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Evaluating the Influence of Eco-friendly Cryogenic Coolants on Hole Parameters in Deep Hole Drilling of Inconel 718 Alloy

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ABSTRACT

Deep hole drilling is a complex process, especially with heat-generating high-strength alloys like Inconel 718. Key challenges include heat management and effective chip removal to preserve tool life, hole accuracy, and surface finish. This method is ideal for applications like gun barrels, fuel lines, lubricant channels, and aircraft components. While cutting fluids cool and lubricate, they can cause health issues. Cryogenic coolants offer an eco-friendly, safer alternative that enhances machining performance. This study constitutes an experimental investigation of deep-hole drilling processes performed on a GUNDRILL CNC machine. The primary objective is to establish a comprehensive understanding of the interplay between cutting speed, feed rate, and various coolants concerning key performance indicators, including surface roughness, hole wall temperature, hole quality, material removal rate and tool wear. The coolants considered in this study encompass traditional cutting oil, cryogenic liquid nitrogen (LN_2), and carbon dioxide (CO_2) in cryogenic form. The use of cryogenic LN_2 coolant during Inconel 718 machining led to a significant reduction in hole wall temperature compared to wet and cryogenic CO_2 deep-hole drilling. This was due to the low temperature of LN_2, which allowed efficient heat dissipation from the contact zone. LN_2 also improved surface roughness by 29-55% compared to traditional oil coolant and 22-39% compared to cryogenic CO_2 cooling. Additionally, cryogenic LN_2 cooling decreased circularity error by 12-22% compared to oil coolant and 8-21% compared to cryogenic CO_2 conditions. The cryogenic LN_2 coolant enhanced chip breakability and extended tool life without damaging the cutting-edge insert.

Keywords: Cryogenic coolants; Inconel 718; Deep hole drilling; Tool wear; Surface roughness; Chip morphology.

1. INTRODUCTION

Deep-hole drilling is a specialized machining process known for its capacity to achieve high metal removal rates, precision in hole straightness, dimensional tolerances, and quality of the machined surface (Zhu *et al.* 2021; Guba *et al.* 2022). The benefits of deep-hole drilling make it ideal for precision applications such as gun barrels, fuel injector lines, lubricant channels in gears and crankshafts, and critical aircraft components like landing gear, where accuracy, straightness, and surface quality are essential. Deep-hole drilling refers to the machining process where the depth of the hole is at least ten times greater than its diameter (Rizzo *et al.* 2020). In the context of small-diameter deep-hole drilling, the challenges are augmented, introducing an additional parameter: that of hole depth. A prominent challenge within the domain of deep-hole drilling pertains to the effective application of coolant or lubricant at the tool tip and workpiece interface. This application is progressively constrained as a consequence of the accumulating swarf generated during the cutting process. Deep-hole drilling operations frequently encounter variations in workpiece material composition, leading to fluctuations in mechanical properties. Additionally, geometric complexities such as cross holes may be incorporated into the workpiece design. These factors can contribute to the risk of catastrophic tool failure and potential damage or even scrapping of the workpiece being machined (Oezkaya *et al.* 2021).

Cutting fluid is a crucial process parameter in machining processes, enhancing economic viability by cooling and lubricating cutting edges. It is primarily incorporated with chemically active extreme-pressure additives and polar effective substances to reduce wear and friction. The fluid also serves the crucial role of evacuating the swarf from the cutting zone when delivered under high pressure. This requires a meticulously engineered fluid circuit with a recirculation

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rate of no more than 6 lph and products with low foam and minimal oil-mist generation (Oezkaya *et al.* 2023). Traditional coolant solutions pose substantial health and environmental risks to individuals. Those exposed to these cutting coolants may suffer from skin diseases, inhalation of mists or vapours, and, in severe cases, inadvertent ingestion of mist particles from these fluids. The inherent toxicity within cutting fluids can lead to a range of health issues, encompassing dermatitis, respiratory ailments, digestive system complications, and, in extreme instances, the development of cancer. Moreover, improper disposal of these cutting fluids can trigger serious environmental challenges, including water pollution and soil contamination. The persisting problems associated with conventional cooling systems have underscored the pressing need for environmentally friendly coolants within the manufacturing industry (Elanchezhian *et al.* 2015; Trung *et al.* 2021). Consequently, the exploration of liquid nitrogen as a cryogenic coolant has been underway since the 1950s within the metal cutting industry (Bejjani *et al.* 2021).

Cryogenic cooling, high-pressure cooling (HPC), and minimum quantity lubrication (MQL) are methods used in machining superalloys like Inconel 718. LN_2 offers exceptional cooling due to its ultra-low temperature, reducing tool wear and improving surface finish. CO_2 is cost-effective for moderate operations, offering good heat dissipation and surface quality. HPC evacuates chips during deep-hole drilling but has high energy demands and setup costs. MQL is energy-efficient but lacks sufficient cooling capacity for high-speed or heat-resistant material machining. Cryogenic cooling offers superior machining outcomes and sustainability, while HPC and MQL are suitable for low-cost operations. Cryogenic cooling, particularly in the context of machining high-temperature aerospace alloys, is strongly recommended not only for the enhancement of machining performance metrics like surface roughness, tool lifespan, and cutting forces but also for a substantial improvement in the performance of machined components (Jebaraj *et al.* 2020). Research on the impact of cryogenic cooling in deep drilling operations is relatively scarce. This scarcity primarily arises due to the challenges associated with accessing the cutting tool and implementing modifications in drilling and milling, as opposed to turning, where tool modifications or the application of an external nozzle to the cutting zone are more feasible (Xu *et al.* 2021). The Taguchi method was used to investigate the roundness of holes in BTA deep-hole drilling, analyze process parameters and predict optimal settings. The feed rate was found to be the most influential process variable affecting hole roundness, highlighting the importance of statistical techniques in this study (Bronis *et al.* 2022). The machinability and characteristics of deep-hole drilling in high-temperature alloy 718 were assessed using tools composed of varying raw materials and featuring different angles. The study delved into the morphologies of drilling chips, tool damage, chip formation mechanisms, and the identification of wear and tool breakage. It was determined that tool wear primarily manifests as adhesive and abrasive wear, and the desirable chip morphology corresponds to a short conical spiral shape. Additionally, the research observed that optimizing tool angles and drilling parameters could effectively address wear and tool breakage issues, leveraging the production of short spiral chips during the drilling process (Liu *et al.* 2023). A Computational Fluid Dynamics (CFD) analysis study has determined that the optimization of gun drill designs can significantly enhance tool longevity. The efficacy of coolant application is contingent upon factors such as the nose grind contour, coolant hole arrangement, and shoulder dub-off angle of the drills. Employing a kidney-shaped coolant hole configuration effectively mitigates hydraulic pressure loss across the rake face. Maintaining a minimal shoulder dub-off angle is imperative to ensure efficient pressure transmission. The most proficient gun drill design for Inconel 718 drilling operations encompasses N4 nose grind geometries, a kidney-shaped coolant hole configuration, and a 0° shoulder dub-off. Nonetheless, it's important to note that the tool shaft's length reduction compromises its stiffness, rendering it susceptible to deflection, potentially jeopardizing the quality of machined holes and overall performance (Aamir *et al.* 2021; Kočiško *et al.* 2023). These variations in quality manifest in response to varying deep-hole drilling conditions, often necessitating adjustments to machining parameters in pursuit of high-quality holes (Kumar *et al.* 2020; Boughdiri *et al.* 2021).

Post-machining analysis of the BTA deep-hole drilling process, involving an assessment of the drilled hole's surface finish and roundness, serves as a means to gain insights into the cutting process and aids in the identification of optimal cutting conditions (Yu *et al.* 2017). Consequently, the determination of suitable machining conditions to achieve optimized machining quality becomes imperative. Furthermore, it is essential to monitor and replace the worn tip of the gun drill to ensure the attainment of high-quality holes, as wear adversely impacts the surface integrity of the drilled hole (Han *et al.* 2020; Felinks *et al.* 2021). This study evaluates the effectiveness of oil coolant fluid and cryogenic coolant in chip evacuation from drilled holes. The main objective is to characterize the BTA deep-hole drilling process after cutting, using qualitative and quantitative analyses. The research includes an experimental procedure involving Inconel 718 work material, a drilling machine, a BTA drilling tool, and drilling tests. The study aims to improve chip removal efficiency in the drilling process.

2. EXPERIMENTAL DETAILS

The experimental setup employed a gun drilling machine, specifically a single-axis CNC machine equipped with a three-jaw chuck for workpiece clamping, as depicted in Figure 1. In this configuration, the workpiece remained stationary while the gun drill rotated in conjunction with the spindle, driven by a motor equipped with two distinct pulleys. These pulleys facilitated the adjustment of rotational speeds within the range of 1000 to 4500 rpm. The gun drilling tool utilized in the drilling process was a single-fluted gun drill featuring a brazed carbide head with dimensions of ϕ 10 mm (h5) × 300 mm in overall length (OAL). The carbide grade employed was K15, uncoated, and it was paired with a ZH16-03 driver measuring ϕ 16 × 45/53 mm. The workpiece, composed of Inconel 718, featured dimensions of ϕ 25×160 mm. For each machining parameter, the workpiece underwent drilling to a depth of 120 mm. To facilitate the tool's entry into the workpiece, a pilot hole was initially drilled. During the initial engagement, it was observed that the drill occasionally slipped randomly over the entrance face, a phenomenon commonly referred to as the 'walking phenomenon,' leading to the undesired enlargement of the entrance hole diameter, resulting in what is known as 'bell-mouth formation.' This issue arose when the provided tolerance was insufficient, causing drills to be excessively constrained and frequently resulting in catastrophic failures upon engagement (Pollák *et al.* 2022).

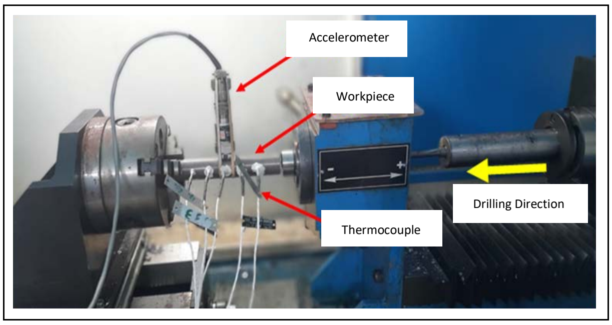
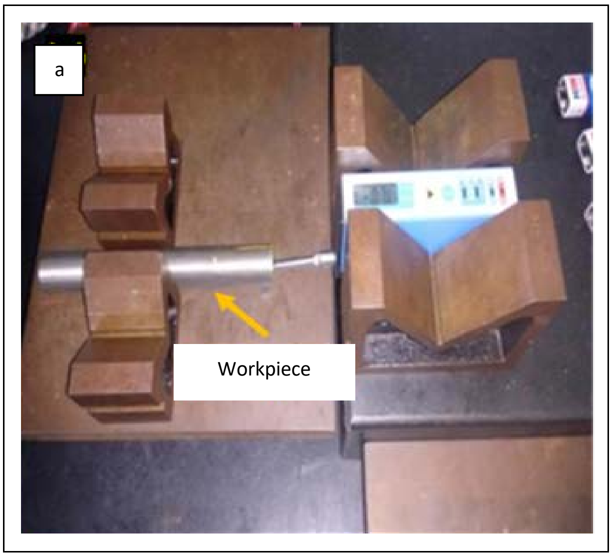


Fig. 1: Deep hole drilling apparatus GUNDRILL 1000 CNC



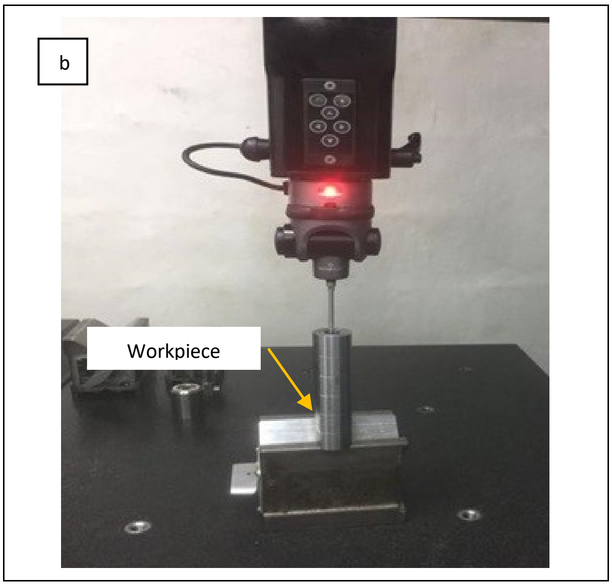


Fig. 2: (a) Surface roughness tester, Surfcorder SE1200 (b) CMM setup for measuring deep hole parameters

A thorough investigation was conducted to find possible influences on tool wear, surface roughness, hole roundness, and cylindricity during the gun drilling process (Chu *et al.* 2020; Soori *et al.* 2023). Cutting speed, feed rate, and coolant type were identified as the key control parameters in this study. The selected control parameters levels are shown in Table 1.

Table 1. Deep hole drilling control parameters and levels

Control factors	Levels
Cutting speed (m/min)	40, 50, 60
Feed rate (mm/rev)	0.02, 0.05, 0.09
Coolant type	Cutting oil, Cryogenic LN_2, Cryogenic CO_2

To ensure consistency, other factors influencing hole quality, such as workpiece material, tool geometry, and the stability of the gun drilling system, were kept constant throughout the experiments. The tests utilized cryogenic fluids (LN_2 and CO_2) as well as oil as coolants. Control factor levels were determined based on the recommended guide values for the tool, which was a type 110 carbide-tipped gun drill with a single flute. A Kosaka Laboratory Ltd (Surfcorder) instrument with a vertical measuring range of 520 m, a horizontal measuring range of 25 mm, a vertical resolution of 0.008 m, and a 0.8 mm cut-off value was used to measure surface roughness after the machining process (Fig. 2a), and a coordinate measuring machine was used to measure the circularity and cylindricity of the drilled hole (Fig. 2b).

3. RESULTS AND DISCUSSIONS

An experimental work was performed on deephole drilling with Inconel 718 material in three different cooling environments: conventional, cryogenic

LN2, and CO2 coolants. The results from experiments including surface roughness (Ra), circularity error, cylindricity, hole wall temperature, tool wear, surface modification, and chip morphology were compared to those from wet machining.

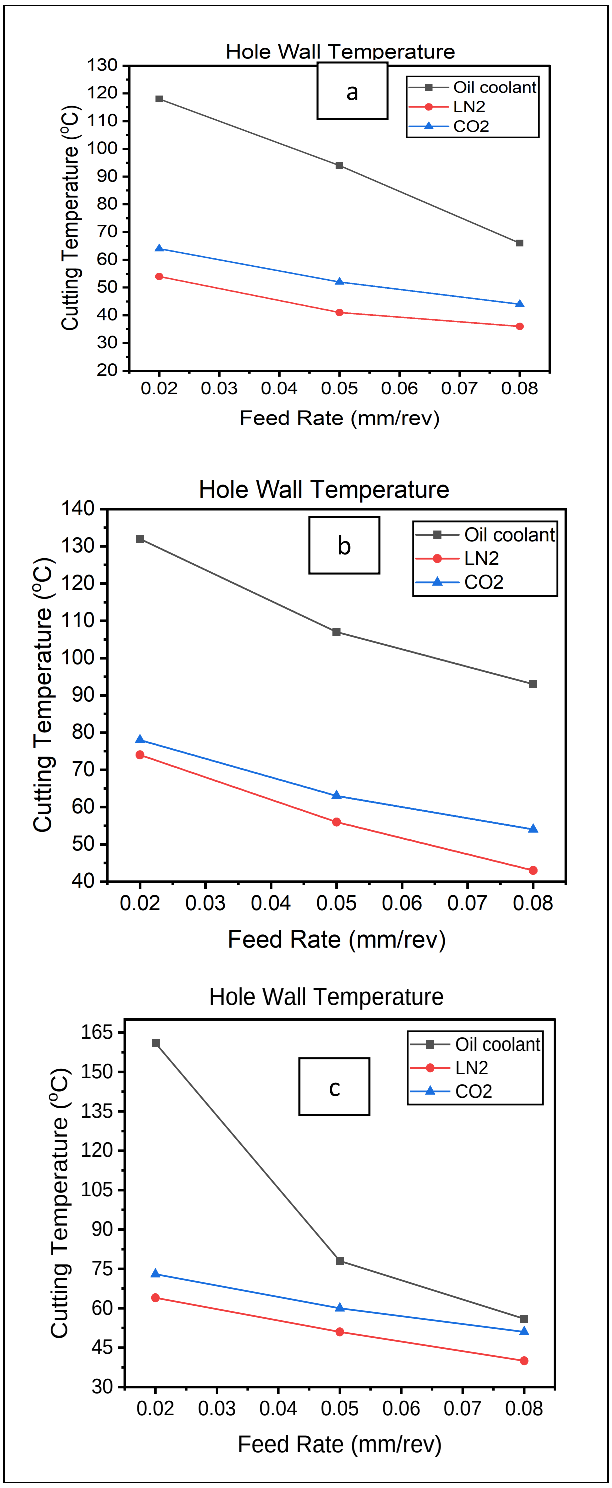


Fig. 3: Hole wall temperature variations in deep hole drilling processes under wet Oil coolant, LN2, and CO2 machining conditions at various feed rates for cutting speed (a) 40 m/min (b) 50 m/min (c) 2389 60 m/min

3.1 Effect of Hole Wall Temperature

The influence of cutting temperature on the feed rate and cutting speed in the deep-hole drilling of Inconel 718 alloy under both wet and cryogenic cooling conditions is graphically presented in Fig. 3 (a – c). As the cutting speed increases, the hole wall temperature rises proportionally under both wet and cryogenic cooling (LN_2 and CO_2 conditions). Cryogenic LN_2 cooling exhibited a notable reduction of 17.98% in cutting temperature compared to wet cooling. This reduction also led to a 9.63% decrease in CO_2 emissions. Specifically, when the feed rate was elevated to 0.2 mm/rev at a slower cutting speed, the cutting temperature for cryogenic LN_2 and wet cooling was 33.25 °C and 26.06 °C, respectively, representing a substantial 22.29% reduction in cutting temperature due to cryogenic LN_2 cooling. Cutting temperatures for wet and cryogenic LN_2 cooling were 37.68 °C and 27.08 °C, respectively, with an increased feed rate of 0.3 mm/rev and a slower cutting speed. This indicates a remarkable 28.13% drop in cutting temperature using cryogenic LN_2 cooling compared to wet cooling.

For various combinations of cutting speed and feed rate, the reported decrease in cutting temperature varied from 17.98% to 28.13% under cryogenic LN_2 cooling in comparison to wet cooling. When cryogenic LN_2 was applied at an atmospheric pressure of 4 bar, it rapidly absorbed and dissipated the generated heat in the coolant medium. Moreover, the liquid nitrogen reached the machining area, resulting in a notable reduction in hole wall temperature at the workpiece-tool interface. The low-temperature properties of LN_2 and CO_2 enhance heat dissipation during machining, effectively lowering hole wall temperatures even at higher cutting speeds and feed rates. This study demonstrates the novelty of comparing these two cryogenic coolants under varying machining conditions, providing insights into their distinct cooling mechanisms and their impact on machining performance. By reducing heat generation and improving thermal management, this approach showcases a sustainable and efficient alternative to traditional cooling methods. The implementation of cryogenic LN_2 and CO_2 cooling in this study led to a substantial reduction of hole wall temperature by 14.69%–30.88% compared to wet cooling. The significant reduction in hole wall temperature also minimizes thermal expansion, preserving dimensional accuracy and improving hole quality. These results underscore the capacity of cryogenic LN_2 and CO_2 coolants in vapor form to enhance lubrication within the cutting zone.

3.2 Effect of Surface Roughness (Ra)

Deep-hole drilling employs a combined cutting and rubbing motion to generate a machined surface. The finish components associated with cutting are predominantly influenced by the feed rates per revolution, while those related to rubbing are affected by factors such as margin design, land width, and the material's plastic response, including hardness and ductility.

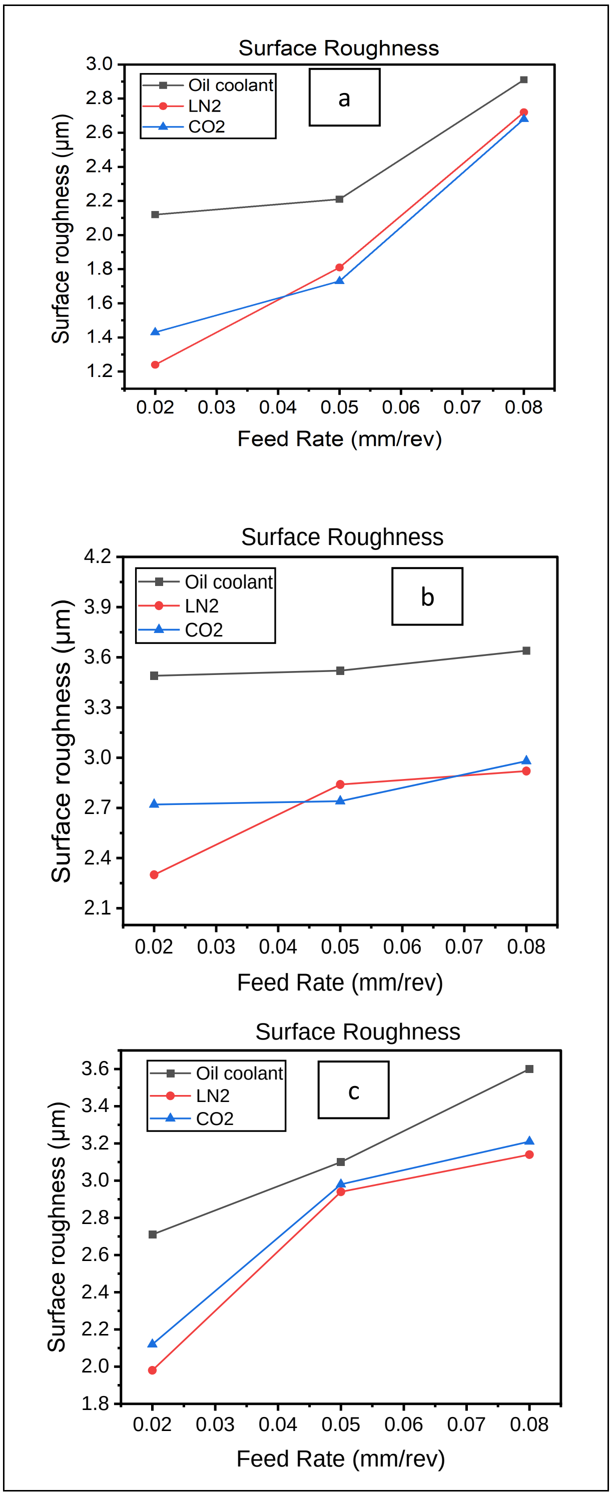


Fig. 4: Surface roughness variations in deep hole drilling processes under wet, LN2, and CO2 machining environments at various feed rates for cutting speed (a) 40 m/min (b) 50 m/min (c) 2389 60 m/min

Traditionally, deep hole drilling has been considered a roughing operation, with limited research conducted on evaluating surface roughness as an indicator of process consistency. Surface roughness is an important factor in metal cutting operations, acting as an important measure for evaluating surface quality and having a significant impact on production costs. Figure 4 illustrates a comparison of surface roughness concerning feed rate and cutting speed when employing wet, cryogenic LN_2 and CO_2 coolants (a – c).

The average surface roughness exhibited a reduction from 2.68 µm to 1.021 µm when the cutting speed was set at 40 m/min and the feed rate at 0.02 mm/rev. This signifies a 42.68% decrease in surface roughness attributed to the use of LN_2 coolant compared to wet coolant and a 27.36% reduction when compared to CO_2 coolant. An alteration in the feed rate from 0.02 to 0.05 mm/rev while maintaining the same cutting speed resulted in a 17.12% decrease in surface roughness when LN_2 coolant was employed. Similarly, a 5.36% reduction in surface roughness was observed when the feed rate was increased from 0.05 to 0.08 mm/rev with constant cutting speed, thanks to the implementation of cryogenic LN_2 coolant. Figure 4.4(b) visually depicts how cryogenic LN2 coolant contributed to reducing surface roughness by a range of 15.12% to 50.77% as the cutting speed was raised from 40 m/min to 50 m/min across three distinct feed rates. Furthermore, the application of cryogenic LN_2 coolant, as compared to wet coolant, resulted in a surface roughness reduction ranging from 13.05% to 24.81% at a cutting speed of 60 m/min, encompassing all three feed rates, as depicted in Fig. 5(c). The results revealed that using cryogenic LN_2 and CO_2 coolants reduced the surface roughness by 4.36 to 51.67% and 8.27 to 30.72%. The superior heat dissipation, minimized built-up edge, improved chip evacuation, and reduced tool wear collectively contribute to LN2 improving surface finish, especially at lower feed rates. At higher feed rates, both LN2 and CO2 outperform oil coolant due to their ability to handle the increased thermal loads effectively, ensuring consistent machining performance and smoother surface finishes. Compared to wet coolants, cryogenic coolants reduce the surface roughness of drilled holes. Cryogenic cooling, particularly with LN_2 and CO_2, influences the machining process through its superior thermal management capabilities. Surface roughness improves under cryogenic cooling due to the rapid heat dissipation, which prevents thermal softening of the workpiece material and reduces built-up edge (BUE) formation. The improved tool life and reduced manufacturing costs were directly correlated with the improved surface roughness in cryogenic LN_2 cooling. In contrast to the cryogenic LN_2 coolant, the wet coolant may worsen the surface roughness. As a consequence of decreased tool wear and increased productivity from the use of cryogenic LN_2 and CO_2 coolants, improvements in the high-quality surface finish may be noted.

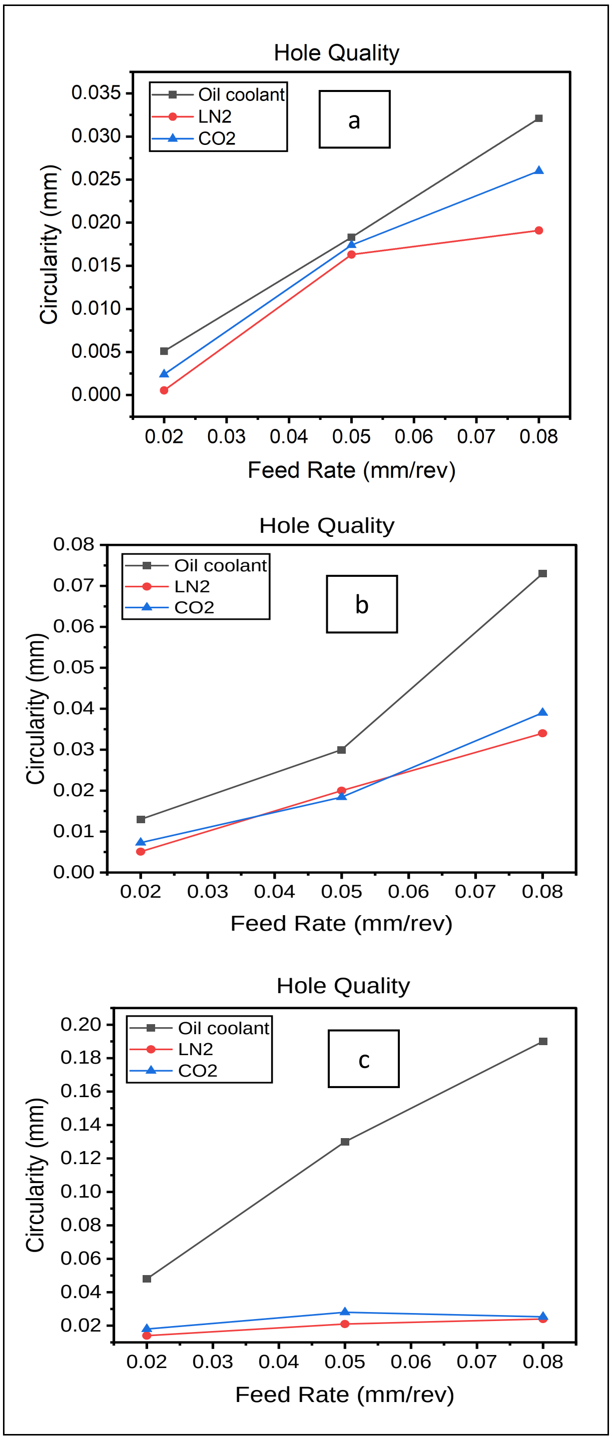


Fig. 5: Hole quality variations in deep hole drilling processes under wet, LN2, and CO2 machining environments at various feed rates for cutting speed (a) 40 m/min (b) 50 m/min (c) 2389 60 m/min

3.3 Effect of Hole Quality

Figure 5(a-c) visually shows the circularity fluctuations related to cryogenic liquid nitrogen (LN_2) cooling, carbon dioxide (CO_2) cooling, and wet cooling. Improvements in hole quality parameters were connected with observed increases in cutting speed and feed rate over a range of coolant conditions. As cutting speeds were uniformly adjusted at 10 m/min for all feed rates, circularity values under cryogenic LN_2 cooling showed an incremental range of 45.86% to 90.02% as compared to wet cooling. Similar to this, applying cryogenic LN_2 cooling led to improvements in circularity values ranging from 17.80% to 89.21% while maintaining a consistent cutting speed of 20 m/min for all feed rates. Cryogenic LN_2 cooling produced circularity gains ranging from 6.78% to 91.96% in compared to wet cooling at a greater cutting speed of 30 m/min across all feed rates. It is noteworthy that wet cooling consistently generated lower circularity values than cryogenic LN_2 and CO_2 cooling across all cutting parameters. In terms of hole quality with minimal variance, wet cooling was identified as a more effective cooling method than cryogenic LN_2 cooling. However, it is important to acknowledge that cryogenic LN_2 cooling exhibited deteriorations in hole surface quality, which were attributed to wobbling effects.

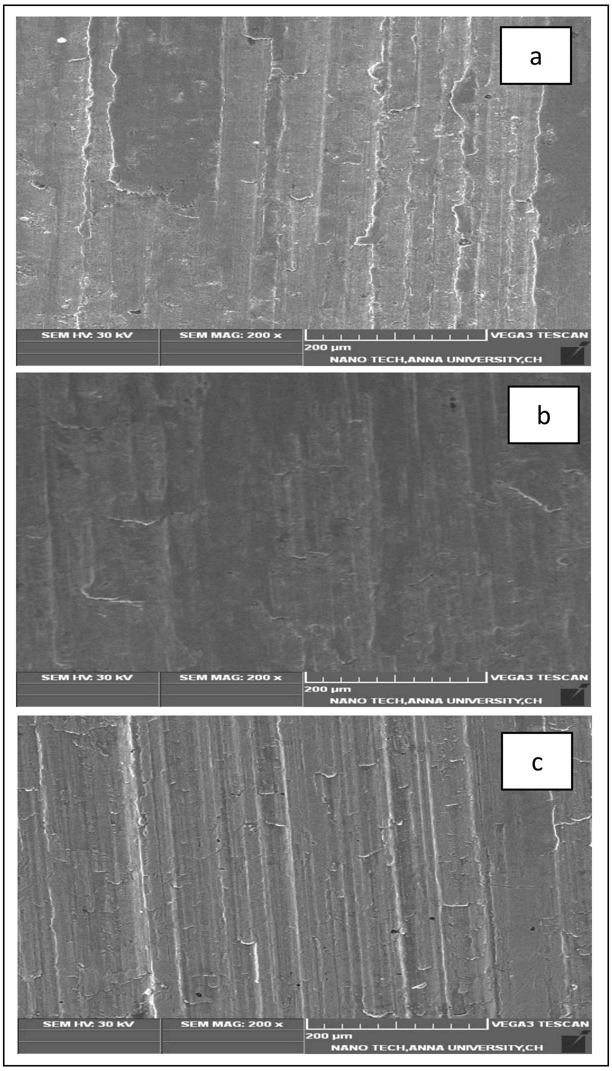


Fig. 6: SEM images showing the hole's cross section drilled at a feed rate of 0.08 mm/rev with a cutting speed of 60 m/min (a) Wet oil coolant (b) LN_2 coolant (c) CO_2 coolant

3.4 Effect of Surface Morphology

Wet coolant application has a negative influence on the quality of drilled holes by increasing surface roughness when cryogenic liquids like liquid nitrogen (LN_2) and carbon dioxide (CO_2) are present. This is mostly caused by material redeposition and feed band development during the wet chilling process. The Scanning Electron Microscope (SEM) pictures of the drilled holes in Figure 6 provide a visual representation of this occurrence. One of the factors contributing to the greater surface roughness values under wet cooling is chip drag across the surface of the wall. Wet cooling cannot be compared with the benefits and superiority of cryogenic LN_2 and CO_2 cooling.

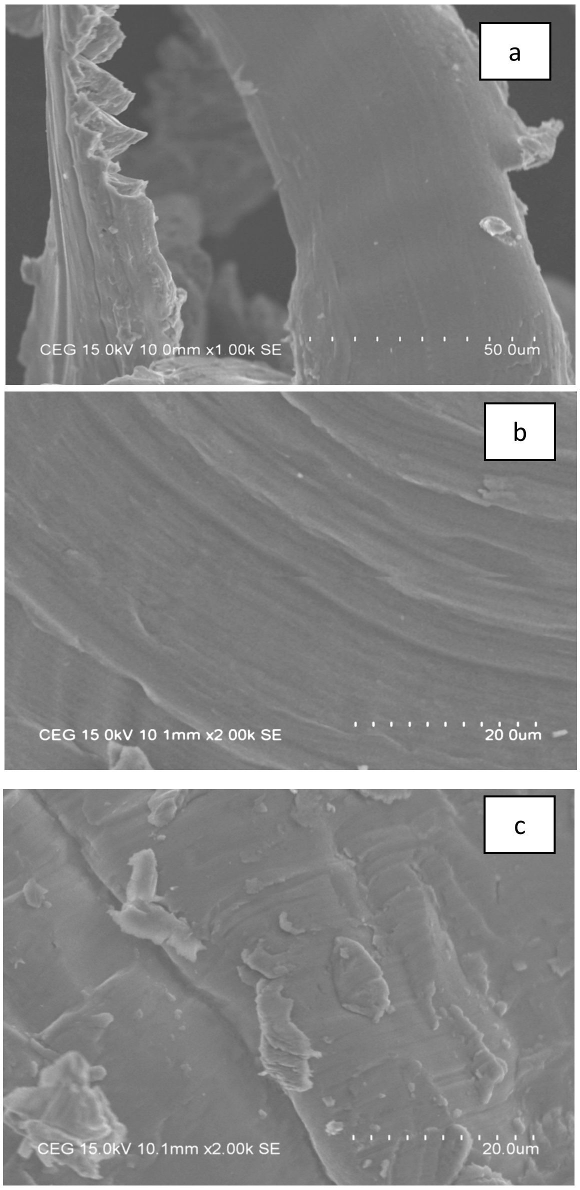


Fig. 7: SEM images of the chip cross section at cutting speed 60 m/min and feed - 0.08 mm/rev (a) wet oil coolant (b) LN_2 (c) CO_2

3.5 Effect of Chip Morphology

Figure 7(a-c) displays the chip samples obtained during deep hole drilling Inconel 718 using various speed-feed configurations while using wet machining and cryogenic coolants. In wet machining, the chip's outer surface has rough serration, indicating an intense shearing action at the cutting zone interface. The surface was uneven on both sides and contained some holes or cavities. In both cutting situations, the upper surface of the chip was rough with few stops or corrugations. The chip is lengthy and continuous, and from time to time, it cracks, causing the outside border to split into a number of pieces. For all cutting conditions, there were fewer metal particles on the chip surface under cryogenic LN_2 and CO_2 cooling conditions. In addition, it has a narrower width and a regular segmented structure.

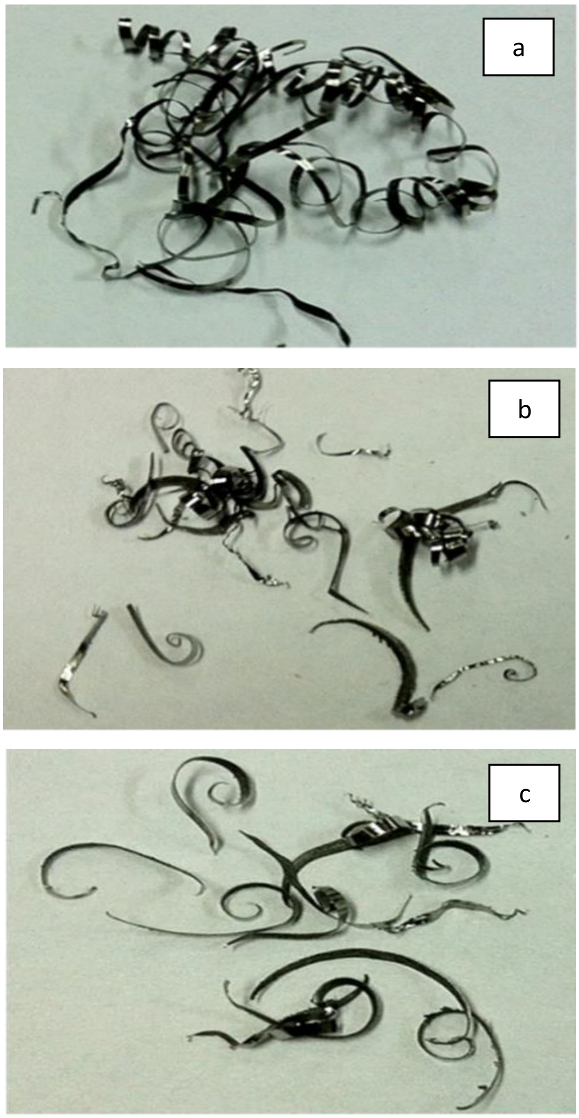


Fig. 8: Optical images of the chip breakage at a cutting speed of 60 m/min and feed 0.08 mm/rev (a) wet oil coolant (b) LN_2 coolant (c) CO_2 coolant

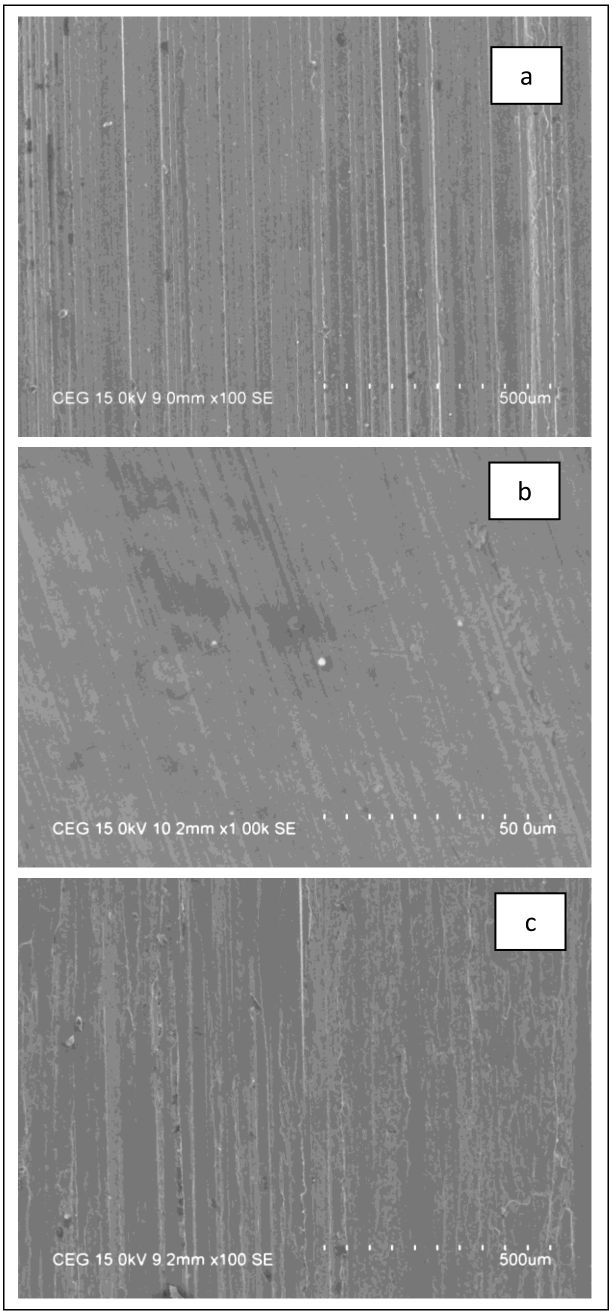


Fig. 9: Microstructure of the hole surface after machining with (a) Wet oil coolant (b) LN_2 coolant (c) CO_2 coolant

The chip exhibits a smooth edge and surface; however, it does exhibit a slight serration. The segments were closely spaced. The research outcomes reveal that extended chips feature a higher density of grain boundaries and minimal particle residue along their edges, as visually presented in Figure 8. This observed phenomenon can be attributed to the increased hardness of the tool insert induced by the application of cryogenic coolants. A reduction in particle remains on the chip's surface as a result of increased tool insert hardness indicates the preservation of the chip's cutting edge. Additionally, the performance of breaking chips is improved when cryogenic liquid nitrogen (LN_2) in vapor form is used. Regarding chip breakability, cryogenic cooling rapidly cools the chips, leading to embrittlement and fragmentation. This facilitates easier chip evacuation, reducing the chances of chip dragging or scratching the hole surface, a common issue observed with traditional oil coolants. Unlike wet cooling methods, which only lubricate the surface, cryogenic coolants effectively reduce cutting zone temperatures, enhancing tool life and maintaining consistent cutting-edge geometry. This improvement is attributed to its enhanced penetration of the chip-tool interface region, effectively reducing friction.

3.6 Microstructure of the Hole Surface

The microstructure of the reamed surface is depicted in Figure 9. It exhibits an identical grain size under both wet and cryogenic coolant environments, utilizing liquid nitrogen (LN_2) and carbon dioxide (CO_2), respectively. However, the grain size is observed to be smaller than that of the bulk material. In the context of deep-hole drilling, an escalation in the feed rate results in an elevation of cutting temperature, whether wet or cryogenic coolant is employed. A comparative analysis between wet and cryogenic cooling (LN_2 and CO_2) reveals no significant alterations in the microstructural characteristics.

4. CONCLUSION

The effect of cryogenic cooling with LN_2 and CO_2 as the cutting coolant was studied and compared with conventional oil machining in terms of hole wall temperature, surface roughness, hole quality, chip morphology, surface morphology, and microstructure. Cryogenic cooling, particularly with liquid nitrogen (LN_2), offers significant environmental benefits compared to traditional wet cooling methods. Unlike oil-based coolants, LN_2 evaporates into nitrogen gas, which constitutes 78% of Earth's atmosphere, leaving no hazardous residue or waste. This eliminates the need for coolant disposal and reduces the risk of water and soil contamination. Additionally, cryogenic cooling minimizes the volume of coolant required, as it relies on evaporation rather than recirculation. This reduction in resource usage translates to lower environmental impact and operational costs, aligning well with sustainable and eco-friendly manufacturing practices. The major conclusions drawn from the experimental work are summarized below.

1. Cryogenic cooling using LN2 and CO2 as coolants is an environmentally friendly alternative method for reducing the hole wall temperature at various cutting speeds and feed rates.

2. Under the conditions of cryogenic cooling, elevated surface roughness was consistently

observed across a range of cutting speeds and feed rates. Notably, the surface roughness in the presence of cryogenic liquid nitrogen (LN_2) coolant exceeded that observed in the wet coolant environment. This discrepancy can be attributed to the phenomenon of chip dragging on the hole surface, which is more pronounced in the cryogenic cooling setting.

3. The hole quality was inferior under cryogenic LN_2 cooling conditions. The hole quality (circularity and cylindricity) values were higher for cryogenic LN_2 cooling than for wet cooling.

4. In the context of cryogenic cooling employing liquid nitrogen (LN_2) and carbon dioxide (CO_2), it was observed that chip breakability surpassed that achieved under wet cooling conditions.

5. As per the experimental findings, the utilization of cryogenic liquid nitrogen (LN_2) cooling demonstrates significant advantages in terms of lowering cutting temperatures, as well as enhancing surface roughness and hole quality. Small and uniform segment chips were produced by cryogenic LN_2 cooling at different speeds and feed combinations.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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