



Research Paper

A brief review on the cryogenic-assisted machining processes

Nguyen Phu Son

Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen, 250000, Vietnam
Corresponding author: Nguyen Phu Son

Abstract

This work provides a concise review of the influence of cryogenic environments on machining performance. It highlights significant experimental findings on the cooling effectiveness of cryogenic techniques and their impact on cutting efficiency. Furthermore, the study analyzes and discusses key cutting parameters that strongly affect process performance in turning, milling, and drilling, establishing a foundation for future research. It also identifies critical factor domains and existing research gaps to support the advancement and industrial implementation of cryogenic technologies. Finally, potential research directions are proposed to enhance cutting efficiency while mitigating environmental impacts.

Keywords: Cutting process, cutting parameter, cryogenic cooling, surface roughness, cutting temperature

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I. Introduction

Cryogenic-assisted machining is an advanced machining technology that uses extremely low-temperature fluids, primarily liquid nitrogen (LN₂) or cryogenic carbon dioxide (CO₂), to control the temperature in the cutting zone during precision machining [1]. In traditional cutting processes, most mechanical energy is converted into heat due to intense friction between the cutting tool, chip, and workpiece surface. This heat is concentrated locally in the contact area, causing rapid tool wear, surface hardening, reduced dimensional accuracy, and decreased surface quality. For difficult-to-machine materials such as titanium alloys, nickel-based superalloys, Inconel, or carbon fiber-based composites, cutting temperature issues become more serious due to the materials' low thermal conductivity and high thermal stability [2]. Cryogenic machining technology was developed to directly address these limitations by introducing a supercooled fluid into the cutting zone to absorb heat instantaneously and maintain a stable thermal state for the tool-workpiece system [3].

In principle, liquid nitrogen at approximately -196°C or deep-freeze CO₂ is channeled through specialized nozzles or integrated cooling channels within the cutting tool, then sprayed directly onto the front and back surfaces of the cutting edge. Upon contact with the high-temperature zone, the cryogenic medium evaporates rapidly and absorbs a large amount of heat through phase transition, thereby significantly reducing the cutting zone temperature [1]. This mechanism not only limits diffusion wear and oxidative wear of the tool but also reduces the formation of built-up edges and improves chip evacuation conditions. Furthermore, maintaining a low temperature contributes to stabilizing the microstructure of the surface layer after machining, limiting residual tensile stress and thermal deformation, thereby improving geometric quality and workpiece lifespan.

One of the outstanding advantages of cryogenic machining is its ability to significantly extend the lifespan of cutting tools. Numerous experimental studies have shown that tool life can increase by two to five times compared to dry machining or traditional coolant machining. Particularly in machining titanium and Inconel alloys used in the aerospace industry, cryogenic machining allows for increased cutting speeds while maintaining the thermal stability of the tool. At the same time, this technology also improves surface roughness, reduces surface burn, and limits cold hardening in the machined metal layer. From an environmental

perspective, cryogenic machining is also considered a green manufacturing solution because it significantly reduces the amount of cutting fluid used, limits industrial waste generation, and reduces the cost of coolant disposal after production [4].

However, despite its superior technical advantages, cryogenic processing technology also presents several challenges. Liquid nitrogen supply systems require insulated storage tanks, pressurization equipment, and specialized conduit systems, resulting in relatively high investment costs. Careful optimization of flow rate and injection location is necessary because excessively low temperatures can cause localized material embrittlement or increase the risk of thermal cracking in certain alloys. Furthermore, the operation process demands strict safety measures to prevent frostbite and reduce oxygen levels in the enclosed working environment. This article will present a brief review of existing research on the application of this technology to machining processes, highlighting the positive effects it offers. Furthermore, the review results will also identify remaining issues and areas requiring further research and development in the future.

II. Turning process under cryogenic condition

The turning process under cryogenic conditions involves the use of extremely low-temperature coolants—most commonly liquid nitrogen (LN₂) or liquid carbon dioxide (CO₂)—to enhance machining performance. Instead of conventional flood cooling or dry cutting, a cryogenic medium is directed toward the cutting zone (tool–chip interface and/or flank face), providing rapid heat removal and altering material behavior during machining. In cryogenic turning, the intense cooling effect significantly reduces cutting temperature, which is one of the primary factors influencing tool wear and surface integrity. Lower temperatures help maintain tool hardness, especially for carbide and coated tools, thereby prolonging tool life. Additionally, the reduction in thermal softening of the workpiece can lead to improved dimensional accuracy and surface finish. Another important aspect is the modification of chip formation. Cryogenic cooling tends to make chips more brittle, facilitating easier chip breakage and evacuation. This reduces the chances of built-up edge (BUE) formation and improves process stability. However, in some ductile materials, excessive cooling may increase cutting forces due to higher material strength at low temperatures. Cryogenic turning has shown notable advantages when machining difficult-to-cut materials such as titanium alloys (e.g., Ti-6Al-4V), nickel-based superalloys (e.g., Inconel 718), and hardened steels. These materials typically generate high cutting temperatures and tool wear under conventional conditions, making cryogenic assistance particularly beneficial. Despite its advantages, several challenges remain. The implementation cost, handling of cryogenic fluids, and optimization of delivery methods (nozzle design, flow rate, and direction) are critical factors. Moreover, improper application may lead to thermal shock or reduced machinability in certain cases. Sartori et al. [5] studied the temperature effects on the turning performance of Ti6Al4V under cooled gaseous nitrogen condition. The authors assessed the performance of an innovative cooling technique that employs gaseous nitrogen (N₂) chilled by liquid nitrogen (LN₂) across a temperature range from 0 °C to –150 °C. The approach was implemented in the semi-finishing turning process of the titanium alloy Ti6Al4V. A series of experiments was carried out to investigate the influence of temperature on the machinability of Ti6Al4V and to determine the optimal cooling condition in terms of tool wear and surface integrity. The results indicate that coolant temperature has a significant effect on machinability, with a threshold temperature below which no further improvements are observed compared to conventional wet and LN₂ cooling methods used as references. Among the tested conditions, N₂ cooled to –150 °C provided the best performance, leading to a notable reduction in both rake and flank wear, as well as enhanced surface quality. Additionally, an analytical model of the coolant's cooling capacity was developed to support and explain the experimental findings. Bagherzadeh and Budak [6] combined the CO₂ cryogenic method with minimum quantity lubrication (CMQL), delivered from the rake face, was compared with other cooling strategies, including CO₂ and MQL supplied separately from the rake and flank faces, as well as CO₂ applied alone from the rake face, during the turning of Ti6Al4V and Inconel 718. Tool wear, surface roughness, and temperature were measured to evaluate the cooling effectiveness of each method. Based on comprehensive experimental results, CMQL was identified as the most effective cooling approach, offering advantages in terms of environmental impact, reduced tool wear, improved surface quality, favorable chip formation, and lower cutting forces. Iturbe et al. [7] investigated the surface integrity in the turning process of Inconel 718 under conventional and cryogenic cooling conditions. The authors found out that the benefits of the cryogenic + MQL machining are evident in terms of surface microstructure when compared to conventional cooling condition.

III. Milling process under cryogenic condition

Cryogenic milling is an advanced machining approach and is an up-to-date research topic. Unlike conventional cooling methods, cryogenic cooling provides rapid and localized heat extraction, which is particularly important in milling due to its intermittent cutting nature. During milling, the cutting tool periodically engages and disengages with the workpiece, generating cyclic thermal loads. Cryogenic cooling

helps stabilize these temperature fluctuations by maintaining a lower average cutting temperature. This significantly reduces tool wear mechanisms such as abrasion, adhesion, and diffusion, thereby extending tool life, especially for coated carbide and ceramic tools. One of the key benefits of cryogenic milling is the improvement in surface integrity. The lower cutting temperature minimizes thermal damage, residual tensile stresses, and surface oxidation. As a result, better surface finish and enhanced fatigue performance of machined components can be achieved—an important requirement in aerospace and biomedical industries. Cryogenic conditions also influence chip formation and material behavior. The reduced temperature increases the brittleness of chips, promoting easier chip breakage and evacuation. However, similar to turning, the increased material strength at low temperatures may lead to higher cutting forces in some cases, requiring careful optimization of cutting parameters such as cutting speed, feed rate, and depth of cut. This technique is especially effective when machining difficult-to-cut materials such as titanium alloys, nickel-based superalloys, and hardened steels. In these applications, cryogenic cooling can outperform dry and minimum quantity lubrication (MQL) methods in terms of tool life and productivity. Ahmed et al. [8] investigated the cryogenic-assisted micro-milling process of aluminum (Al-7075) by using 4-flute micro-endmills ($\phi = 800 \mu\text{m}$) with a $5 \mu\text{m}$ thick layer of TiAl₆CrN protective coating. The authors aimed at suppressing burr formation during machining, thereby eliminating the need for post-processing and reducing overall production costs. In this approach, a liquid nitrogen (LN₂) jet is directed ahead of the tool path, inducing microstructural modification in the top surface layer of the workpiece. This alteration enhances the material's mechanical properties and reduces excessive plastic deformation during the cutting process. To validate this mechanism, micro-hardness measurements were conducted beneath the treated surface, confirming a significant increase in hardness due to the cryogenic effect. Experimental results demonstrate that the application of cryogenic treatment substantially reduces burr formation while improving overall machining performance, including lower cutting forces, more favorable chip morphology, and improved surface finish. Pereira et al. [9] proposed the novel cooling–lubrication system for milling Inconel 718. Two types of nozzle adapters, featuring different CO₂ outlet configurations, were designed and developed. During these tests, tool life was evaluated under various cooling–lubrication conditions, including dry machining, wet cooling, standalone CO₂, standalone MQL, and the combined CO₂ + MQL approach proposed in this study. The experimental results indicated that wet machining generally delivers superior performance among conventional approaches. However, a key objective is to reduce or eliminate the use of mineral oil emulsions in order to achieve a more sustainable and cost-effective process. In addition, the combined MQL + CO₂ technique emerges as the most promising alternative, achieving over 90% of the performance of wet machining while offering significantly improved environmental compatibility. Despite its advantages, challenges in cryogenic milling include the design of effective coolant delivery systems (e.g., through-tool vs. external nozzles), higher initial setup cost, and safety considerations when handling cryogenic fluids. Additionally, the intermittent nature of milling may cause thermal shock to the tool if cooling is not properly controlled.

IV. Drilling process under cryogenic condition

The cryogen is delivered either externally to the drill–workpiece interface or internally through the drill channels, which is especially effective for deep-hole drilling where heat accumulation and chip evacuation are critical challenges. A primary advantage of cryogenic drilling is its ability to significantly reduce cutting temperature in the tool–chip interface. This helps preserve tool hardness and coating integrity, thereby reducing wear mechanisms such as flank wear, crater wear, and adhesion. As a result, tool life is extended, particularly when drilling difficult-to-machine materials like titanium alloys, nickel-based superalloys, and stainless steels. Cryogenic cooling also enhances chip formation and evacuation. At low temperatures, chips tend to become more brittle and fragment more easily, reducing the risk of chip clogging inside the hole—a common issue in conventional drilling. Improved chip evacuation leads to better dimensional accuracy and hole quality, including reduced surface roughness and improved roundness. In addition, cryogenic conditions help improve the surface integrity of drilled holes. Lower temperatures minimize thermal damage, work hardening, and residual tensile stresses on the machined surface. This is particularly important for components used in aerospace, automotive, and biomedical applications, where fatigue performance and structural reliability are critical. Geng et al. [10] proposed an external cryogenic airflow-assisted electrochemical discharge drilling (ECDD) technique. They employed a glycol-based working fluid with ultra-low conductivity neutralizing salt, replacing highly conductive acidic solutions or spark oil, thereby enabling environmentally friendly machining without the formation of a recast layer. Furthermore, the incorporation of cryogenic gas into the glycol significantly suppresses stray corrosion and enhances surface quality compared to traditional ECDD methods. From a theoretical perspective, the effect of low-temperature conditions on the electrochemical interface was investigated using electrochemical analysis techniques. A multi-physic simulation model was also developed and subsequently validated through experimental results. Surface characteristics were further examined using transmission electron microscopy (TEM). The findings reveal that the cryogenic environment strengthens the

passivation effect, resulting in a 35% reduction in taper at 258 K and a 28.2% decrease in stray corrosion. The machined hole surface exhibits nanoscale roughness (R_a 0.512 μ m). More importantly, the material removal rate remains high at low temperatures, reaching 0.1 mm/s, which surpasses that of EDD. Since no additional post-processing is required, the authors concluded that the strong potential for achieving sustainable, efficient, and high-quality manufacturing can be achieved. Piche and his co-authors [11] used liquid and supercritical CO₂ as cryogenic coolant for machining with internally cooled drills. The effects of CO₂ mass flow rate, injection temperature, and the addition of lubricating oil on drilling performance in 1.4571 stainless steel were investigated. For an 8 mm drill, a CO₂ mass flow rate ranging from 0.3 g/s to 1.7 g/s combined with lubricant resulted in moderate drilling forces, the formation of small segmented chips, and a minimum borehole surface roughness of $S_a = 0.22 \mu$ m.

V. CONCLUSION

This paper presents a concise review of the effects of cryogenic cooling on the cutting performance of turning, milling, and drilling processes. Key studies and notable findings are summarized to evaluate the influence of cryogenic cooling on machining outcomes. Based on the analysis of experimental results, the critical process parameters that exert strong or weak effects on performance metrics are identified. In addition, existing research gaps are highlighted to provide a foundation for future investigations aimed at refining and advancing technological guidelines, particularly in hard turning. The review also indicates that several challenges remain, emphasizing the need for further research to enhance machining efficiency, with a particular focus on the development and implementation of environmentally friendly cooling technologies in manufacturing practice.

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References

- [1] N. Khanna, P. Shah, Chetan, Comparative analysis of dry, flood, MQL and cryogenic CO₂ techniques during the machining of 15-5-PH SS alloy, *Tribology Int.* 146 (2020) 106196, <https://doi.org/10.1016/j.triboint.2020.106196>.
- [2] S. Cordes, F. Hübner, T. Schaarschmidt, Next generation high performance cutting by use of carbon dioxide as cryogenics, *Procedia CIRP* 14 (2014) 401–405, <https://doi.org/10.1016/j.procir.2014.03.091>.
- [3] S. Yaqoob, J.A. Ghani, A.Z. Juri, S.S. Muhamad, C.H. Che Haron, N. Jouini. A review of sustainable hybrid lubrication (Cryo-MQL) techniques in machining processes, *Int. J. Adv. Manuf. Technol.* 131 (2024) 151–169, <https://doi.org/10.1007/s00170-024-13135-4>.
- [4] D. Gross, M. Bigelmaier, T. Meier, S. Amon, N. Ostrowicki, N. Hanenkamp. Investigation of the influence of lubricating oils on the turning of metallic materials with cryogenic minimum quantity lubrication, *Procedia CIRP* 80 (2019) 95–100, <https://doi.org/10.1016/j.procir.2019.01.005>.
- [5] S. Sartori, A. Ghiotti, S. Bruschi. Temperature effects on the Ti6Al4V machinability using cooled gaseous nitrogen in semi-finishing turning, *Journal of Manufacturing Processes*, 30, 2017, 187-194, <https://doi.org/10.1016/j.jmapro.2017.09.025>.
- [6] Amin Bagherzadeh, Erhan Budak, Investigation of machinability in turning of difficult-to-cut materials using a new cryogenic cooling approach, *Tribology International*, 119, 2018, 510-520, <https://doi.org/10.1016/j.triboint.2017.11.033>.
- [7] A. Iturbe, E. Hormaetxe, A. Garay, P.J. Arrazola, Surface Integrity Analysis when Machining Inconel 718 with Conventional and Cryogenic Cooling, *Procedia CIRP*, 45, 2016, 67-70, <https://doi.org/10.1016/j.procir.2016.02.095>.
- [8] Farooq Ahmed, Furqan Ahmad, S. Thirumalai Kumaran, Mohd Danish, Rendi Kurniawan, Saood Ali. Development of cryogenic assisted machining strategy to reduce the burr formation during micro-milling of ductile material, *Journal of Manufacturing Processes*, 85, 2023, 43-51, <https://doi.org/10.1016/j.jmapro.2022.11.036>.
- [9] O. Pereira, P. Català, A. Rodríguez, T. Ostra, J. Vivancos, A. Rivero, L.N. López-de-Lacalle, The Use of Hybrid CO₂+MQL in Machining Operations, *Procedia Engineering*, 132, 2015, 492-499, <https://doi.org/10.1016/j.proeng.2015.12.524>.
- [10] Tianyu Geng, Zhengyang Xu, Jiangwei Lu. A sustainable, high-quality method for machining film cooling holes: Cryogenic airflow-assisted electrochemical discharge drilling, *Journal of Cleaner Production*, 426, 2023, 139017, <https://doi.org/10.1016/j.jclepro.2023.139017>.
- [11] Nathalie Piche, Stefan Pollak, Marcus Petermann. Liquid and supercritical CO₂ as cryogenic coolant for machining with internally cooled drills, *The Journal of Supercritical Fluids*, 235, 2026, 107000, <https://doi.org/10.1016/j.supflu.2026.107000>.