful selection of laser parameters, such as power, pulse duration, and frequency, to achieve the desired hole characteristics without causing excessive tool wear or thermal damage to the material [5]. Inconel 718 can be suitable for laser micro-drilling processes in aerospace applications, but it is essential to carefully optimize the laser parameters and consider specific drilling requirements to achieve the desired results. It's recommended to conduct thorough testing and experimentation to determine the most effective laser drilling parameters for the given application and material thickness.

5. Results

5.1. Optimum Laser Pre-hole Diameter and Shape

Table 1, presents the results of the laser drilling phase, emphasizing the quest for the optimum pre-hole diameter and shape for aerospace applications. Each data point represents the average of at least eight runs, ensuring robust and reliable findings. The analysis reveals that achieving uniformity in the recast layer along the hole periphery is crucial for maintaining good roundness and symmetrical wall characteristics. Runs 1 and 5 emerge as the best, with the laser-drilled hole sizes of 340mm and 250mm in diameter, respectively, under the conditions of 2.7J, 25Hz, and 5 bars, using oxygen and air assist gases [2].

Table 1 Laser drilling experiment design and results [2]

Run	Factors			Results			
	Gas	Pulse Energy (J)	Freq. (Hz)	Mean Dia. (µm)	Roundness	Recast (µm)	Drilling time (s)
1	O_2	2.7	25	340±22	0.95	80	4.2
2	O_2	2.7	50	360±28	0.92	70	1.2
3	O_2	3.6	25	375±47	0.89	90	2.0
4	O_2	3.6	50	410±60	0.86	125	0.5
5	Air	2.7	25	250±18	0.93	100	2.6
6	Air	2.7	50	310±25	0.90	85	1.0
7	Air	3.6	25	330±50	0.88	100	0.7
8	Air	3.6	50	370±55	0.84	110	0.3

Notably, the drilling speed with air surpasses that with oxygen under identical laser parameters, attributed to the formation of oxides requiring more energy and cycle time when using oxygen. Longitudinal cross sections of laser-drilled holes (Run 1 and Run 5) are depicted in Fig.3, showcasing an average Heat Affected Zone (HAZ) of 70mm and

65mm for Run 1 and Run 5, respectively. The mechanical drilling process is subsequently poised to address the defects associated with laser-drilled holes.

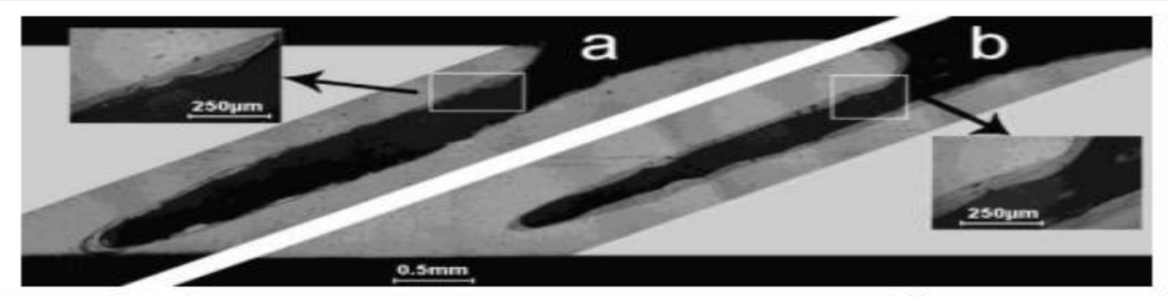

Figure 3 Sectioned laser-drilled hole showing the recast region with; (a)oxygen assist gas and (b) air assist gas [2]

5.2. Mechanical Micro-Drilling Process

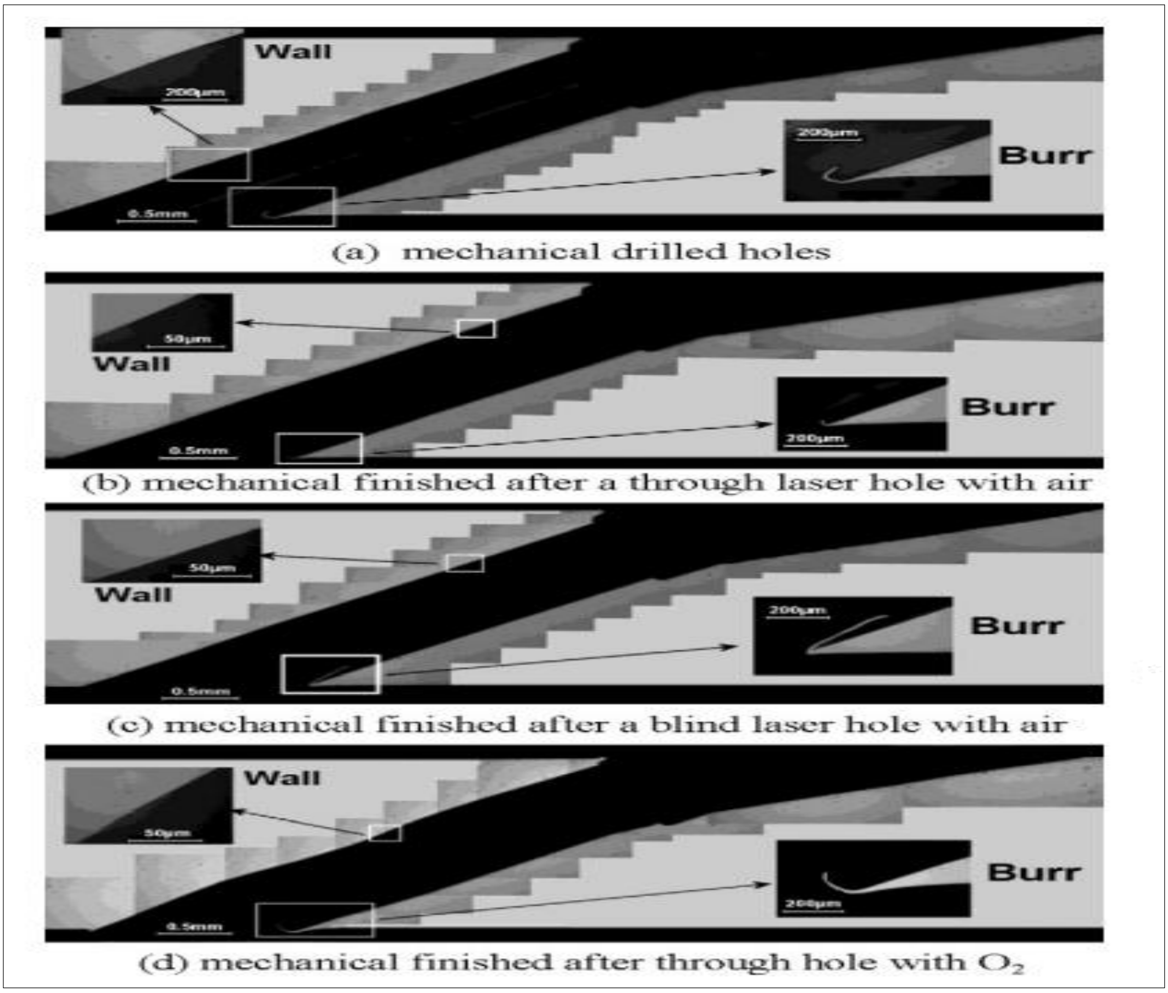

Figure 4 Comparison of mechanical and hybrid drilled holes [2]

Four approaches to laser pilot drilling were explored, involving through and blind hole arrays produced using oxygen and air-assist gases. The mechanical micro-drilling process was employed to finish these categories, alongside purely mechanical drilling. Fig.4a shows that the exit edge of the mechanically drilled hole is affected by the long and thick burr. The burr hits the drill in the retraction stroke and pushes the tool to damage the opposite wall. In the case of the laser-through hole drilling with compressed air and mechanical finishing, Fig.4b, the burr is very small, and no wall damage was detected. The burr length associated with laser-blind hole drilling with air and mechanically finished, Fig.4c is comparable to mechanical drilling but with a smaller thickness and it could be pulled by the tool in the retraction stroke. In Fig.4d, laser-through with oxygen and mechanical finishing shows a wavy hole surface and a larger diameter at the exit than at locations along the hole depth. This phenomenon is known as ‘‘bell mouth’’. Also, a large burr was found at the exit. These defects are also found in laser-blind hole drilling with oxygen and mechanically finished holes. The HAZ from the laser drilling was removed by the mechanical drilling process [2].

5.3. Tool Life Evaluation

Tool life evaluation becomes paramount in assessing the viability of the hybrid drilling approach. At a spindle speed of 2000 rpm, with feed rates of 22 and 28mm/min, Fig.5 illustrates the results. Sequential laser drilling followed by mechanical micro-drilling enhances tool life by 2.5 times compared to purely mechanical micro-drilling at the higher feed rate. This improvement is attributed to the reduced mechanical and thermal loads on the drill during hybrid drilling, leading to a more effective lubrication process [7]. The tool life is comparable at lower feed rates, emphasizing the nuanced dynamics of the hybrid drilling approach and its dependence on specific drilling conditions. The findings underscore the potential for significant advancements in tool life through the strategic integration of laser and mechanical micro-drilling techniques in aerospace applications.

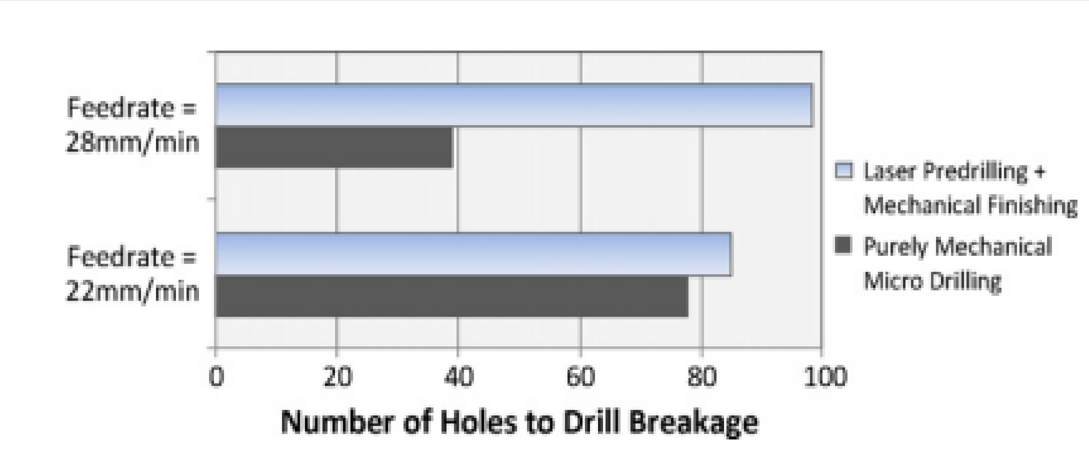

Figure 5 Tool life comparisons [2]

6. Discussion

Laser micro-drilling of Inconel 718 alloy for aerospace applications has provided compelling insights, based on this study. Notably, the utilization of air-assist gas has demonstrated a remarkable 1.5 times increase in drilling speed compared to oxygen. Further, research indicates that employing argon (an inert gas) during laser drilling of CMSX-4 (Ni-superalloys) with pulsed Nd: YAG laser, results in a staggering 5 times higher drilling speed than oxygen, especially with intensities exceeding 75 MW/cm^2 [8]. A crucial observation arises when contrasting air and oxygen as process gases – the residual oxide detected at hole walls with oxygen can have a substantial impact. This includes the formation of oxides like N_iO and $C_{r2}O_3$ during the interaction of Inconel 718 with oxygen, leading to the development of a black oxide layer [9]. A schematic representation of hole diameter measurements made in a laser-drilled hole to ascertain taper variation is shown in Fig.6.

This layer diminishes hole wall reflectivity, reducing multiple reflections and lowering beam intensity at the bottom. The elevated melting temperatures of N_iO (1980°C) and $C_{r2}O_3$ (2435°C) in comparison to Inconel 718 (1260°C) necessitate higher energy for melting the hole wall. Additionally, the lower ionization potential of O_2 (12.20 eV) compared to air (15.88 eV) facilitates plasma formation with O_2 jets, influencing the drilling dynamics [5].

This reviewed research has unveiled that the mechanical quality of drilled holes is influenced by burr size, with larger burrs impacting the quality adversely [3]. However, adopting a laser pre-drilled hole slightly smaller than the chisel edge length, especially in laser-through/blind hole drilling with air assist and subsequent mechanical finishing, substantially mitigates cutting resistance, thrust force, and heat generation. This improvement in cutting efficiency is attributed to the laser pre-drilled hole providing crucial support to the drill, thereby preventing lateral bending moments induced by vibration.

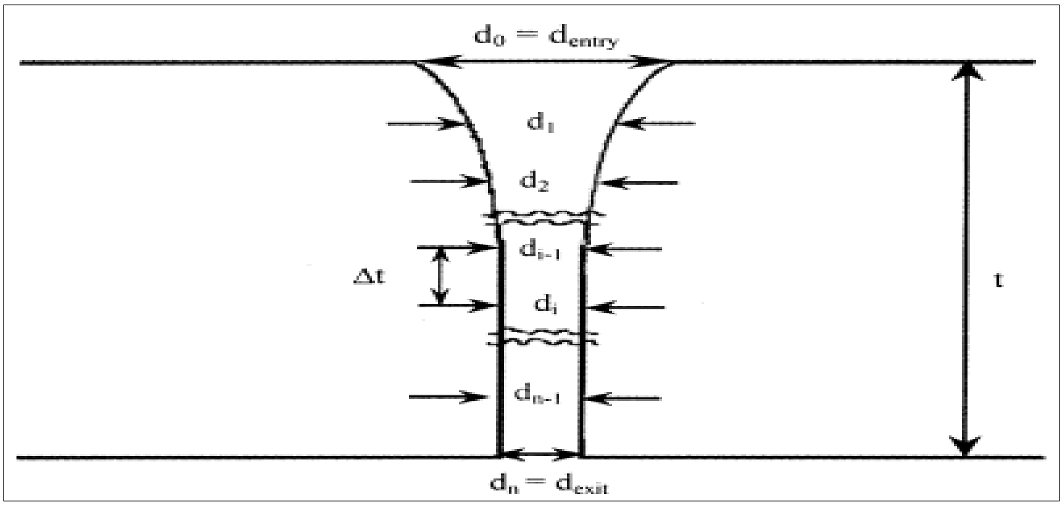

Figure 6 Schematic representation of hole diameter measurements made in a laser-drilled hole to ascertain taper variation with depth [9]

Furthermore, pre-drilling with a size exceeding the chisel edge length results in less tool support, leading to undesirable helical wandering, bell-mouthing, and wavy-hole surfaces [10]. The unsupported drill is susceptible to lateral bending moments induced by vibration, resulting in inferior hole quality.

In the context of mechanical drilling, the entrapment of hot chips between flute margins and hole walls can form a smear on the workpiece surface. Reducing the effective radial width of the cut not only decreases friction between the tool and workpiece and lowers the temperature in the drilling zone and at the tool-chip interface. This contributes to easier chip removal from the tool rake face, ultimately decreasing tool wear.

A recent model assessing the total thrust force in drilling has revealed intriguing insights. By factoring in forces from the primary cutting edge, secondary cutting edge, and indentation zone, it was found that these zones contribute approximately 25%, 69%, and 6%, respectively, at an undeformed chip thickness of 0.075mm for a 5mm diameter carbide drill [6]. The application of sequential laser and mechanical micro-drilling in nickel alloys, using micro-tools under flood coolant, presents its own set of challenges due to a high noise-to-signal ratio. However, the laser pilot hole significantly reduces the force components associated with the indentation zone and most of the secondary cutting edge, rendering them nearly negligible. Moreover, the micro-drill, with a relatively larger secondary edge (37.5% of the tool diameter) compared to a small-size drill (15.6%), aligns with drilling mechanics, suggesting a potential step change reduction in thrust force during sequential laser and micro-drilling [2]. This augurs well for superior tool life performance, marking a significant advancement in the field.

7. Conclusion

In the culmination of this groundbreaking exploration into the realm of precision machining for aerospace applications, our research has ushered in a new era with the first-ever demonstration of laser and mechanical micro-drilling of nickel-based superalloys, specifically focusing on Inconel 718. The implications of these pioneering endeavours extend far beyond mere technological achievement, as they promise to revolutionize the very fabric of aerospace component manufacturing. A paramount revelation from the reviewed study revolves around the remarkable efficacy of the sequential laser and mechanical micro-drilling process. By strategically deploying acute angles, this approach significantly reduces the width of the cut compared to conventional mechanical drilling. This not only relieves the load on the drill point but also catapults the drill life to unprecedented levels, showcasing a remarkable 2.5-fold increase for through holes in comparison to purely mechanical micro-drilling, particularly at high feed rates of 28mm/min. The superior performance observed at higher feed rates opens the exciting potential for leveraging this hybrid technique to achieve competitive drilling cycle times, thereby enhancing overall efficiency and productivity in aerospace manufacturing.

Furthermore, the synergistic nature of sequential laser and mechanical micro-drilling emerges as a transformative solution to address various challenges inherent in precision machining. The process, acting as a complementary force, extends the life of micro-drills and tackles size effect challenges, most notably mitigating quality issues like burr size arising from the rapid enlargement of the drill edge radius. Importantly, it serves as a panacea for thermal and geometric defects associated with laser-drilled micro-holes, ensuring the integrity of components critical to aerospace applications. Delving deeper into the intricacies of the drilling process, this research paper underscores the pivotal role of the size of the drill chisel edge in determining the target diameter for the laser-drilled pilot hole and, consequently, the choice of drilling parameters. The recommendation to maintain a laser pre-drilled hole size smaller than the chisel edge length serves to promote tool balance and minimize drill wander, highlighting the meticulous precision required in aerospace.

Challenging prevailing practices, particularly those involving micro-drills with a smaller web thickness for improved cutting action, sequential laser and mechanical micro-drilling emerge as a transformative force. By alleviating indentation and secondary cutting-edge actions, this technique empowers manufacturers to grind drills with thicker web thickness, ushering in a new era of enhanced drill strength and structural integrity. Equally noteworthy is the revelation regarding the choice of assist gas during laser drilling. Our research showcases that utilizing compressed air for micro-drilling results in a remarkable 50% reduction in cycle time compared to oxygen gas. This efficiency gain is attributed to the minimized formation of oxides, optimizing the overall drilling process. The adoption of air as an assist gas not only proves economically advantageous but also underscores its environmental benefit, considering its cost-effectiveness and abundance as a resource.

In a final revelation, this research illuminates the effectiveness of sequential laser and mechanical drilling in addressing a persistent challenge - the back-wall problem in laser drilling of hollow parts. Particularly relevant for components with closed cavities or challenging exit surfaces, this technique emerges as a robust solution, underscoring its adaptability to complex aerospace machining scenarios.

In conclusion, integrating sequential laser and mechanical micro-drilling techniques for Inconel 718 in aerospace applications transcends the boundaries of conventional machining methodologies. The insights gleaned from this research not only propel the aerospace industry into a new era of precision and efficiency but also lay the foundation for future innovations in aerospace component manufacturing. As we celebrate the culmination of this research journey, the echoes of its transformative impact resonate through the halls of aerospace engineering, promising a future where precision and efficiency harmoniously converge in the realm of aerospace machining.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest is to be disclosed.

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