

# **A novel approach of the cryogenic-assisted machining processes: A brief review**

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## **Abstract**

*This study presents a concise overview of the effects of cryogenic environments on machining performance. It emphasizes key experimental results regarding the cooling capability of cryogenic techniques and their influence on cutting efficiency. In addition, the work examines critical machining parameters that significantly impact performance in turning, milling, and drilling processes, thereby providing a basis for future investigations. It also identifies essential parameter domains and existing research gaps to facilitate the development and industrial adoption of cryogenic technologies. Finally, prospective research directions are suggested to improve cutting efficiency while reducing environmental impact.*

**Keywords:** *Metal cutting; difficult-to-cut materials; cryogenic cooling; cryogenic-assisted machining; cutting parameter; surface quality; cutting temperature*

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## **I. Introduction**

In the last decades, cryogenic-assisted machining is an advanced manufacturing technique that employs ultra-low-temperature media, most commonly liquid nitrogen (LN<sub>2</sub>) or cryogenic carbon dioxide (CO<sub>2</sub>), to regulate the temperature within the cutting zone during precision machining [1]. In conventional machining processes, a significant portion of mechanical energy is transformed into heat due to severe friction at the interfaces between the cutting tool, chip, and workpiece. This localized heat accumulation accelerates tool wear, induces surface hardening, reduces dimensional accuracy, and deteriorates surface finish quality. These challenges are further intensified when machining difficult-to-cut materials such as titanium alloys, nickel-based superalloys, Inconel, and carbon fiber-reinforced composites, owing to their low thermal conductivity and high thermal resistance [2]. To overcome these limitations, cryogenic machining has been developed as an effective solution, introducing super-cooled fluids directly into the cutting zone to rapidly dissipate heat and maintain a stable thermal environment for the tool-workpiece system [3]. In this technique, liquid nitrogen at approximately -196 °C or deeply cooled CO<sub>2</sub> is delivered through specialized nozzles or internal channels integrated within the cutting tool and directed onto both the rake and flank faces of the cutting edge. When the cryogenic medium contacts the high-temperature cutting zone, it rapidly vaporizes, absorbing a substantial amount of heat through phase transformation, which leads to a significant reduction in cutting temperature [1]. This cooling mechanism effectively suppresses diffusion and oxidation wear of the tool, while also minimizing built-up edge formation and enhancing chip evacuation. Moreover, maintaining a low thermal environment helps preserve the microstructural integrity of the machined surface, reduces residual tensile stresses and thermal distortion, and ultimately improves dimensional accuracy and extends the service life of the workpiece.

One of the most notable advantages of cryogenic-assisted machining is its ability to substantially extend the service life of cutting tools. Numerous experimental studies have reported that tool life can be increased by two to five times compared with dry or conventional flood cooling conditions. This benefit is particularly evident in the machining of titanium alloys and Inconel used in aerospace applications, where cryogenic cooling enables higher cutting speeds while preserving tool thermal stability. In addition, the technique enhances surface finish, reduces the risk of surface burn, and mitigates work hardening in the machined layer. From an environmental standpoint, cryogenic machining is regarded as a sustainable manufacturing approach, as it significantly decreases the reliance on conventional cutting fluids, minimizes industrial waste, and lowers the costs associated with coolant treatment and disposal after production [4]. Although it has notable technical advantages, cryogenic machining also presents several challenges. The implementation of liquid nitrogen systems requires insulated storage tanks, pressurization units, and specialized delivery channels, leading to relatively high initial investment costs. In addition, precise control of flow rate and injection position is essential, as excessively low temperatures may induce localized embrittlement or increase

the risk of thermal cracking in certain materials. The process also necessitates strict safety protocols to prevent frostbite and to mitigate oxygen depletion in enclosed working environments. This article provides a concise review of current research on the application of cryogenic technology in machining processes, emphasizing its beneficial effects. It also identifies existing limitations and highlights areas that require further investigation and development in the future.

## **II. Turning process under cryogenic condition**

There have been some studies on cryogenic-assisted turning and indicated the promising results. The turning process under cryogenic conditions utilizes ultra-low-temperature coolants—typically liquid nitrogen (LN<sub>2</sub>) or liquid carbon dioxide (CO<sub>2</sub>)—to enhance machining performance. Unlike conventional flood cooling or dry cutting, the cryogenic medium is directed precisely toward the cutting zone, particularly the tool–chip interface and flank face, enabling rapid heat extraction and influencing material behavior during cutting. This intense cooling effect significantly lowers the cutting temperature, a key factor governing tool wear and surface integrity. As a result, tool hardness—especially for carbide and coated tools—is better preserved, leading to extended tool life. Furthermore, reduced thermal softening of the workpiece contributes to improved dimensional accuracy and superior surface finish. Another important benefit lies in chip formation behavior. Under cryogenic conditions, chips tend to become more brittle, which promotes easier fragmentation and evacuation. This reduces the likelihood of built-up edge (BUE) formation and enhances overall process stability. However, in the case of highly ductile materials, excessive cooling may increase cutting forces due to elevated material strength at low temperatures. Cryogenic turning has demonstrated significant 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 excessive heat and rapid tool wear under conventional machining conditions, making cryogenic assistance particularly effective. Despite these benefits, several challenges remain. High implementation costs, the complexity of handling cryogenic fluids, and the need to optimize delivery parameters—such as nozzle design, flow rate, and injection direction—are critical considerations. Additionally, improper application may result in thermal shock or reduced machinability in certain situations. Llanos and his co-authors [5] studied the hard turning performance of AISI 52100 under cryogenic CO<sub>2</sub> condition. The authors found out that a more stable and localized cooling of the cutting zone is achieved compared to direct delivery systems reported in the literature. This approach is subsequently applied in hard turning experiments on hardened AISI 52100 bearing steel, where tool wear and surface integrity are evaluated against dry air blow and conventional cooling conditions. The results indicate that cryogenic cooling outperforms both conventional and dry cutting methods, particularly in semi-finishing operations at elevated cutting speeds, leading to improved tool performance and enhanced surface quality. Jadhav et al. [6] investigated the performance of the cryogenic-assisted turning process of Nimonic C-263 alloy. In their study, the application of finite element modeling (FEM) to simulate machining processes remains a highly debated topic. Both numerical and experimental approaches are employed to investigate the cryogenic turning of Nimonic C-263 superalloy, with the aim of evaluating the influence of process parameters on machining responses and overall machining quality. Numerical simulations are conducted using LS-DYNA software, and the results are validated against experimental data. The authors concluded that increasing cryogenic temperature and soaking time leads to higher cutting forces and cutting temperatures. The maximum values of these responses are observed at higher cutting speeds, feed rates, and depths of cut, particularly under conditions of low temperature and short soaking time. Notably, the simulation results show strong agreement with the experimental data, with minimum deviations of approximately 5.77% for cutting force and 7.71% for cutting temperature. These results demonstrate that the developed three-dimensional FEM model is both effective and reliable for predicting machining performance with a relatively low margin of error. Bagherzadeh and Budak [7] investigated a hybrid cooling strategy by combining CO<sub>2</sub>-based cryogenic cooling with minimum quantity lubrication (CMQL), delivered through the rake face, and compared it with other approaches. These included the separate application of CO<sub>2</sub> and MQL from the rake and flank faces, as well as the use of CO<sub>2</sub> alone applied from the rake face, during the turning of Ti-6Al-4V and Inconel 718 alloys. Tool wear, surface roughness, and cutting temperature were evaluated to assess the effectiveness of each cooling method. The experimental results demonstrated that CMQL is the most efficient approach, providing superior performance in terms of reduced tool wear, improved surface finish, enhanced chip formation, and lower cutting forces, while also offering environmental benefits.

## **III. Milling process under cryogenic condition**

Cryogenic milling is a modern and rapidly evolving machining technique that has attracted significant research interest. Unlike conventional cooling strategies, cryogenic cooling enables rapid and localized heat removal, which is particularly advantageous in milling due to its inherently intermittent cutting process. As the cutting tool repeatedly engages and disengages with the workpiece, cyclic thermal loads are generated. Cryogenic cooling effectively stabilizes these fluctuations by maintaining a lower average cutting temperature,

thereby reducing thermal shock and enhancing process stability. This substantial reduction in temperature mitigates dominant tool wear mechanisms such as abrasion, adhesion, and diffusion, leading to a marked extension of tool life—especially for coated carbide and ceramic tools. In addition, cryogenic milling significantly improves surface integrity. Lower cutting temperatures help minimize thermal damage, residual tensile stresses, and surface oxidation, resulting in improved surface finish and enhanced fatigue resistance of machined components. These benefits are particularly critical in high-performance industries such as aerospace and biomedical engineering. Cryogenic conditions also affect chip formation and material behavior. Reduced temperatures increase chip brittleness, facilitating easier fragmentation and evacuation. However, similar to cryogenic turning, the increased material strength at low temperatures may lead to higher cutting forces under certain conditions, necessitating careful optimization of machining parameters, including cutting speed, feed rate, and depth of cut. Many studies indicated that cryogenic milling is especially effective for machining difficult-to-cut materials such as titanium alloys, nickel-based superalloys, and hardened steels. In such applications, it often outperforms dry machining and minimum quantity lubrication (MQL) in terms of tool life, surface quality, and overall productivity. Xu et al. [8] studied the machinability efficiency of cryogenic-ultrasonic vibration-assisted milling Inconel 718 alloy. From the experimental results, the cryogenic assistance can significantly enhance the machining environment by reducing the coefficient of friction (CoF) and improving surface integrity. However, an increase in cutting force is observed under cryogenic cooling machining (CCM), primarily due to the low-temperature-induced brittleness of Inconel 718. This drawback can be effectively mitigated by incorporating ultrasonic vibration, as demonstrated in cryogenic ultrasonic vibration-assisted machining (CUVAM). CUVAM successfully integrates the benefits of both cryogenic cooling and ultrasonic assistance. Compared to conventional machining (CM), the CUVAM approach reduces cutting forces by up to 36.5% and contributes positively to tool life. Additionally, chip fragmentation becomes more pronounced, facilitating improved chip evacuation. In comparison with CCM, surface roughness achieved through CUVAM is reduced by approximately 39.1%, indicating a substantial improvement in surface quality. Furthermore, the superior machinability achieved with CUVAM is validated through both experimental and theoretical analyses, highlighting its potential as an effective method for high-quality, high-efficiency, and environmentally friendly machining of Inconel 718. Pereira and his co-authors [9] introduced a novel cooling–lubrication system for milling Inconel 718, in which two types of nozzle adapters with different CO<sub>2</sub> outlet configurations were designed and evaluated. Tool life was assessed under various conditions, including dry machining, conventional wet cooling, standalone CO<sub>2</sub>, standalone minimum quantity lubrication (MQL), and a hybrid CO<sub>2</sub> + MQL approach proposed in the study. The results showed that wet machining generally provides the best performance among conventional methods. However, reducing or eliminating mineral oil emulsions remains a key objective to achieve more sustainable and cost-effective manufacturing. In this context, the combined CO<sub>2</sub> + MQL strategy emerged as a highly promising alternative, achieving over 90% of the performance of wet machining while offering significantly improved environmental compatibility. Despite these advantages, cryogenic milling still faces several challenges. These include the need for efficient coolant delivery system design—such as through-tool supply versus external nozzles—relatively high initial investment costs, and strict safety requirements when handling cryogenic media. Furthermore, due to the intermittent nature of the milling process, improper cooling control may induce thermal shock in the cutting tool, potentially affecting tool life and process stability.

#### **IV. Drilling process under cryogenic condition**

For the drilling process, the cryogenic medium can be supplied either externally to the drill–workpiece interface or internally through the drill’s coolant channels, with the latter being particularly effective for deep-hole drilling where heat buildup and chip evacuation are critical concerns. A key advantage of cryogenic drilling is its ability to substantially reduce the temperature at the tool–chip interface. This cooling effect helps maintain tool hardness and coating integrity, thereby minimizing wear mechanisms such as flank wear, crater wear, and adhesion. Consequently, tool life is significantly extended, especially when drilling difficult-to-machine materials such as titanium alloys, nickel-based superalloys, and stainless steels. In addition, cryogenic cooling improves chip formation and evacuation. At low temperatures, chips become more brittle and are more easily fragmented, reducing the likelihood of chip clogging within the hole—a common issue in conventional drilling processes. Efficient chip removal contributes to improved dimensional accuracy and hole quality, including lower surface roughness and better roundness. Furthermore, cryogenic conditions enhance the surface integrity of drilled holes. Reduced cutting temperatures help minimize thermal damage, work hardening, and residual tensile stresses on the machined surface. These improvements are particularly important for components in aerospace, automotive, and biomedical industries, where high fatigue resistance and structural reliability are essential. Merzouki et al. [10] investigated the hole shrinkage in cryogenic-assisted drilling Ti6Al4V titanium alloy. In this work, the authors established a relationship between the phenomenon of hole shrinkage and measurements obtained during and after the machining process. Since hole shrinkage is closely linked to heat

generation—one of the primary challenges in drilling titanium alloys—the work aims to investigate the influence of liquid nitrogen cooling on this effect. The study seeks to quantify hole shrinkage under cryogenic conditions and correlate it with machining responses. In particular, variations in cutting forces and final hole geometry are examined and interpreted based on the measured shrinkage behavior, providing deeper insight into the thermal–mechanical interactions during drilling. Dix et al. [11] modeled the drilling process under cryogenic cooling for higher efficiency. They stated that in high-performance drilling operations, the substantial thermal load imposed on the cutting tool necessitates effective cooling strategies. Cryogenic machining offers a unique advantage by enabling lubricant-free processing while maintaining low tool wear, even at high material removal rates, due to its ability to significantly reduce tool temperatures. Comparative analyses between experimental results and validated finite element models reveal that tool geometry—particularly the positioning of internal cooling channels—plays a critical role in achieving efficient cryogenic drilling. The developed process model is based on an innovative integration of multiple modeling approaches, providing a more accurate representation of the behavior of cryogenically cooled tools.

## V. CONCLUSION

This paper provides a brief review of the effects of cryogenic cooling on cutting performance in turning, milling, and drilling processes. Key studies and significant findings are synthesized to assess the influence of cryogenic cooling on machining outcomes. Based on the analysis of experimental data, critical process parameters with strong and weak impacts on performance metrics are identified. Furthermore, existing research gaps are highlighted to support future investigations aimed at refining and advancing technological guidelines, particularly in hard turning applications. The review also underscores several remaining challenges, emphasizing the need for continued research to improve machining efficiency, with a particular focus on the development and industrial adoption of environmentally sustainable cooling technologies.

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