

Review

Review on design and development of cryogenic machining setups for heat resistant alloys and composites

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ARTICLE INFO

Keywords:

Cryogenic machining
 Design of the delivery system
 Machining of superalloys
 Machining of composites

ABSTRACT

Cryogenic machining is becoming a sustainable choice due to its extraordinary performance (such as non-toxic and environmentally friendly) superiority to other traditional coolants and lubricants to produce products with superior quality. This paper also critically reviews improvements in designing the cryogenic delivery setup used by researchers for machining low machinability materials like titanium alloys, nickel alloys, ferrous alloys, composites, and other difficult-to-cut materials. It also briefs the economic and sustainable perspective of this state-of-art technology. The aim is to maximize the usage of sustainable cryogenic and hybrid machining technologies in the global manufacturing industry by highlighting their advantages. An overview of in-house developed cryogenic and hybrid machining techniques is presented. Various challenges and future needs related to cryogenic and hybrid-machining techniques are also discussed in the articles. Although remarkable results are obtained with the available literature's delivery methods, there is still no consensus regarding the best cryogenic delivery methods for machining the aforementioned materials. In addition, further hybridization of cryogenic delivery techniques with near dry machining techniques such as minimum quantity lubrication (MQL), electrostatic-MQL (EMQL), and nanofluid based MQL (nMQL) can be beneficial for machinability improvements of difficult-to-machine materials.

1. Summary

This article presents an overview of the current scenario in cryogenic machining in the introduction section. The aim and methodology of this article are presented in the subsection of the first section. The second section of the article discusses different aspects of cryogenic machining's sustainable superiority over conventional machining methods. This section also presents different delivery methods of cryogenic fluids to the cutting zone. A detailed review is presented for different categories of alloys in the third section. Key patents published related to strategies

to deliver cryogenic fluids to the cutting zone are discussed in the first subsection of Section 3. Other subsections of Section 3 contain the review of cryogenic fluid delivery setup parameters and machinability improvements for machining titanium-based alloys, nickel-based alloys, difficult-to-cut ferrous alloys, composites, and NiTi shape memory alloys. Each subsection contains a table to summarise findings. In-house designed and developed indigenous sustainable cryogenic and hybrid machining techniques are discussed in Section 4. Challenges and future needs are discussed in the penultimate section of this article. The last part discusses the key conclusions of this review.

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<https://doi.org/10.1016/j.jmapro.2021.05.053>

Received 14 December 2020; Received in revised form 16 April 2021; Accepted 22 May 2021

Available online 5 June 2021

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2. Introduction

Sustainability refers to an idea that caters to the present human needs without jeopardizing future generations to fulfil their needs [1]. There are three sustainability dimensions, i.e., environmental, economic, and societal factors [2]. There is intense pressure on the governments of different countries to compose strong legislation to curb the menace of environmental pollution and health issues arising out of modern manufacturing processes. Among the various manufacturing processes, machining is one of the most comprehensive metal shaping processes [3].

Cutting conditions is a critical aspect of the machining process that decide machining performance. During metal cutting, heat is generated at the cutting interfaces, resulting in rapid tool wear and low surface integrity. To overcome this problem, cutting fluid is used to improve the cutting condition, which, apart from reducing the temperature in the cutting zone, also performs functions such as lubrication, corrosion inhibition, and flushing of chips [4]. The development of new materials and associated manufacturing processes demand excessive use of cutting fluids, enabling the machining of hard-to-cut materials, thereby further enhancing the severity of the economic, health, and environmental problems. According to one estimate, cutting tooling cost constitutes 4% of the cost of manufacturing and the cost of cutting fluid varies from 7% to 17% of the total cost [5]. As reported by the study from Narutaki et al. [6], the cutting fluid accounts for almost 16% of the total machining costs, including purchase and disposal costs. For difficult-to-cut materials, cutting fluid cost increases by up to 20% [7]. Excessive use of cutting fluids in metal cutting results in the formation of a vast amount of used waste fluid that has to be either recycled or disposed of responsibly. Recycling cutting fluids waste is a tedious task and involves much expenditure, and it is approximately 2–4 times that of the purchasing cost of fresh cutting fluid [8]. However, if it is disposed of even with the best handling systems, it may pollute natural resources like rivers, lakes, air, and underground water [4].

Along with environmental concerns, extensive use of cutting fluids also introduces several health and safety issues, including skin infection and respiratory diseases such as pneumonia and lung cancer [9,10]. According to Elsner et al. [11], cutting fluids are the most important cause of skin dermatitis in the metal industry. Shashidhara et al. [12] commented that 80% of infections are related to cutting fluids direct or indirect contact with the skin. Clapp et al. [13] revealed that cutting fluids can cause esophageal, pancreatic, and prostate cancer.

The world uses many new materials in today's development era, offering versatility in weight, cost, and ergonomics. In the manufacturing industry, machining operations such as milling, turning, and drilling are generally used to achieve near tolerances on the final part. Cutting fluid, tool geometry, and input cutting process parameters affects the machining operations in terms of efficiency and sustainability of machining processes. Strict environmental legislation, high precision demand, and customer awareness about processes are pushing the manufacturing industry to strive for continuous improvement and sustainable solutions [14]. Modern industry wants to maximize the efficiency of machining process and minimize energy consumption to meet global competition, strict environmental legislation, and sustainability initiatives [15].

To improve the machining output, the application of cutting fluid is one of the most critical factors. The primary functions of cutting fluids are lubricating the chip-tool-workpiece interfaces and dissipating heat in the machining process. Traditionally, water and oil-based coolants and lubricants are used during machining, but industries are forced to use fewer harmful coolants due to many techno-environmental problems. Another solution to this problem is the use of MQL. MQL technology can also slightly increase the cutting speed and tool life. It provides lubrication for the process, but it is not efficient in absorbing a high amount of heat from the cutting area [16]. Hence, the next-generation challenge is to replace traditional cooling methods with

dry and near dry cooling methods [17]. Cryogenic machining shows excellent cooling efficiency; it is an environmentally friendly technology.

The latest research in the last ten years shows cryogenic cooling superiority over flood cooling and other dry and near dry machining techniques in terms of improved tool life and surface integrity as it keeps the tool well below its softening temperature. For maximum efficiency of cryogenic cooling, the cryogen's accurate penetration is required at the cutting interfaces [18]. By using cryogenic machining techniques, a contamination-free machined surface and reduction in white layer formation can be achieved, which contributes to the fatigue life of the component. [19]. The main advantage of using cryogenic fluids, especially liquid nitrogen (LN₂) and liquid carbon dioxide (LCO₂) is their tendency to evaporate at atmospheric condition by extracting heat from the cutting region. These fluids do not generate any harmful fumes because of the inert nature. Cryogenic science deals with the behavior of materials and processes at ultra-low temperatures. In literature, cryogenics can be defined as the process occurring below −153 °C. Moreover, according to the National Institute of Standards and Technology (NIST), cryogenic temperatures at those below −180 °C (292 °F or 93.15 K) [20]. Though, there is no strictly defined temperature for the term 'cryogenic' [21]. Fig. 1 shows various cryogenic machining and processing applications.

According to this figure, cryogenic can be used in three ways in the machining process. Cryogenic machining deals with the direct application of cryogen in the cutting zone to reject heat to reduce tool wear rate and improve surface integrity. Cryo-processing of the tool is a method to improve tool resistance to wear by treating them cryogenically before the machining process. In cryo-processing, workpiece is treated under the cryogenic condition to improve the machinability. This technique restricts temperature below glass transition temperature during machining to improve the machinability of workpiece.

The first patent related to cryogenic cooling appeared when it was used to cool the grinding wheel [22]. Since then, the cryogenic machining technique was also investigated for difficult-to-machine materials such as titanium alloys, nickel alloys, and composites, which has proven to be a sustainable option.

A recent review was presented on progress made in cryogenic machining of superalloys in the globe's different continents [23]. Another detailed review was focused on major cryogenic manufacturing processes, and it discussed progress made in predictive performance models and future outlook [24]. A separate review study was presented focusing on surface integrity characteristics induced due to cryogenic cooling compared to dry, MQL, and flood cooling machining techniques [25]. Shokrani et al. [26] examined changes in material properties, friction coefficients, and the cutting area temperature under a cryogenic environment. The previous review articles considered cryogenic machining a favourable option because of the huge benefits of tool life and surface finish and great potential for improving low-machinability aerospace superalloys [27–29].

Despite the ample research on the cryogenic machining of various engineering materials, no focused study has been carried out in the literature on the parameters used to design a cryogenic delivery setup. This review critically focuses on the design parameters used for the cryogenic delivery setup. This area is still unexplored and needs to be addressed to achieve better performance by cryogenic assisted machining. By developing an understanding of these design parameters, it will be conceivable to lessen the machining cost of advanced engineering materials. From the above discussions and current literature available, the following aspects of cryogenic machining need attention to help industries to understand and practice cryogenic machining effectively and to find remedies for problems related to it:

- What are the various methods used by different researchers to address the above issues of cryogenic machining to make this process more productive and sustainable?

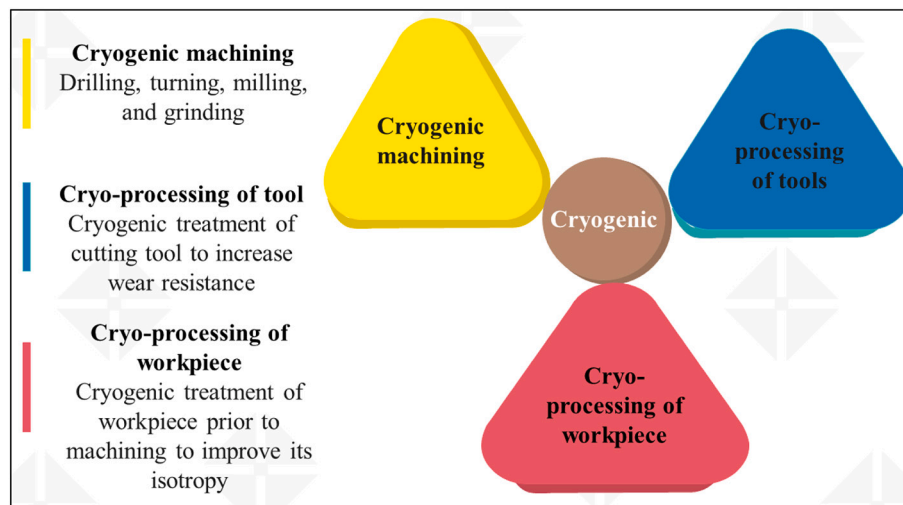


Fig. 1. Cryogenic machining and processing application.

- What are gaps in the knowledge that require immediate investigation?
- What opportunities and new areas in cryogenic machining of difficult-to-cut heat resistant alloys and carbon fibre composites need to be explored?

2.1. Aim and methodology

This review focuses critically on the design parameters used for cryogenic fluid delivery setups for sustainable production. To achieve better performance with cryogenic assisted machining is a necessity to address this issue comprehensively. Because of the above aspects, the present work has addressed the following issues:

- Deliberations on sustainable benefits of cryogenic and hybrid machining techniques;
- Compilation of the research work available in literature related to the design and development of cryogenic fluid delivery setups and its parameters used for difficult-to-machine alloys and composites;
- Overview of in-house developed cryogenic and hybrid machining techniques;
- To analyse present literature and identify the benefits and challenges of using cryogenic machining technology.

By focusing on the above aspects of cryogenic machining, a detailed analysis is carried out in cryogenic machining of heat resistant alloys such as titanium alloys, low-machinability ferrous alloys, nickel-based alloys, composites, and other low machinability alloys. The survey is also extended to analyse the impact of the cryogenic machining techniques on the performance and sustainability aspects of machining. The main keywords used to search literature are cryogenic machining of heat resistant alloys, cryogenic machining of carbon fibre composites, sustainable machining, advanced machining technique, and advancement in aerospace-grade machining superalloys.

This article focuses on the progress made in cryogenic machining in the past 15 years. There are varieties of machine tool manufacturers globally, with their products usually being utilized in the automobile, aerospace, biomedical, and other CNC machine tool manufacturing industries globally. These products are customized to suit original equipment manufacturers (OEMs) related to aeronautics, defense, automotive, and marine sectors. It is found that machining performed on difficult-to-cut materials on these machine tools leads to lower tool-life, which significantly increases machining costs. These negative impacts

lead to the decreased energy efficiency of machine tools. Therefore, research work is required in this direction so that the gained knowledge can be used to develop an energy-efficient cryogenic machining facility. The adoption of sustainable development in production will provide a cost-effective way for the manufacturing industry to improve environmental, economic and social performance.

3. Sustainability concern

The three dimensions of sustainability are economic, environmental and social. The economic dimension includes production rate, costs, and management as well as cutting quality. The environmental dimension covers cutting fluid consumption, energy consumption, waste management, and environmental regulation. The social dimension includes workers' health and safety [30]. Fig. 2 shows different aspects of sustainability gains using cryogenic technologies. Cryogenic machining requires less infrastructural facility as compared to a conventional cooling method and has lower operating costs. The cryogenic machining cost can be reduced by efficient application of cryogen at the cutting interface. Cryogenic machining enables high-speed machining for difficult-to-machine materials with longer tool life to reduce the part's per-unit cost [31]. Since cryogen easily evaporates into the atmosphere and leaves dry chips, it also eliminates disposal management costs. Considering the global challenge to reduce carbon footprints, industries are adopting sustainable machining methods. In the last decade, much research has been done to limit the use of oil-based cutting fluids in machining because most of them pollute the environment and not good for worker's health [32]. LN_2 is considered naturally recyclable and environment friendly, and its over presence can be monitored using an oxygen sensor for worker's safety. Moreover, CO_2 is considered a greenhouse gas. However, cryogenic machining using LCO_2 is not harmful if waste LCO_2 obtained from other manufacturing processes as a byproduct is used for machining before releasing it into the atmosphere.

Pusavec et al. [14] performed a life cycle assessment (LCA) of conventional machining, high-pressure jet-assisted machining (HPJAM), and cryogenic machining (Fig. 3). Conventional and HPJAM techniques include oil-based cutting fluid handling and maintenance. Use of these cutting fluids produce many adverse effects on the environment. While in the case of cryogenic machining, cutting fluid vaporizes after coming in contact with the heat produce in the cutting zone. It has several advantages in terms of clean chips, no circulation and maintenance requirements, environment friendly and no adverse effects on workers' health. Improved machining performance and sustainability in machining are proven functional features that justify cryogenic assisted

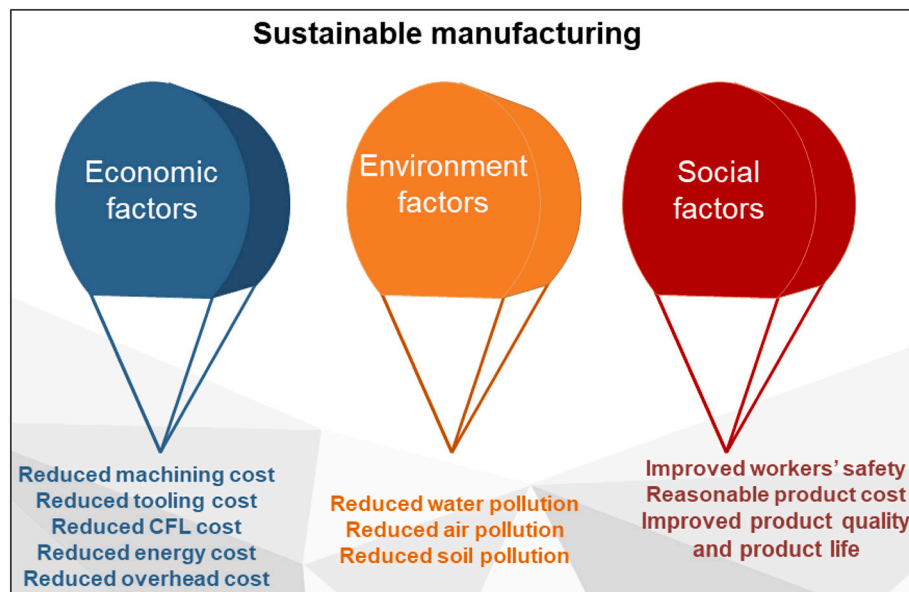


Fig. 2. Sustainability gains in machining using cryogenic fluid as a coolant and lubricant.

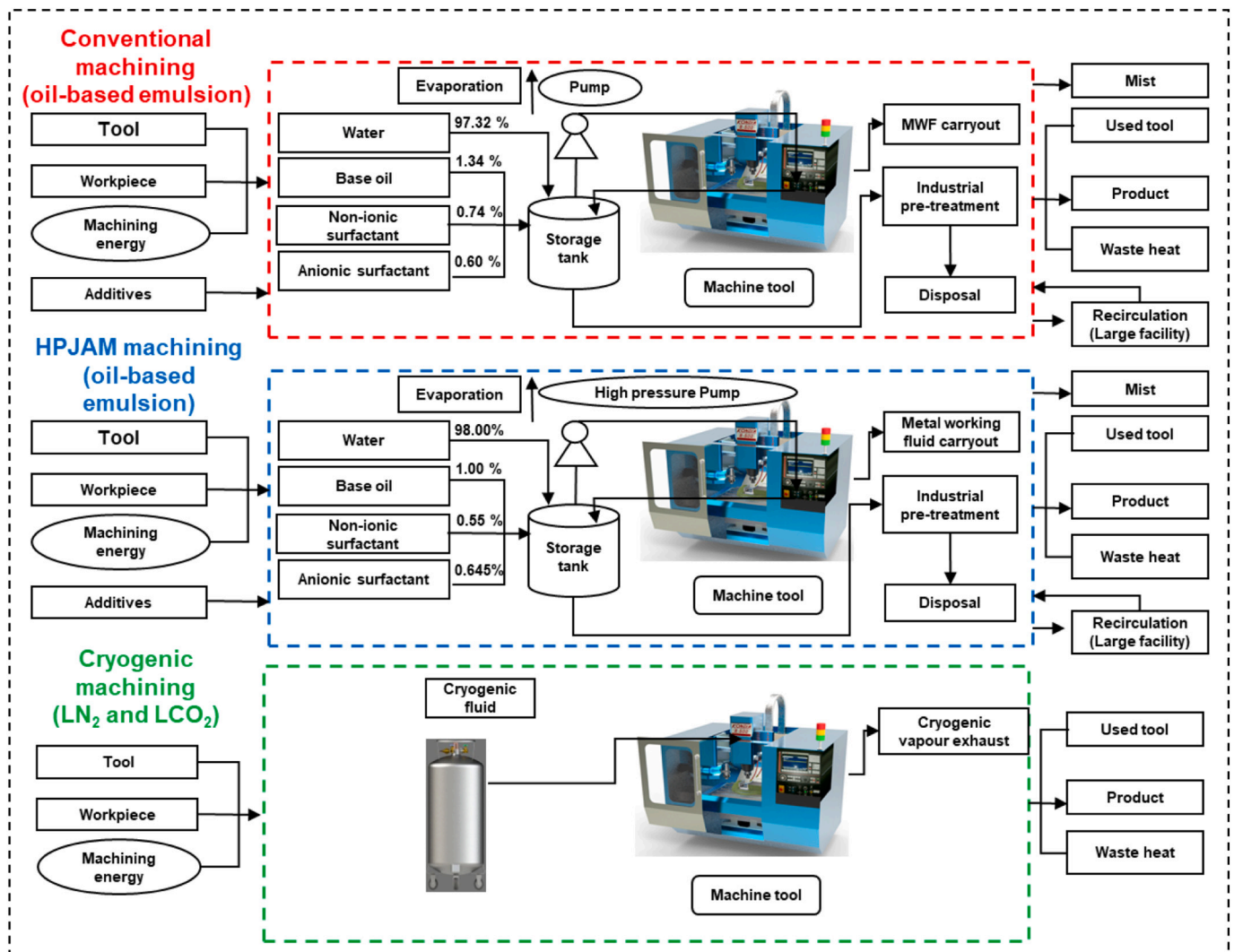


Fig. 3. Schematic comparison of machining technologies, as a platform for the LCA (Adopted and modified) [14].

machining economics.

Agrawal et al. [33] performed a detailed sustainability assessment to compare wet and LN₂ machining techniques. They analysed the effects of machining techniques on the environment concerning carbon emissions. Detailed cost and machinability analysis were also performed to evaluate the economic and social sustainability of machining processes. The authors reported LN₂ turning is more sustainable at higher process parameters in comparison to wet turning.

Another viewpoint to analyse sustainability was presented by Pereira et al. [34]. They investigated the productivity and ecology aspects of different methods for machining machine steel alloy (AISI 304). Authors compared performances under dry, LCO₂, LN₂, MQL, LN₂MQL (LN₂ + MQL), and LCO₂MQL (LCO₂ + MQL) cutting conditions. They reported hybrid-machining solutions (LN₂MQL and LCO₂MQL) results in improved tool life (up to 50%) and enables 30% higher cutting speed than in conventional machining solution. Moreover, hybrid-machining solutions were also beneficial in terms of ecological view to strike a balance between technical and environmental issues. Moreover, sustainability evaluation of different cryogenic and hybrid machining techniques remain relatively less explored. More investigation in this direction could help industries to adopt these technologies.

Hegab et al. [35] proposed an algorithm to evaluate the sustainability of machining techniques. It includes all four life cycle stages of machining (Pre, manufacturing, use, post) to evaluate overall sustainability. Weightage can be given differently to performance attributes in this algorithm. Later this algorithm was used by Khanna et al. [36] to compare the sustainability of the LCO₂ technique with conventional machining techniques. Khanna et al. [37] also analysed LCA of dry, flood, LN₂, LCO₂ using the ReCiPe 2016 midpoint (H) method in terms of ecological impact and energy consumption. They identified LN₂ as the best cooling method as compared to dry, flood, and LCO₂ methods.

3.1. Cryogenic cooling methods

LN₂ is used as a cryogenic cutting fluid during machining to extract heat from the cutting zone. The use of LN₂ as a cutting fluid is eco-friendly than conventional oil-based cutting fluid. Moreover, LCO₂ is also gained attention as a cryogenic cutting fluid as an alternative to LN₂. Sometimes, LCO₂ does not count as cryogenic fluid as it has a slightly higher boiling point than cryogenic fluids, but it is cooled enough to evacuate heat from the cutting zone. Moreover, CO₂ is a greenhouse gas, but abundant LCO₂ is produced in industrial processes that can be used for machining before releasing into the atmosphere [21].

For using LN₂ as a cutting fluid, it is stored in insulated tanks at high pressure. At atmospheric condition, it starts boiling at −196 °C, absorbs the heat dissipated in the cutting zone, and evaporates without leaving any residue over the workpiece and cutting tool. However, in some cases, an insulating film created by vapour nitrogen over the heating surface may reduce the cooling effects [8].

For using LCO₂ as a cutting fluid, it is stored in medium pressure (5.7 MPa) and atmospheric temperature. At atmospheric condition, LCO₂ experiences a major pressure drop, causing it to cool down and expand due to the Joule-Thomson effect. Heat is absorbed from the cutting zone due to sudden vaporization and expansion of LCO₂ in the air without leaving any residue at cutting zone. This characteristic makes it a suitable choice for machining materials that are inept of using liquid coolants [38]. However, an advantage of using these fluids is not fully explored in terms of their cooling capability. Heat extraction is mainly dependent on the convective heat transfer coefficient, which is directly proportional to the difference of cooling media and contact surface temperatures. Pusavec et al. [39] explored the cooling capabilities of LN₂ and LCO₂. They reported increased cooling capability with an increase in the mass flow rate of cryogen. The mechanics of heat extraction also depends on the phase of cryogen in the cutting zone. It means for cryogen total heat transfer is a summation of sensible heat and latent

heat of evaporation. While in the case of emulsion cooling heat transfer depends on sensible heat only, as emulsion remains in a liquid state during cooling. The authors also analysed the effect of nozzle orientation on cooling capability and they reported orthogonal orientation is best for maximum cooling efficiency. The main functions of LN₂ and LCO₂ are:

- Remove the heat from the cutting region.
- Cutting edge cooling.
- Reduce the friction of the cutting interfaces when combined with the MQL technique.
- Cooling of the workpiece in case of composites.
- Chip embrittlement for easy chip breaking in case of ductile materials.

The different cooling methods reported in the literature is as shown in Fig. 4 [40]. Astakhov and Godlevskiy [41] have also documented different delivery methods for conventional and cryogenic machining in a book section.

Cryogenic cooling of the workpiece is a widely used technique used for machining. The main aim of this technique is to change the properties of the material to enhance machinability. For this technique, cryogenic bath (submerged workpiece) or spray (cooling with jets) methods are used. This technique is also used to keep the temperature of elastomers of different materials below their glass transition temperature during machining [42].

Spray cooling is useful for embrittlement of chips for easy disposal, decreasing friction between chip-tool-workpiece interfaces, and extracting heat from the cutting zone [43]. Many researchers investigated the effect of LN₂ application from both the flank and rake face of the tool from two different nozzles, while others attempted with just a single nozzle on either face of the tool [26]. For instance, Hong and Ding [44] presented a method to supply the LN₂ in the vicinity of the cutting zone and reported a two-fold increase in productivity as compared to conventional machining of Ti6Al4V.

Indirect cooling is used to facilitate cooling of the tool and not to the workpiece. In this technique, the cryogen is not in direct contact with the workpiece; therefore, the negative effects of cooling the workpiece, such as geometrical deviations and increase in material strength and hardness can be eliminated. It can either be done by mounting a heat sink (cryogen container) at the top/side/bottom of the cutting tool [45] or by making a hole or internal passes in the tool bit [46]. This technique of cooling can be used when geometrical deviation and changes in material properties due to cryogenic conditions need to be avoided [47]. Moreover, the efficiency of this method is dependent on the properties of the cutting tool material [26]. Dandekar et al. [45] employed this technique for cooling the tool as they required no effect of cryogen of the workpiece. Ahmed et al. [48] modified tool holder to enable cooling of cutting edge without exposing the workpiece to the cryogenic conditions.

Moreover, vacuum-jacketed hose, phase separator, cryogen flow controller, swivel joint, suitable nozzles should be used to increase the efficiency of cryogenic delivery setups for machining. Vacuum jacketed hose and phase separator helps to deliver cryogen to the cutting zone in the liquid phase. Swivel joints are good for drilling and milling setups as they disallow torque within the hose. Bellin et al. [49] presented a tool holder specially designed for cryogenic machining. This tool holder has provision for through passes of cryogen. Moreover, increased tool holder stability was reported in their work by restricting distortion in the tool holder due to cryogenic condition. The authors used sensors and a heating cartridge to monitor and regulate the temperature of tool holder. Cryogenic and hybrid machining may need a change in cutting tool geometry for optimum performance. One investigation in this direction is presented by Shokrani and Newman [50]. Authors optimized end mill geometry for cryogenic machining to achieve a higher material removal rate and productivity. They stated that the higher rake and

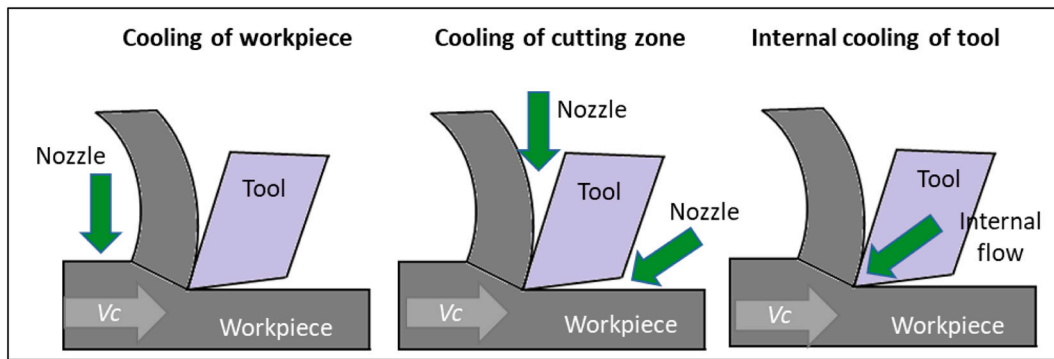


Fig. 4. Cryogenic cooling methods (Copyrights reserved) [40].

clearance angles are suitable for cryogenic condition as this geometry enables a sharper cutting edge. Few of the industries like 5S, ChilAire, BeCold, Rothers technology, 5MG, Mag cryogenics, ICEFLY's, and Cryofab provide ready to use cryogenic delivery setups for machining.

4. Improvement in cryogenic fluids delivery setups and machinability improvements of difficult-to-cut materials using sustainable machining techniques

This section focuses on the design parameters delivery setups for cryogenic and hybrid machining, and improvements in tool and tool holder modifications and different nozzle positions to deliver cryogen in the cutting zone. Machinability improvements in difficult-to-cut titanium-based alloys, nickel-based alloys, ferrous alloys, composites, and NiTi shape memory alloys are critically reviewed.

4.1. Patents in the field

In the past, researchers have widely investigated the application of cryogenic fluids for machining in different ways. Most of the patents filed are identified with strategies for delivering LN₂ to minimize the quantity of fluid used in the cutting region to get maximum advantage in terms of surface and subsurface characteristics of the workpiece. The recent patent on optical sensor arrangement [51] makes the machining process more efficient due to the capability to sense the cryogenic fluid phase. Recently, cryo-lubrication is a new trend in machining research, few of the patents are also reported in this direction [52,53]. Table 1 reports the key patents related to sustainable cryogenic and hybrid machining.

4.2. Review of improvements in cryogenic and hybrid machining setups and machinability of titanium-based alloys

Titanium alloys have significant mechanical and thermal characteristics. Titanium has a very low density, and due to alloying it with aluminium and vanadium, its hardness increases close to nickel alloys with considerable fatigue strength [73]. That makes titanium alloys suitable for high strength-to-weight ratio applications like the aerospace industry, automobile engines, gas turbines, nuclear industry, and biomedical field. Other exceptional mechanical properties such as high creep, yield stress, corrosion resistance, toughness, wear resistance, and biocompatibility makes titanium alloys suitable for many applications [74]. The titanium also poses, between all common metals, the highest strength to weight ratio up to 550 °C. All those properties combined lead to the following low-machinability characteristics [75]:

- The titanium alloys low thermal conductivity makes a poor contribution to the cutting zone heat dissipation;
- Strong chemical reactivity with most of the tool material leads to a high adhesion and diffusion wear rate;

Table 1
Patents in the field of cryogenic machining.

Inventors	Invention
Dudley et al. [54]	Internal passes in the tool to supply cryogenic fluid during machining
Lightstone and Mazzarella [22]	Method to cool workpiece up to cryogenic temperature during machining
Jaskowiak et al. [55]	Method to use cryogenic fluid for breaking chips during machining of ductile materials
Hong et al. [56] [57]	Chip breaker modification for cryogenic channel and method to deliver LN ₂ to a rotating tool
Zurecki et al. [58–60]	Method to avoiding heat interaction from the surrounding to LN ₂ during machining
Frey et al. [61]	Methods for remote cooling of a cutting tool
Jackson [62,63]	Methods for there through the machined channel to apply cryogenic and hybrid fluids
Ghosh et al. [64]	Method for cooling the portion of the material to be machined up to a temperature at or below the material's glass transition temperature
Pusavec and Kopac [51,65]	Systems and methods for delivering cryogenic fluid in liquid form to machining tools and sensor arrangements to detect the phase of a cryogenic fluid
Zhigang et al. [66]	A low-temperature abrasive jet machining device
Rozzi et al. [67]	Indirect cooling using a micro-channel heat exchanger mounted on the insert's rear face
Rozzi et al. [67,68]	Method to direct and indirect supply cryogenic fluid to rotating cutting tool
Shin [69]	Laser-assisted cryogenic machining
Levasseur [70]	Feedback-controlled system for cryogenically cooling machining tools
Khanna [71]	Cryogenic liquid fluid delivery to the cutting zone without wasting the converted vapour phase
Erliang et al. [72]	A new method for cryogenic fluid delivery using the multi-angle inclined jet
Opalka et al. [52]	Introducing a cryo-liquid mixed with nanoparticles in the vicinity of the cutting zone.
Neto et al. [53]	Method of simultaneous injecting both CO ₂ in a liquid state (without ice formation) and micro-particles to machining zone

- Low heat dissipation capacity from the cutting zone by conventional coolant media [44];
- High thermo-mechanical stresses near the cutting edge due to the small tool-chip interface.

Many authors have extensively investigated machinability of titanium alloys using cryogenic and hybrid machining techniques. The majority of the studies evaluated the Ti6Al4V using coated and uncoated carbide tools. The researchers established that the performances could be improved by spraying LN₂ into the cutting area. Few of them also provided a schematic diagram of the device for conveying LN₂. Therefore, in this section, cryogenic delivery methods and machinability improvements are carefully reviewed.

Hong and Ding [44] introduced a dispensing method that directs LN₂

through microjets to different positions on the cutting edge, resulting in reduced tool wear even at the high-speed cutting of Ti6Al4V due to a reduction in diffusion rate under cryogenic temperature. The authors reported that it is adequate to apply LN₂ directly to the rake face while cutting performs at low speeds. Hong et al. [76] modified the chip breaker and nozzle location and proposed a concentrated spray method. In another study done by Hong et al. [77], the effect of cryogenic conditions on friction coefficient was examined in machining AISI 1018 and Ti6Al4V at different cutting speeds. LN₂ is supplied at 2.4 MPa pressure through a high vacuum transfer hose with an average volumetric flow rate of 0.9 L/min.

Venugopal et al. [18] investigated tool wear for Ti6Al4V under cryogenic cooling. To get a continuous LN₂ flow, trial and error methods were used to finalize delivery settings. They reported an increased tool life using cryogenic machining. They also discussed the possibility of overcooling of workpiece that can result in embrittlement of work material. Dandekar et al. [45] proposed a hybrid technique to machine Ti6Al4V. In this process, they designed a setup for heating of work material using laser and cooling of tool edge by cryogenic fluid, simultaneously (Fig. 5).

Courbon et al. [78] explored the tribology behavior of Ti6Al4 V and Inconel 718 under cryogenic and dry conditions. They reported that cryogenic condition is beneficial in reducing heat transfer to the pins. El-Tayeb et al. [79] compared the effect of dry and cryogenic conditions on the coefficient of friction (CoF). They analysed CoF of Ti6Al4V and Ti54 experimentally (using pin on disk method) and numerically. Authors reported increased CoF for Ti6Al4V (up to 20%) and a decrease in CoF for Ti54 under cryogenic environment than in dry environment.

Dhananchezian and Pradeep Kumar [46] proposed a cryogen delivery set up for machining Ti6Al4V. The same setup was also used by Dhananchezian et al. [80] for the machining of AISI-4037. The schematic diagram of the cryogenic delivery setup is presented in Fig. 6(a). LN₂ passes through a hole with a size of Ø2 mm × 2.5 mm and the dimensions on the main side and secondary side are Ø 1 mm × 2 mm, as shown in Fig. 6(b). They reported decreased cutting force, surface roughness, flank wear, and cutting temperature under cryogenic environment when compared to wet environment.

Birmingham et al. [81] delivered cryogenic fluid at a pressure of 0.8 MPa from the LN₂ pressurized tank through the SecoJetStream™ tool

holder through different copper nozzles (Fig. 7) with a diameter of 1.77 mm placed approximately 10 mm away from the cutting edge. The effect of applying cryogenic fluid to the flank face reduced the abrasive wear rate. However, the tool's nose that was not the delivery point of LN₂ concentrated the wear and results show that there is a decrease in feed force and increase in thrust force. The friction coefficient did not decrease in cryogenic cooling in comparison with high-pressure emulsion cooling [82].

Rotella et al. [83] examined the effect of LN₂ on the surface integrity of the workpiece. LN₂ was delivered via a 2 mm nozzle at 1.2 MPa, resulting in significant product surface characteristics. Raza et al. [84] investigated the machining of Ti6Al4 V under cryogenic and hybrid conditions using uncoated carbide tools. They report that at cutting speed of 90 m/min, MQCL outperforms other turning techniques in terms of extending tool life. However, at cutting speed of 120 m/min, it was found that the tool life under cryogenic conditions was longer. Authors also recommended the use of vegetable oil in MQL and MQCL processes to enhance the sustainability of these techniques [85]. Safari et al. [86] characterized workpiece roughness and cutting force in the milling process at high-speed cutting velocities. The only thing discussed in terms of design is the vortex tube's nozzle position, located at 12 mm away from the cutting tool edge with an angle of 10° to feed direction. Bordin et al. [31] presented an experimental set-up consisting of two flows of LN₂ directed onto the flank and rake faces employing external copper nozzles with an internal diameter of 0.9 mm. A vacuum jacketed hose was used to supply LN₂ at the cutting zone at a pressure of 1.5 MPa and a flow rate of 1.11 L/min. They reported reduced adhesive wear when EBM Ti6Al4V was machined under a cryogenic environment. In another study, they have reported improved tool life and chip morphology under a cryogenic environment when additively produced Ti6Al4V was machined [87]. Ahmed and Kumar [88] evaluated the drilling performance of Ti6Al4V under cryogenic condition. LN₂ supplied under 0.4 MPa of pressure directed to the cutting interface. The results showed improvement in surface finish, tool life, and chip breakability using cryogenic drilling.

Aramcharoen [89] reported reduced chip morphology and tool wear using cryogenic machining than in flood machining. For the delivery system, a tailored insulated integrated system was developed and retrofitted to the tool holder. A further pivot nozzle function can control the angle of delivery LN₂. A flow rate of 0.35 L/min and a pressure of 0.4 MPa were set for delivering LN₂.

Shokrani et al. [43] presented a design of the delivery system (refer to Fig. 8) to deliver LN₂ for CNC milling of the Ti6Al4V alloy. A flow rate of 0.4 L/min at a pressure of 1.5 MPa was the machining time's delivery parameters. Moreover, a phase separator was not employed in their setup. LN₂ delivery setup without phase separator can significantly affect cooling efficiency due to the presence of vapour N₂ in the cutting fluid. Authors compared the cryogenic environment's effect during the milling of titanium alloys. The results were compared with flood and dry milling of Ti6Al4V. They placed nozzles at 0.5 mm away from cutting edges and LN₂ was delivered at 0.15 MPa and 0.4 L/min. The result shows reduced thermally induced tool wear and surface roughness (up to 40%).

Sartori et al. [90] discussed the effects of cryogenic turning on surface integrity of a Direct Melting Laser Sintering (DMLS) Ti6Al4V alloy. LN₂ was delivered at 1 ± 0.05 MPa of pressure, with the responses with dry machining. They reported higher residual compressive stress and fewer surface defects under a cryogenic environment. However, it was observed that the surface morphology has generally deteriorated.

Imbrogno et al. [91] examined the microstructural alteration, cutting force, and temperature for semi-finishing machining of Ti6Al4V under dry and cryogenic conditions. During the experiments, cryogenic fluid was supplied through a 0.9 mm diameter nozzle to the rake face and primary cutting edge at a pressure of 1.2 MPa. Kim et al. [92] proposed a model to predict cutting force during Ti6Al4V turning under cryogenic condition. They incorporated phase transformation of LN₂ during

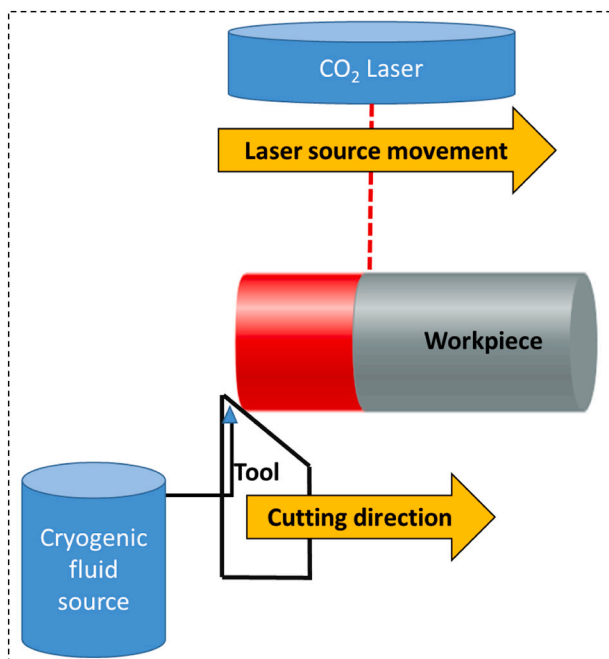


Fig. 5. Hybrid model (laser assistance + cryogenic cooling).

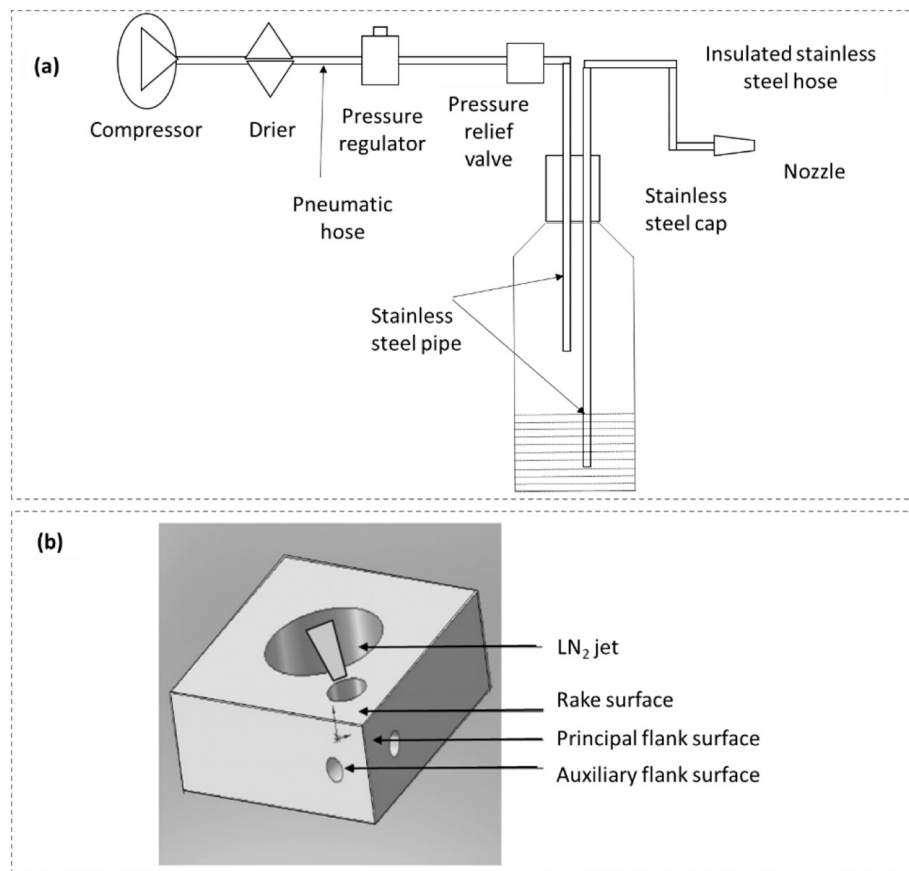


Fig. 6. (a) LN₂ delivery system, (b) Modified tool insert (Copyrights reserved) [46].

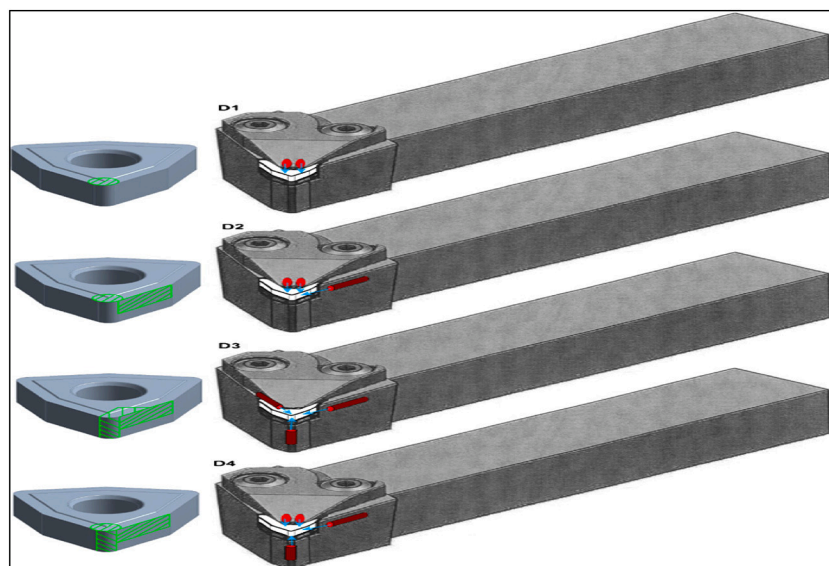


Fig. 7. Schematic of coolant delivery (Copyrights reserved) [82].

machining in their modelling. Sun et al. [93] compared the machinability under MQL, flood and cryogenic atmospheres of the Ti-5553 alloy. The cryogenic fluid was delivered at 1.5 MPa of pressure, and 0.74 L/min of flow rate from the tool rake face direction. The results showed a better surface finish and reduced thrust force (30%). Umbrello et al. [94] developed a numerical model to predict nano-hardness, microstructure, and machining-induced plastic deformation under

cryogenic machining. Experimental parameters used to deliver LN₂ were 1.5 MPa pressure and 0.9 mm diameter nozzle placed on rake face and primary cutting edge.

Schoop et al. [95] investigated high-speed hybrid (LN₂MQL) turning of Ti6Al4V for finishing operation. They suggested that this process could be used as an alternative to grinding operation. They used a 3 mm diameter nozzle to deliver LN₂ at the primary edge at 1.5 MPa of

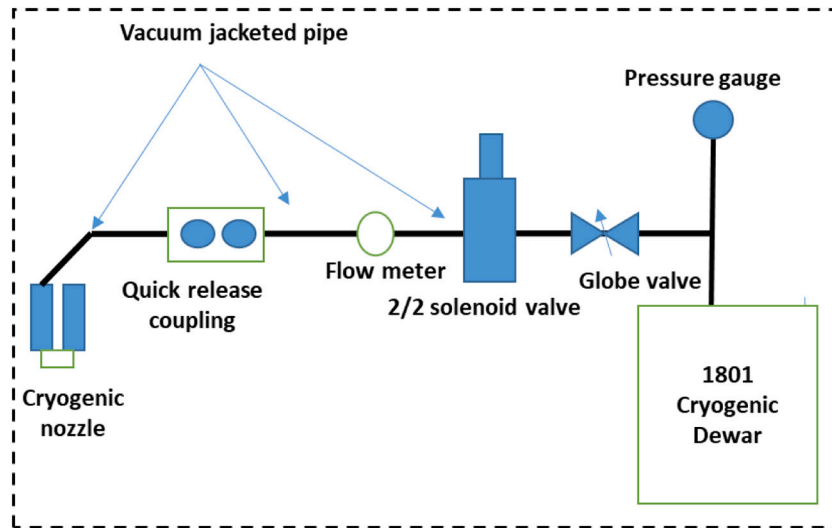


Fig. 8. LN₂ delivery system (Adopted and modified) [43].

pressure and 0.74 L/min flow rate. They reported reduced surface roughness and increased cutting force using LN₂MQL technique than in the flood technique.

Park et al. [96] investigated machinability improvement using MQL and cryogenic machining when compared with dry and wet machining. For cryogenic machining, they used a phase separator, sub-cooler, and vacuum-jacketed hose to promote consistent spray of LN₂ in a liquid state as presented in Fig. 9. They used 0.25 MPa pressure and a 1 mm nozzle to deliver LN₂. They reported improved performance using MQL and cryogenic turning techniques. Moreover, due to increased thermal gradient, hardening of the workpiece and excessive tool wear due to micro chipping were reported using cryogenic machining.

The impact of supply condition of LN₂ on surface integrity and tool life for turning of Ti6Al4V is investigated by Ayed et al. [97]. They considered two different pressures and flow rates of LN₂. The authors reported improved surface integrity and a fourfold increase in tool life using high flow rate and high pressure of LN₂. The authors have also mentioned a need for further optimization of LN₂ cutting conditions.

Tahri et al. [98] investigated the phenomenon occurring inside the pipe using the CFD technique for different inlet parameters such as pressure, liquid/gas volume fraction, and velocity; it was observed that the cooling effectiveness process depends on pipe geometry and inlet parameters. The reported best inlet pressure of 0.6 MPa and liquid/gas volume fraction of 90%. The liquid/gas volume fraction and inlet pressure combination give to the outlet the maximum pressure and

minimum temperature. Tapoglu et al. [21] investigated Ti6Al4V milling under LCO₂, flood, dry, MQL and LCO₂ mixed with air or MQL conditions. They reported the best milling performance in terms of improved tool life under LCO₂MQL condition. Lequien et al. [99] investigated the thermal interaction occurring between jet-workpiece interfaces. They highlighted that the cryogen delivery parameters such as diameter, projection angle, and nozzle diameter affect convection heat transfer and heat distribution in the cutting vicinity. Novella et al. [100] presented a numerical model to predict dimensional deviation due to the cooling effect on tool holders under the cryogenic condition. Delivery pressure of 1.5 MPa and nozzle diameter of 0.8 mm were used as the delivery system setting.

Zhao et al. [101] proposed a cryogenic system that enables adjustable temperature in the range of 20 to −196 °C. They mixed pressurized air with LN₂ in different proportion to get the required temperature. They used LN₂ at a pressure below 0.1 MPa. The authors revealed a significant effect of cutting condition on chip morphology and serrated characteristics. Later Zhao et al. [102] analysed the milling performance of Ti6Al4V under dry and cryogenic conditions. The authors reported higher micro-hardness and increased compressive residual stress using cryogenic milling as compared to dry milling.

Jamil et al. [103] compared the machinability of titanium alloys using LCO₂ and hybrid Al₂O₃-CNT nano-fluids. They reported improvement in tool life and surface finish and reduction in thrust force using hybrid technology. Also, the temperature in the cutting region

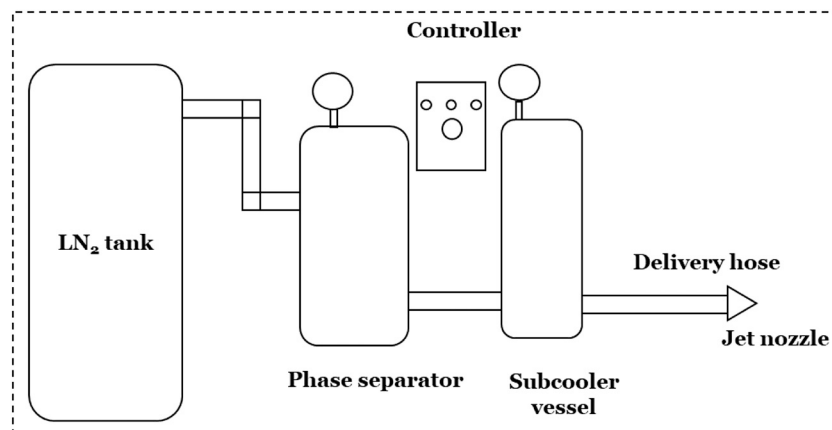


Fig. 9. LN₂ delivery setup for cryogenic machining (Copyrights reserved) [96].

reduced using LCO₂ environment. In other studies, they analysed machinability under different cryogenic conditions. The authors reported a decrease in tool wear, carbon emissions, and surface roughness under cryogenic conditions than in conventional machining [104,105].

Mia et al. [106] examined and compared the machinability of Ti6Al4V under the effect of mono and dual-jets of LN₂. They found that dual-jets of LN₂ could improve machinability performance. Authors have also carried out life cycle assessment and multi-objective optimization in their study.

Pusavec et al. [39] explored cryogenic milling of Ti6Al4V under LN₂, LCO₂, and emulsion cooling. They supplied emulsion (7% concentration) and LCO₂ from inside the cutting tool through a 0.8 mm diameter nozzle at a pressure and temperature of 0.5 MPa and 20 °C respectively. LN₂ was supplied from a pressured vessel at 0.4 MPa through a 0.8 mm diameter nozzle at two different flow rates. They found the best milling performance in terms of tool life under LN₂ conditions at a higher flow rate. In another study, Pusavec et al. [107] compared the lubrication capability of solid-lubricated LCO₂ in comparison to flood lubrication, LCO₂MQL, and LCO₂. They reported the best lubrication results using solid-lubricated LCO₂ condition. A clean machined surface with no particle adherence was observed under SEM also echoes the suitability of solid-lubricated LCO₂ as a good cutting fluid for machining.

Moritz et al. [108] analysed the application of LCO₂ technique for

intermediate milling during additive manufacturing of Ti6Al4V. They reported layer addition on the LCO₂ machined surface gives better results as compared to the dry machined surface. This is due to the contamination-free and better surface finish machined part is obtained using the LCO₂ technique. It is also economical due to increased tool life and elimination of cleaning requirement of the machined surface.

Gajrani [109] analysed the machinability of Ti6Al4V under LN₂MQL condition as compared to dry and MQL conditions. The author observed decreased cutting force, surface roughness, and tool wear under LN₂MQL condition as compared to dry condition. The SEM image of the workpiece shows that the adhesion is lower under the modified cutting condition and that is the reason for the improvement of machining performance.

Shah et al. [110] compared drilling of titanium alloy (VT 20) under LN₂, LCO₂, dry, and flood conditions in terms of tool life, thrust force, power consumption, and hole quality. Higher tool life is obtained under LN₂ (299 holes) condition as compared to LCO₂ (202 holes), dry (20 holes), and flood (140 holes) conditions. Moreover, thrust force, torque, and power consumption were lowest using LCO₂ conditions. Hole quality was superior under both cryogenic drilling compared to conventional drilling. Agrawal et al. [111] analysed the machinability of Ti6Al4V using dry, wet, and LN₂ machining techniques. An increased tool life (80–200%) and decreased energy consumption (9–61%) were

Table 2

Review of cryogenic and hybrid machining of titanium alloys.

Authors	Machinability assessment			Sustainability assessment	Machining condition		
	Tool Wear	Surface Integrity	Energy consumption		Cryo_LN ₂		Other
					Mono-jet	Dual-jet	
Hong et al. [44,76,77,113]	×	×	×	×	✓	×	×
Venugopal et al. [18,114,115]	✓	✓	×	×	✓	×	×
Courbon et al., El-Tayeb et al. [78,79]	×	×	×	×	×	×	^a
Dandekar et al. [45]	✓	×	×	✓	×	×	LN ₂ LAM
Dhananchezian and Pradeep Kumar [46]	✓	✓	×	×	✓	×	×
Birmingham et al. [81,82]	✓	✓	×	×	✓	×	×
Rotella et al. [83]	×	✓	×	×	✓	×	×
Raza et al. [84]	✓	✓	×	×	✓	×	MQCL
Safari et al. [86]	×	✓	×	×	✓	×	×
Bordin et al. [31,116]	✓	✓	×	×	×	✓	×
Ahmed and Kumar [88]	✓	✓	×	×	✓	×	×
Aramcharoen [89]	✓	✓	×	×	✓	×	×
Shokrani et al. [43,117–119]	✓	✓	✓	×	✓	×	LN ₂ nMQL
Sartori et al. [120]	✓	✓	×	×	×	✓	×
Imbrogno et al. [91], Kim et al. [92], Sun et al. [93], and Umbrello et al. [94]	×	✓	×	×	✓	×	^b
Park et al. [96]	✓	✓	×	×	✓	×	×
Schoop et al. [95]	×	✓	×	×	×	×	LN ₂ MQL
Ayed et al. [97]	✓	✓	×	×	✓	×	×
Tahri et al. [98]	×	×	×	×	✓	×	^c
Tapoglau et al. [21]	✓	×	×	×	×	×	LCO ₂
Lequien et al. [99]	×	×	×	×	✓	×	^d
Zhao et al. [101,121]	×	✓	×	×	✓	×	×
Jamil et al. [103–105]	✓	✓	✓	✓	×	×	LCO ₂ and LN ₂ nMQL
Mia et al. [106]	×	✓	✓	✓	×	✓	×
Pusavec et al. [39,107]	✓	×	×	×	✓	×	LCO ₂
Nimel Sworna Ross and Ganesh [122]	✓	✓	×	×	✓	×	LCO ₂
Moritz et al. [108]	✓	✓	×	×	✓	×	×
Gajrani [109]	✓	✓	×	×	×	×	LN ₂ MQL
Shah et al. [110]	✓	✓	✓	×	✓	×	LCO ₂
Agrawal et al. [111]	✓	✓	✓	×	✓	×	×

^a Analysed friction coefficient at cutting interface under cryogenic conditions.

^b Finite element modelling to simulate machining performance under cryogenic cutting conditions.

^c CFD analysis to analyse cryogenic machining efficiency concerning pipe geometry.

^d Analytical modelling to predict convective heat transfer coefficient concerning LN₂ jet parameters.

reported in their study using LN₂ turning technique as compared to dry and wet turning techniques. Moreover, improved surface finish (64–71%) was also reported using LN₂ turning. Later, Agrawal et al. [112] compared the machinability of Ti6Al4V using hybrid and LN₂ turning techniques. In their study, hybrid machining namely, cryogenic-ultrasonic assisted turning (CUAT) and cryogenic-ultrasonic-MQL assisted turning (CUMQLAT) are developed. They reported a decrease in active energy consumption (1.8–3.6%) using CUAT and CUMQLAT than LN₂ turning. An increase in the surface finish (32–42%) was reported using the hybrid techniques. Relative sustainability of process (RSP) is used to quantify and compare the sustainability of these turning techniques. Table 2 presents a summary of this section.

4.3. Review of improvements in cryogenic and hybrid machining setups and machinability of nickel-based alloys

Nickel alloys are known as low machinability materials due to their high strength and work hardening tendency [123]. Other properties of the nickel-based alloy, which make them hard to the machine, are [124].

- High cutting zone temperatures (up to 1200 °C) due to a combination of high heat capacity and low thermal conductivity;
- High reactivity with most tool materials, which results in build-up edge formation and adhesion;
- The high material strength and work hardening tendency at elevated temperatures lead to high cutting forces and vibrations;
- Abrasive wear due to the material's carbide particles;
- The small tool-chip contact area leads to high mechanical and thermal stresses near the cutting edge.

The heat dissipation is prevented by the nickel-alloys low thermal conductivity resulting in considerably high cutting temperatures. A combination of high temperature and high cutting forces usually leads to lower surface finish and tool life. The surface quality is a critical concern as it affects the machined parts' performance and overall service life [125]. A systematic review is presented for the various cryogenic and hybrid techniques and different parameters used by researchers for LN₂ delivery.

Wang et al. [125] proposed a hybrid technique for machining Inconel 718. They combined plasma heating to soften the workpiece and LN₂ to reduce thermally induced tool wear, thereby making the most of these two processes. They observed a reduction in surface roughness (250%) and cutting force (30–50%) and improvement in tool life (170%) using modified cutting conditions.

Kenda et al. [126] used LN₂ to machine Inconel 718 with setup parameters as, pressure of 1.5 MPa and flow rate of 0.74 L/min per nozzle and compared the performance parameter with dry, MQL, and LN₂MQL cooling lubrication options. The result showed that higher compressive residual stresses are generated due to cryogenic machining. These residual stresses result in improved product quality and performance characteristics regarding fatigue and wear resistance. The authors also presented a nozzle positional schematic for the different delivery systems.

Shokrani et al. [9] studied the cryogenic cooling effect on milling performance of Inconel 718 in terms of surface roughness. They reported a 40% decrease in surface roughness of machined component under LN₂ condition than in dry condition.

Aramcharoen and Chuan [127] investigated cryogenic milling and its sustainability assessment. A custom-designed cryogenic cooling system retrofitted on the machining center was used (Fig. 10). Nozzle with the insulated hose connected to LN₂ dewar and nozzle was attached to the spindle to move simultaneously with the cutter. The results of this investigation supported cryogenic machining as a sustainable option.

Pusavec et al. [128] performed tests to evaluate the influence of the cryogenic fluid phase on friction. To model the cryogenic machining process Abaqus/Explicit© FEM simulator with ALE approach was used.

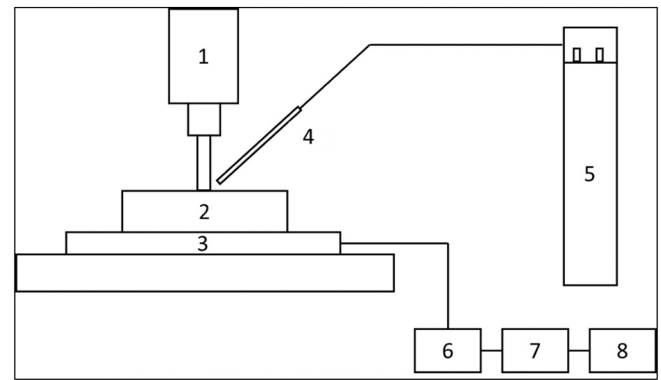


Fig. 10. Retrofitted machine center schematic view (1) spindle, (2) workpiece, (3) dynamometer (4) nozzle (5) LN₂, (6) amplifier, (7) data acquisition system, and (8) computer (Copyrights reserved) [127].

The simulated parameters were: (a) delivery at 77 K of LN₂ and (b) delivery at 80 K of gaseous nitrogen. They reported the significance of the phase of the nitrogen in reducing the friction that results in a reduction in the sticking zone. The authors emphasized the need for optimal control of cryogen delivery parameter for machining application. Iturbe et al. [129] discussed the Inconel 718 cryogenic machining compared with MQL lubrication. The nozzle is placed to deliver LN₂ at the cutting tool's rake face in the form of a jet to facilitate chip evacuation and reduce the temperature at the cutting zone.

Pereira et al. [130,131] used a patented Coanda effect nozzle [63] to deliver LCO₂ and MQL simultaneously for the end milling of Inconel 718. They used computational fluid dynamics to optimize nozzle dimension. Outer channels of LCO₂ were modified from convergent (Fig. 11a) to convergent-divergent (Fig. 11b). The result shows improvement in tool life (93.5%) when using the LCO₂MQL combination instead of dry machining. Pereira et al. [132] have also compared LCO₂MQL, MQL, and wet techniques for milling of Inconel 718. They have reported reduced cutting force (21%) and increased tool life (57%) using the LCO₂MQL technique than in MQL technique. Moreover, an increased cutting force (11%) and decreased tool life (12%) were reported using LCO₂MQL milling techniques in comparison to wet milling techniques. Moreover, the authors stated the hybrid process (LCO₂MQL) to be advantageous to strike a technical and environmental balance.

Fernández et al. [38] analysed the milling performance of Inconel 718, EA1N Steel and Gamma TiAl using LCO₂ machining technique and conventional machining technique (oil emulsion). The authors used a modified multipoint delivery setup to deliver LCO₂ in the cutting zone. They reported comparative tool life for Inconel 718 for both cutting techniques. Moreover, tool life improved by 100% and 175% for Grade EA1N steel and Gamma TiAl milling using cryogenic machining than in conventional machining.

Hribersek et al. [133] investigated problems related to finding the heat transfer coefficient between LN₂ and Inconel 718. The finite element methods result showed that the heat-transfer coefficient decrease with an increase in temperature of LN₂.

Chaabani et al. [134] compared LN₂, LCO₂, and conventional machining techniques for finish turning of Inconel 718. The authors reported improved tool life using the LN₂ machining technique as compared to the other two techniques. They have also reported improved surface integrity under cryogenic conditions in comparison with conventional conditions.

Khanna et al. [135] analysed drilling of Inconel 718 under dry and cryogenic environments. They reported improved tool life and hole quality using cryogenic drilling in comparison with dry drilling. The authors reported increased thrust force and decreased torque using cryogenic drilling in comparison with dry condition. Later authors compared the turning performances of Inconel 718 under dual-jet LN₂,

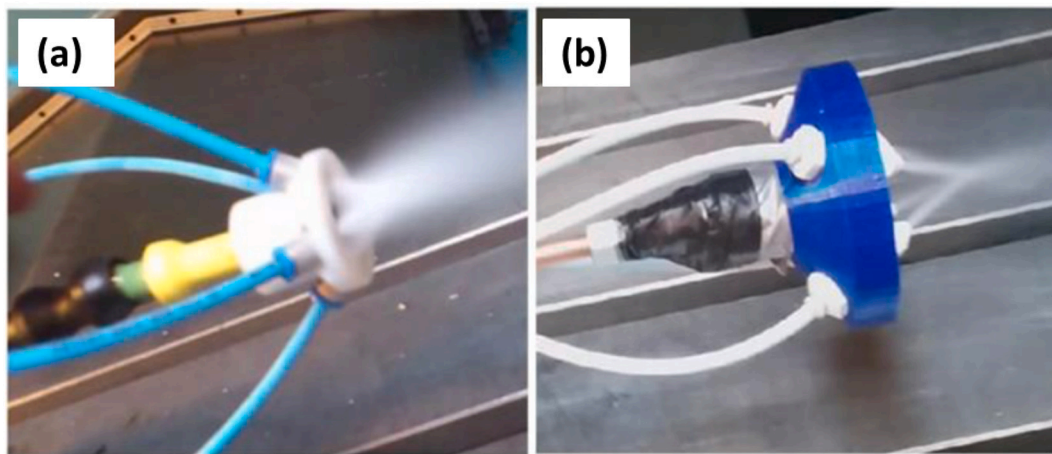


Fig. 11. Modified nozzle adapter (Copyrights reserved) [131].

wet and dry conditions [136]. Tool life was highest under the LN₂ turning condition as compared to the other two conditions. Khanna et al. [137] analysed the machinability and sustainability of Nimonic 90 under hybrid turning as compared to LN₂ turning. They reported superior performance using CUAT as compared to LN₂ turning in terms of surface quality and energy consumption. The authors also reported lesser carbon emissions in the case of CUAT as compared to the LN₂ turning technique. Patel et al. [138] compared the turning performance of Nimonic 90 under wet and LCO₂ condition. They reported a better surface finish obtained using wet turning. Moreover, lesser power consumption and improved chip breakability were observed under LCO₂ condition as compared to wet condition. Shah et al. [139] performed LCA for Inconel 718 drilling under LN₂ and LCO₂ conditions. They used ReCiPe 2016 midpoint (H) method to analyse the impacts on the resources, workers' health, and environment. Improved machining performance with lower power consumption was reported using LCO₂

condition as compared to LN₂ condition. However, LCO₂ machining was not reported to be a good option in terms of ecological aspects. The summary of this section is presented in Table 3.

4.4. Review of improvements in cryogenic and hybrid machining setups and machinability of difficult-to-cut ferrous alloys

Ferrous alloys, i.e. stainless steel, low carbon ductile steel, and hardened steel, are categorized as low-machinability materials due to the following properties:

- Poor chip breakability of low carbon ductile steel [144];
- High workpiece hardness that leads to the cutting edge plastic deformation;
- High cutting temperatures that lead to workpiece and tool materials diffusion;

Table 3

Review of cryogenic and hybrid machining of nickel-based alloys.

Authors	Workpiece material	Machinability assessment			Sustainability assessment	Machining condition		
		Tool Wear	Surface Integrity	Energy consumption		Cryo_LN ₂		Other
						Mono-jet	Dual-jet	
Wang et al. [125]	Inconel 718	✓	✓	×	×	✓	×	LAM + LN ₂
Kenda et al. [126]	Inconel 718	×	✓	×	×	×	✓	×
Pusavec et al. [15,128,140,141]	Inconel 718	✓	✓	×	✓	×	✓	LN ₂ MQL ^a
Shokrani et al. [9]	Inconel 718	✓	✓	×	×	✓	×	×
Aramcharoen and Chuan [127]	Inconel 718	✓	✓	×	✓	✓	×	×
Iturbe et al. [129]	Inconel 718	×	✓	×	×	✓	×	×
Pereira et al. [130–132]	Inconel 718	✓	✓	×	×	×	×	LCO ₂ and LCO ₂ MQL ^b
Hribersek et al. [133]	Inconel 718	×	×	×	×	×	×	×
Khanna et al. [142]	Inconel 718	×	✓	×	✓	✓	×	CUAT ^c
Chaabani et al. [134]	Inconel 718	✓	✓	×	×	✓	×	LCO ₂
Khanna et al. [135,136]	Inconel 718	✓	✓	×	×	✓	×	×
Khanna et al. [137]	Nimonic 90	✓	✓	✓	✓	✓	×	CUAT
Tej et al. [138]	Nimonic 90	×	✓	✓	×	×	×	LCO ₂
Shah et al. [139]	Inconel 718	×	✓	✓	✓	✓	×	LCO ₂
Chetan et al. [143]	Nimonic 90	✓	✓	×	×	✓	×	×
Fernández et al. [38]	Inconel 718, EA1N Steel, and Gamma Titanium	✓	✓	×	×	✓	×	LCO ₂

^a Analysed effect of nitrogen phase on cutting performance.

^b Finite element modelling to simulate heat transfer coefficient between LN₂ and the workpiece.

^c Cryogenic-ultrasonic assisted turning.

- Built-up edge formation due to high chemical affinity of tool and its coatings with ferrous materials;
- Unpredictable catastrophic tool failure due to non-uniform flank wear [7].

To eradicate these problems, researchers can opt for cryogenic and hybrid machining as alternatives to flood and dry cooling practices. A systematic review of delivery setup parameters and their effect is presented in this section. Ding and Hong [145] tried to improve the performance by chilling the workpiece before or during the cutting process to achieve embrittlement temperature of the material and it was found to be beneficial to improve machining performance. Later the same authors tried to take advantage of the cooling chips to ease their breaking [144]. In later studies, they [146] have analysed micro-temperature manipulation of the same material, and the chip breakability control has been reported. The embrittlement temperature of AISI1008 low carbon steel is at -55°C . At this temperature, the shear force does not increase significantly and the chip-tool interface temperature is reduced. Hong et al. [147] analysed the tool's cryogenic cooling by delivering LN_2 to rake and flank faces. To deliver the LN_2 , an aluminium plate was clamped on the rake face having two nozzles focused on the tooltip, while a stainless steel pipe of 1.59 mm diameter is attached to flank clearance to cool the flank face (Fig. 12).

LN_2 supplied from Dewar at 2 MPa pressure, resulting in the LN_2 flow rate of 0.3 L/min; a sub-cooler is used to ensure liquid phase delivery of LN_2 . This system yielded a 67% and 43% improvement in tool life at cutting speed of 229 m/min and 204 m/min, respectively, in comparison to emulsion cooling. Paul et al. [148] studied the benefits of machining of AISI 1060 steel under cryogenic cooling. In their works, two pre-designed nozzles are used to deliver LN_2 from the rake and flank side to protect the auxiliary flank to maintain a good dimensional accuracy workpiece and surface finish. The result shows improved surface finish, and tool life compared to wet and dry machining.

Dhar et al. [149] also presented a schematic for cryogenic machining of AISI 1040 and E4340C steel. LN_2 , in the form of thin but high-speed jets, was delivered from a previously designed nozzle in direction to the cutting zone along under two almost parallel directions to the cutting edges. Dhar et al. [150] also evaluated the effect of cryogenic cooling on AISI 4140 steel, and improvement is reported in tool wear, dimensional deviation, and surface roughness. Zurecki et al. [19] investigated white layer formation in hard cutting steel AISI 52100, using LN_2 discharged at the rake face under 0.69 MPa of pressure and 0.72 L/min of flow rate, while the 2-phase flow was used (90% volume of liquid & 10% volume of gas). Results revealed a significant decrease in white layer formation.

Dhar and Kamruzzaman [151] used cryogenic cooling for machining of AISI-4037 steel. LN_2 (-196°C) was delivered at high speed, from a specially developed nozzle along the insert's cutting edge. This nozzle enabled efficient reaching of coolant at cutting interface. The LN_2 jet targeted the rake and flank surface along the tool's auxiliary cutting

edge, protecting the secondary flank and enabling better dimensional accuracy. The result shows improvements in tool wear, dimensional deviations, and surface finish.

Jerold and Kumar [152] proposed a setup shown in (Fig. 13) used to deliver LN_2 to machining AISI-1045. In their setup, compressed air was used to build the pressure inside LN_2 container to bring out fluid for cryogenic machining. They placed a drier before delivery of compressed air inside the container. This easy to fabricate setup is useful for small and medium-sized industries. However, the principle of pushing the LN_2 with pressurized air is very dangerous. At -196°C , the oxygen in the air is liquid, and LO_2 is flammable. It may result in an explosion due to a sudden pressure rise in the LN_2 vessel.

Nalbant and Yildiz [153] performed cryogenic milling of AISI 304. LN_2 was supplied to the cutting zone using a nozzle with a diameter of 1 mm with a flow rate of 5.2 L/min. The result shows improvement in cutting forces (6.5%) and torque (7.9%) using cryogenic machining in comparison to dry machining. The authors claimed that the cryogenic cooling's main problem in the climb milling method at low cutting speeds is the tool chattering around the insert nose radius. Umbrello et al. [154] analysed cryogenic machining of AISI-52100 bearing steel. ICE-FLY's delivery system was used to control the flow of LN_2 and reported a positive influence on white layer formation. However, residual stresses are increased that can generally contribute to fatigue life in comparison to dry machining. Bicek et al. [155] also studied the effect of cryogenic cooling on performance parameters such as tool life in the machining of AISI-52100. They used a self-developed setup called the SusCryMac system. Pereira et al. [34] used LN_2 and LCO_2 as cutting fluids for machining at a pressure of 1.5 MPa and temperature of -196°C and -78°C , respectively. They deduced that both lubrication and freezing of chips are required during the machining of low machinability ferrous materials. Therefore, cryogenic is suggested to upgrade to cryoMQL. Magadum et al. [156] introduced a CAD model (Fig. 14) to deliver LN_2 . This CAD model was developed to direct LN_2 to the cutting interface with precision. A provision was made to connect external LN_2 supply to the nozzle. Cryogenic machining of EN24 material, hardened to 45 HRC, results show an increase in tool life up to 38.60%, tangential cutting force decrease up to 15.42%, and improved surface finish in comparison to conventional flood cooling. Sivaiah and Chakradhar [157] presented a schematic of a cryogenic delivery apparatus. To store LN_2 , a TA 55 model cryocan in combination with a compressor was used to pressurize the LN_2 in the tank up to 0.3 MPa. Using a 2 mm nozzle the coolant was directed to the tool rake face. The result showed a reduction when compared to wet machining of the flank wear (53%), cutting temperature (78%), surface roughness (35%), and cutting forces (16%).

Heep et al. [158] analysed machinability improvements in compacted graphite iron 450 when machined under CO_2 -snow jet conditions using a laser additive manufactured tool. To produce CO_2 -snow jet condition, they mixed LCO_2 with air in a nozzle before delivering it to the cutting zone. They tested the machinability under four conditions namely, dry, CO_2 -snow jet on rake face, CO_2 -snow jet on the flank face, and CO_2 -snow jets on both faces. They reported dual-jets of CO_2 snow creates the most suitable turning condition, as tool life increased 2.4 times compared to dry condition. They have also reported an increased cooling rate by up to 32% with an increase in air mass flow rate.

Wika et al. [159] compared the milling performance of austenitic steel (SS 304) under LCO_2 MQL and flood conditions. They reported an increase in tool life (324%) at higher process parameters using LCO_2 MQL milling than in flood milling. Moreover, surface roughness, microstructural changes, residual stress, and micro-hardness were comparable for both milling techniques.

Khanna et al. [160] compared machining performance of 15–5 Precipitation Hardening (PH) Stainless Steel (SS) under dry, flood, MQL and LCO_2 conditions. To enable LCO_2 cutting condition, a dip tube was inserted in an LCO_2 pressurized cylinder. It was transferred to the cutting zone using a thermoplastic hose to the cutting zone via a 2 mm nozzle. They reported reduced tool wear, power consumption,

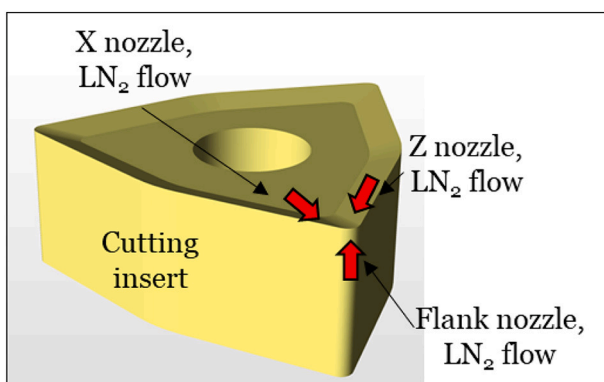


Fig. 12. Nozzle set up for directed flow cryogenic cooling.

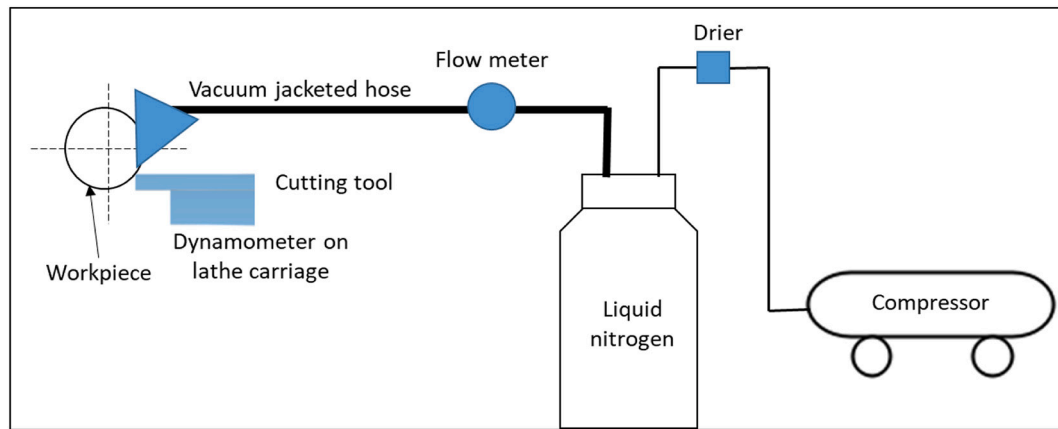


Fig. 13. Schematic view of cryogenic LN₂ machining setup (Adopted and modified) [152].

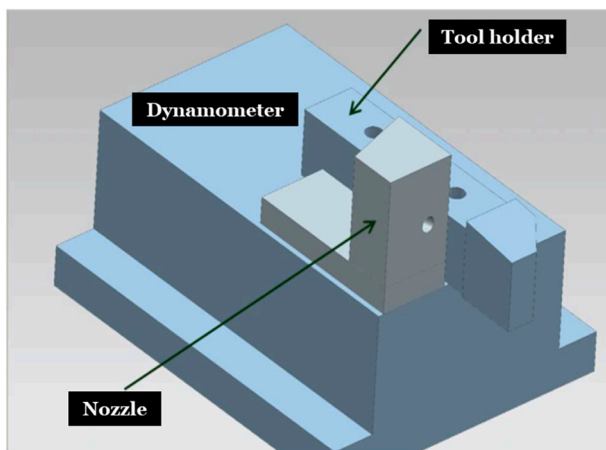


Fig. 14. CAD model for the delivery system (Copyrights reserved) [156].

subsurface micro-hardness, and segmented chips, using LCO₂ turning techniques. They also reported grain refinement under cryogenic condition. Moreover, they obtained a superior surface finish using flood turning.

M. et al. [161] compared milling of 55NiCrMoV7 steel under LN₂, LCO₂, and wet conditions. They reported a high-temperature drop in the cutting zone under the LN₂ cutting condition as compared to the other two conditions. Moreover, the best surface finish was obtained under LCO₂ milling condition. The authors also revealed lesser tool abrasion and improved surface topography under cryogenic cutting conditions than in wet condition. The summary of this section is presented in Table 4.

4.5. Review of improvements in cryogenic and hybrid machining setups and machinability of composites and NiTi shape memory alloys

In this section, machining of fibre reinforcement composites (FRC), Mg-based particulate metal matrix composites (PMMC), and NiTi shape memory alloys are discussed. The cutting of FRP composites presents many challenges such as fibre tearing, delamination, fibre pullout, and dimensional inaccuracies in machined components [166]. Some authors have tried cryogenic cooling of the workpiece to decrease difference in matrix and fibre's mechanical properties to eliminate these problems. Mg-based PMMC has problems of corrosion in machined components and rapid tool wear due to the presence of hard SiC particles in composites. Mg-based PMMC are promising structural materials for both aero and auto industries due to their lightweight characteristics. Now,

they have also used as internal fixation implants material in biomedical applications due to their biodegradable property. Few authors have tried to improve the machinability of this PMMC using cryogenic machining are discussed in this section. NiTi shape memory alloys also have the problem of dimensional inaccuracy in machined components. All these problems can be addressed using cryogenic fluids as lubricant and coolant in the machining process. This section discusses the efforts made in the direction to improve the machinability of these materials using sustainable cryogenic and hybrid machining techniques. It also discusses the input process parameters used to deliver cryogenic fluid during machining.

Bhattacharyya et al. [167] studied machining of Knitted Fabric Reinforce Polymer (KFRP) under a cryogenic atmosphere and observed significant improvements in the machinability. The study compared dipping the workpiece into the LN₂ to the continual application of LN₂ supplied from heating the LN₂ in a Dewar with an immersion heater. This technique allowed to create sufficient pressure to pump LN₂ at a required flow rate (0.4–0.5 L/min), then it proved to be more efficient, and consistently a better surface finish and tool life were observed.

Pu et al. [168,169] have extensively researched the effect of cryogenic machining on Mg-based PMMC to analyse surface integrity and corrosion tendencies when machined under cryogenic working condition. Their experimental setup involves ICEFLY's LN₂ delivery system, where LN₂ was delivered to the cutting tool's flank side.

Outeiro et al. [170] presented a numerical model to compare it with experimental results of surface integrity (residual stress) resulted from cryogenic machining of AZ31B-O Magnesium Alloy. Authors reported improvement in corrosion resistance for cryogenically machined surface. Nor Khairusshima et al. [171] reported improvement in drilling performance of CFRP composites in terms of delamination when drilling was performed under a chilled air environment (−10 °C). They reported an improvement in tool life under modified working condition.

Kaynak et al. [172,173] investigated the effect of cryogenic machining of NiTi shape memory to analyse tool wear, cutting force, microstructural phase transformation, and surface integrity. The result shows a significant improvement in these performance characteristics using cryogenic machining. Design parameters for the delivery setup used were 1.5 MPa pressure, and approximately 0.74 L/min flow rate and nozzle diameters used on rake and flank face were 4.78 mm.

Watzke et al. [174] suggested cryogenic shear cutting of fibre-reinforced plastics to eliminate tearing of fibres, deformation, and delamination issues. Low temperature enabled using cryogenic fluid leads to a decrease in the ductile movement of a molecule in the matrix, possibly because the resin matrix becomes brittle and, hence, fibre-reinforced plastics behave more as homogeneous material. Consequently, it results in less damage in the cutting zone.

Xia et al. [175] studied the improvement in machinability of CFRP

Table 4

Review of cryogenic and hybrid machining of ferrous alloys.

Authors	Workpiece material	Machinability assessment			Sustainability assessment	Machining condition		
		Tool Wear	Surface Integrity	Energy consumption		Cryo_LN ₂		Other
						Mono-jet	Dual-jet	
Ding and Hong [144–146]	AISI 1008	✓	✓	×	×	×	×	^a
Hong and Broomer [147]	AISI 304	✓	×	×	×	✓	×	×
Paul et al. [148]	AISI 1060	✓	✓	×	×	✓	×	×
Dhar et al. [149,150]	AISI 1040 and E4340C steel	✓	✓	×	×	✓	×	^b
Zurecki et al. [19]	AISI 52100 steel	×	✓	×	×	✓	×	×
Dhar and Kamruzzaman [151]	Hardened AISI 4037	✓	✓	×	×	✓	×	×
Dhananchezian et al. [80]	AISI 304	✓	✓	×	×	✓	×	×
Nalbant and Yildiz [153]	AISI 304	✓	×	×	×	✓	×	×
Umbrello et al. [154]	Hardened AISI 52100	×	✓	×	×	✓	×	×
Bicek et al. [155]	AISI 52100	✓	✓	×	×	✓	×	×
Jerold and Kumar [152]	AISI 1045	✓	✓	×	×	✓	×	LCO ₂
Pereira et al. [34]	AISI 304	✓	×	×	×	✓	×	LCO ₂ MQL
Sivaiah and Chakradhar [157,162]	17–4 PH stainless steel	✓	✓	×	✓	✓	×	×
Raof et al. [163]	AISI 4340	×	✓	×	✓	✓	×	×
Varghese et al. [164]	Maraging steel	×	✓	×	×	✓	×	Cryo treatment + cooling
Gong et al. [165]	35CrMnSiA steel	✓	✓	×	×	✓	×	LN ₂ nMQL
Khanna et al. [36,160]	15–5 PH stainless steel	✓	✓	✓	✓	✓	×	LCO ₂
Heep et al. [158]	Graphite iron	✓	×	×	×	✓	×	LCO ₂ Air
Wika et al. [159]	AISI 304	✓	✓	×	×	×	×	LCO ₂ MQL
Jebaraj et al. [161]	55NiCrMoV7 steel	✓	✓	×	×	✓	×	LCO ₂

^a Pre-chilling of workpiece and chip cooling during machining was discussed to improve machinability and chip breakability.^b Finite element modelling to simulate machining performance under cryogenic cutting conditions.

with the modified drill bit with two coolant supply holes to deliver LN₂ to the cutting zone. Cryogenic machining of CFRP leads to an increase in delamination, but it reduces the rounding of cutting edge and outer corner wear. It results in improved hole quality in terms of diameter error compared to dry machining.

Giasin et al. [176] explored the machinability of GLARE laminates under dry, MQL, and cryogenic conditions. They reported an increased thrust force under MQL and cryogenic conditions. Moreover, the surface quality of the machined surface was improved under MQL and cryogenic conditions as compared to dry conditions.

Josyula et al. [177] proposed a system to deliver LN₂ to the cutting zone during machining of metal matrix composite (Al-5%TiCP). The experimental setup consisted of a compressor, a cryogenic tank, a pneumatic pressure gauge, servo, and solenoid valves. A specially designed L-shaped nozzle illustrated in Fig. 15, an LN₂ pressure regulator, and a rotameter to measure flow rate of LN₂. The LN₂ was supplied to tooltip's rake face under 0.2 MPa pressure and a 0.2 L/min flow rate. The authors reported lesser tool wear, reduced surface roughness, and reduced cutting temperature under LN₂ condition as compared to dry,

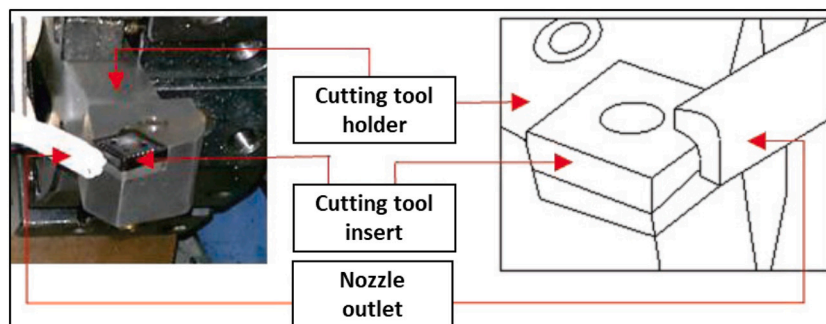
wet, and cryogenically chilled air (CCA) conditions.

Kumaran et al. [178] compared rotary ultrasonic-assisted dry and cryogenic techniques for drilling of woven CFRP composites. They observed an improvement in the surface finish of the drilled hole using cryogenic drilling owing to brittle fracture of fibres as revealed in SEM images. Moreover, lower exit burr area and higher thrust force were also observed under cryogenic conditions.

Basmaci et al. [179] recommended small diameter drills instead of large diameter drills for CFRP composites drilling if design permits. In their study, drilling was performed on a workpiece in the submerged conditions under cryogenic fluid. An increase in thrust force was observed for drilling under the cryogenic condition than in wet condition. However, the use of low-temperature drilling resulted in the improved surface finish of the drilled hole.

Abish et al. [180] explored the machinability of CFRP under chilled air and compared it with performance under dry condition. The authors reported a reduction in delamination, surface roughness, and acoustic emissions under an altered drilling environment.

Impero et al. [181] reported that cryogenic drilling has higher

**Fig. 15.** Arrangement of nozzle outlet on the insert (Copyrights reserved) [177].

productivity as compared with wet drilling. They suggested the use of higher process parameters can be employed using cryogenic drilling of CFRP/Ti stack to improve productivity. Moreover, their observation related to decreased thrust force obtained using cryogenic drilling does not agree with other studies.

Joshi et al. [182] proposed a force-based model to predict delamination using dry and cryogenic drilling. The author also conducted an experimental analysis and reported improved surface finish and tool life using cryogenic drilling as compared with conventional drilling.

Morkavuk et al. [183] found that compared with dry drilling, the cutting force in cryogenic drilling of CFRP composites has increased because the tensile strength has increased by 3%. They also reported improved surface finish and reduced delamination when drilling was performed under a cryogenic environment.

Khanna et al. [184] also analysed turning performance improvements in AZ91/5SiC Mg-based PMMC using CUAT technique than in dry technique. They reported improved surface finish and chip breakability using hybrid technique than the conventional technique.

Kumar and Gururaja [185] studied the drilling of CFRP composites in terms of damage to work material due to process-induced stresses, temperature, and forces. Authors have reported significantly lesser temperatures, surface roughness, and higher surface integrity using cryogenic drilling than in dry drilling. Improved responses were attributed to change in fibre fracture mode using cryogenic drilling. In another investigation Kumar et al. [186] have reported lesser torque, damage at the metal-composites interface, burr formation, and surface roughness using cryogenic drilling than dry drilling of Ti/CFRP/Ti hybrid composite laminate. Although, a single jet non-movable cryogenic delivery setup was used in that investigation.

Kannan and Pervaiz [187] analysed the inclined drilling performance of CFRP composites using dry and cryogenic drilling. They reported higher thrust force, lesser drilling-induced damage under cryogenic drilling condition. The reason stated behind this was that the cryogenic environment promotes the brittle mode of fracture. Moreover, cryogenic drilling enables better quality of hole than dry drilling. They claimed that the drill bit with point angle was more effective than the

flat drill bit, as it helps to reduce the delamination.

Khanna et al. [188] analysed drilling performance of CFRP composites under dry and LN₂ environments. The authors reported increased thrust force, improve hole quality, and reduced entry delamination using LN₂ drilling as compared to dry drilling. Khanna et al. [189] analysed machinability of in-house developed AZ91/5SiC Mg-based PMMC under MQL, LN₂ and LN₂MQL techniques. They reported improved surface finish and chip breakability index using the LN₂MQL technique than MQL and LN₂ machining techniques. Moreover, lesser power consumption and cutting force are observed in the case of MQL techniques as compared to LN₂ and LN₂MQL techniques. Later authors also compared the machinability of another Mg-based PMMC (AXZ911/10SiC PMMC) using dry, LN₂, and LCO₂ machining techniques [190]. They reported better surface finish under the dry condition as compared to cryogenic conditions. Moreover, the cutting force and power consumption were reported to be least under LN₂ condition than dry and LCO₂ conditions. Table 5 presents the summary of this section.

Table 2–5 presents the summary of the work done in cryogenic and hybrid machining techniques of heat resistant alloys and composites. Cryogenic machining has been explored tremendously over the past 15 years. The benefits of using cryogenic machining in terms of many different aspects, i.e., chip breakability, white layer formation, tool life, surface integrity, productivity, and sustainability, are widely investigated. However, there is a lack of work in the direction to optimize cryogen delivery parameters for cryogenic machining. Moreover, many authors have modified the delivery setup in terms of innovative methods for internal and external cooling of a cutting tool. Cryogenic precooling is also an effective method to provide effective cooling compared to external cooling of the cutting zone. From the literature review, it is observed that, in recent years, the surface and surface modification caused by machining has become the subject of attention in the machining industry. Improvements in surface integrity of machined components are necessary to reduce or eliminate failure and to improve functional performance. Machining processes include high temperatures, large strain (2–5), and strain rate (10⁻⁵ - 10⁻⁶ S⁻¹). Machining conditions and parameters affect temperatures, strain, and strain rates

Table 5
Review of cryogenic and hybrid machining of composites.

Authors	Workpiece material	Machinability assessment				Machining condition
		Thrust force	Tool wear	Delamination	Hole quality	
Bhattacharyya et al. [167]	KEVLAR composites	✓	✓	×	✓	LN ₂
Pu et al. [168,169]	AZ31B Mg PMMC	×	×	×	✓	LN ₂
Outeiro et al. [170]	AZ31B-O Mg PMMC	×	×	×	✓	LN ₂ ^{a,b}
Nor Khairussihima et al. [171]	CFRP composites	×	✓	✓	×	LN ₂
Kaynak et al. [172,173]	NiTi shape memory alloy	✓	✓	✓	×	LN ₂
Watzke et al. [174]	CFRP composites	✓	✓	✓	✓	LN ₂
Xia et al. [175]	CFRP composites	✓	✓	✓	✓	LN ₂
Giasin et al. [176]	GLARE laminates	✓	×	×	✓	LN ₂
Josyula et al. [177]	Al-5%TiCP	×	✓	×	✓	LN ₂ and CCA ^c
Kumaran et al. [178]	CFRP composites	✓	×	×	✓	LN ₂
Basmaci et al. [179]	CFRP composites	×	×	✓	✓	LN ₂
Abish et al. [180]	CFRP composites	×	×	✓	✓	LN ₂
Impero et al. [181]	CFRP composites	✓	×	×	×	LN ₂
Joshi et al. [182]	CFRP composites	×	×	✓	×	LN ₂
Morkavuk et al. [183]	CFRP composites	×	×	✓	✓	LN ₂
Khanna et al. [184]	AZ91/5SiC Mg PMMC	×	×	×	✓	CUAT
Kumar and Gururaja [185], Kumar et al. [186]	CFRP composites	✓	×	✓	✓	LN ₂
Kannan and Pervaiz [187]	CFRP composites	✓	×	✓	✓	LN ₂
Khanna et al. [189]	AZ91/5SiC Mg-based PMMC	×	×	×	✓	LN ₂ and LN ₂ MQL
Khanna et al. [188]	CFRP composites	✓	✓	×	✓	LN ₂
Khanna et al. [190]	AXZ911/10SiC Mg PMMC	×	×	×	✓	LCO ₂ and LN ₂

^a Cryogenic machined surface shows lower corrosion cracking susceptibility than dry machined surface.

^b Numerical modelling to predict the cyclic variation of residual stress under different machining conditions.

^c Cryogenically chilled air (CCA).

during machining that result in alterations in flow stress and surface and subsurface properties of the machined surface. Severe plastic deformation is a process that is used to induce nano-crystallization on a machined surface leads to improvement in wear and fatigue resistance of workpiece. However, this improvement is attributed to a combined effect of nano-crystallization and work hardening and it is subjected to machining conditions and process parameters. Grain refinement and yield strength of the machined layer can be modelled using Hall-petch and Zener-Holloman equations [28]. As per these equations, they are dependent on temperature during the deformation process and workpiece temperature. Cryogenic conditions can significantly affect machining zone temperatures and workpiece properties. The improvement of surface quality in terms of surface finish and surface morphology using cryogenic conditions has been widely reported in the literature. This can be mainly attributed to a reduction in tool wear during machining of difficult-to-cut materials under cryogenic condition as compared to dry condition. A cryogenic condition during machining can also reduce the built-up-edge formation and thermal distortion of machined surface. Cryogenic conditions have a significant effect on the depth of machining induced layer in the subsurface due to drastic reduction in temperature that leads to a reduction in plastic deformation depth in the subsurface of workpiece. Besides, the grain boundaries limit the movement of dislocations at low temperatures, which leads to a reduction in the heat-affected zone in the workpiece. Reducing tool wear caused by machining under cryogenic condition also reduces the depth of the heat-affected layer in the workpiece. For machining under cryogenic condition, the thermal softening of the workpiece is reduced and the strain hardening increases. That increases the hardness of the surface and sub-surface. The grain refinement of the machined part is caused by a low temperature that results in increased hardness of surface and sub-surface layer. Cryogenic condition can also cause twinning deformation, leading to the formation of high-density twinning. The cryogenic conditions during machining also suppress the thermally induced phase transition during machining and produce smaller crystal grains due to dynamic recrystallization. Besides, the use of cryogenic condition can also improve the fatigue life of components [126]. Compressive residual stress is locked in the machined part, which significantly increases the fatigue life of the part [191]. In the case of dry machining, due to the high temperature in the cutting area, a tensile nature of residual stresses are locked in the machined part, thereby reducing the fatigue life. Effects of cryogenic conditions during machining on tool life are also a subject of interest among academia and industry. As it directly affects the productivity machining process and quality of the machined component. Many authors have investigated tool wear using different cutting conditions as discussed above. They have reported a significant effect of cryogenic condition on tool life. Enactment of tool nose for a longer time also results in higher surface quality. Cryogenic machining reduces temperature-dependent tool wear significantly as it reduces chemical reactivity at work-tool interface and increases tool resistance to wear [82]. Dissolution-diffusion wear can be reduced under cryogenic condition. Although, the increase in the hardness of the workpiece material under cryogenic conditions will lead to an increase in the plastic deformation of the cutting edge. LN₂ condition during machining increase the hardness of work material and it leads to lesser sticking on the cutting interfaces that resulting in lesser CoF.

For composites, machining under cryogenic conditions is beneficial due to improvement in mechanical properties such as tensile strength and elastic modulus [183]. CFRP composites are drilled in stacks with titanium alloys. Machinability improvements in titanium alloys using cryogenic machining are widely reported. Conventional machining of composites may results in the dimensional inaccuracy of machined component due to moisture absorption [192]. Mg-based PMMC has hard particles of SiC as reinforcement that cause rapid tool wear during machining. Cryogenic machining of PMMC improves wear resistance of tool and reduces impact loading on tool due to contact with SiC particles as it increases isotropy of material. Cryogenic condition also increase

wear resistance of tool. For NiTi shape memory alloys control of temperature during machining is the best methods. As these materials have temperature-dependent properties. The benefits of using LN₂ as a cutting fluid for better machining performance of heat resistant alloys are widely reported in the literature. Moreover, many authors have claimed an increase in machinability of difficult-to-cut materials when machined under LN₂/LCO₂ combined with MQL/nMQL conditions. It is because of the better lubrication ability of MQL/nMQL combined with efficient cooling of cutting zone using LN₂/LCO₂. Many innovative methods are developed to supply cryoMQL mixture to the cutting zone. This technique is also reported to be beneficial for ferrous alloys. As it enables both lubrication and freezing of chips, which is required to improve chip breakability in the case of ferrous alloys. Though, more work is needed to optimize delivery parameters and to analyse machinability improvements in heat resistant alloys, ferrous alloys, and composites using LCO₂ and hybrid machining techniques [110,122]. Considering the global challenge to reduce carbon footprints, industries are adopting sustainable machining methods. Sustainability assessment of cryogenic and hybrid machining techniques can highlight the overall advantages of these techniques. A discussion regarding the in-house design and development of cryogenic and hybrid machining setups is presented in the following section.

5. Development of cryogenic and hybrid machining setups

In this section, different aspects of the design and development of LN₂, LCO₂ and hybrid machining setups are discussed in subsequent subsections.

5.1. LN₂ machining setup

This section discusses components of the LN₂ delivery setup for cryogenic machining in the first subsection. Material selection, insulation aspects, selection of flow parameters, and development of fixtures are discussed in the second, third, fourth, and fifth subsections.

5.1.1. Identification of components of the LN₂ delivery system for cryogenic machining

The schematic of the cryogenic machining setup is shown in Fig. 16. The LN₂ delivery system consists of the following components:

- Pressurized LN₂ container (Dura)
- Vacuum jacketed hose
- Phase separator
- LN₂ level gauge
- Nozzles

A 200-litre Dura is used for the storage and delivery of LN₂. Dura is made up of SS 304 material. It is double-walled construction with a vacuum jacket, equipped with two safety valves and a pressure indicator. LN₂ is supplied from the Dura to the cutting zone through a vacuum-jacketed hose. A phase separator is employed to separate vapour N₂ from the fluid to ensure that the N₂ is in a liquid state when delivered to cutting zone. The vacuum-jacketed hose along with the nozzle(s) are mounted on the fixture to direct the LN₂ to the cutting zone. For calculating the LN₂ flow rate during machining, a capacitance type digital level gauge is installed on Dura. The decrease in liquid level in Dura with time is noted for the calculation of the flow rate of LN₂ during machining.

5.1.2. Material selection for LN₂ delivery system components

The transition from ductile to brittle is determined by the crystal structure and yield strength of a material. Materials having the BCC lattice structure (for example carbon steel) have a lower number of slip planes can fail easily under impact loading due to restricted slip movement under low temperatures [193]. However, materials such as

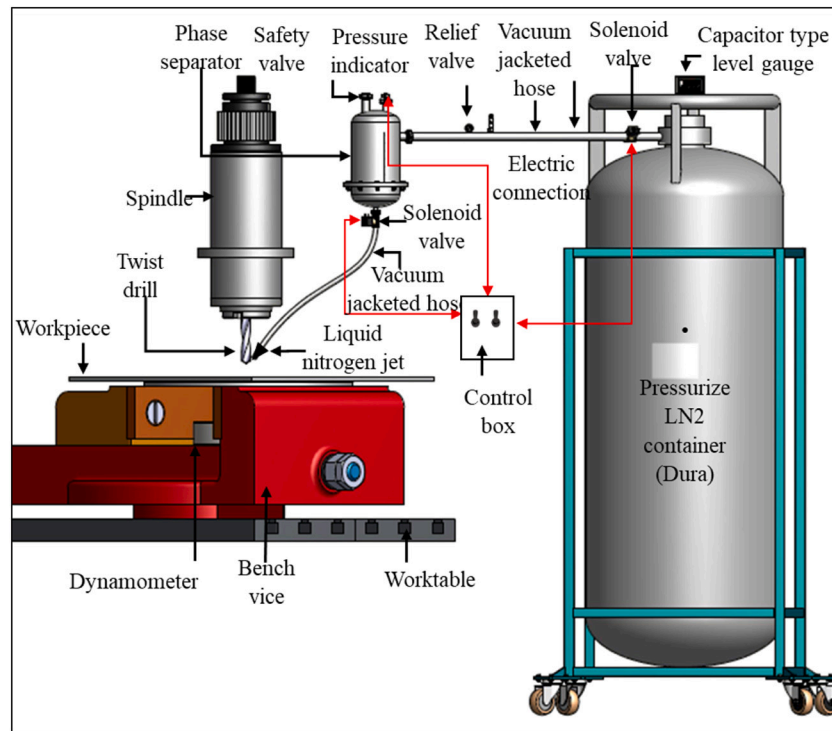


Fig. 16. Schematic of cryogenic machining setup.

α -titanium alloys and steel alloys with HCP and FCC lattice structure have more slip planes, hence they show good impact strength and ductility at cryogenic temperatures [194]. This is why steel, aluminium, and titanium alloys are mostly used for component works in the cryogenic environment [195].

Moreover, titanium and aluminium alloys are mostly used in the aerospace industry where a high strength-to-weight ratio is also required. Austenitic stainless steels such as SS 304 and SS 316 are suitable materials for the structural component of cryogenic machining setup as they show excellent impact strength, corrosion-resistant, ductility, and formability at cryogenic temperatures [196]. In this work, SS 304 is used for the construction of the vacuum-jacketed hose and phase separator. SS 304 shows constant impact strength and ductility at cryogenic temperatures [197]. This material can elongate up to 30% before failure at cryogenic temperatures. It is also an economically efficient option as compared to aluminium and titanium alloys.

5.1.3. Insulation of LN₂ delivery system components

The functional requirement of LN₂ storage and efficient transportation is high thermal insulation to restrict heat burst inside the container. A high level of insulation can be achieved using inner vessel storing/carrying cryogenic fluid enclosed in the outer vessel and vacuum evacuation of enclosed space. Vacuum evacuation between inner and outer vessel eliminates the possible convective heat transfer. Heat conduction is typically controlled by using low thermal conductivity material between the inner and outer vessel. The expanded form is one example of mass insulation that is frequently used in refrigeration applications. The apparent thermal conductivity of these materials falls between 25 and 60 mW/mK. However, due to the high linear thermal expansion coefficient, it cracks at low temperatures. For cryogenic applications, gas-filled power and fibrous insulation are used. For example, perlite, fibreglass, rock wool, silica gel, vermiculite, and santocel are the materials that fall in this category. The apparent thermal conductivity of these materials falls between 20 and 30 mW/mK. The insulation can be either evacuated or non-evacuated. The vacuum in the residual space can further reduce heat transfer. Moreover, the selection of insulation

material is based on the thermal conductivity, temperature, effectiveness of insulation, cost, weight, reliability, and ease of application.

Radiation heat transfer from the atmosphere is controlled by wrapping radiating film on the inner vessel. It is applied in form of a multi-layer stacked in parallel and separated by low thermal conductivity material [198]. The vacuum is obtained by repeated pumping, heating, and purging cycles. Heat transfer due to these modes of heat transfer is calculated using equations presented in Table 6.

5.1.4. Selection of delivery pressure and flow rate of cryogenic fluid

LN₂ inlet pressure, i.e., source pressure is critical, as it affects the outlet condition of LN₂. The selection of inlet pressure is critical, as it affects the outlet condition of the LN₂. As pressure increases, a range for which N₂ does not change its phase also increases shown in Fig. 17. This is why most of the authors have kept pressure above atmospheric pressure (near 1.5 MPa).

However, high pressure can create a problem of turbulence and throttling of the LN₂ and it may lead to more losses. Only a few authors have performed the optimization of cryogenic delivery parameters for machining. For instance, Tahri et al. [98] optimized LN₂ delivery parameters using CFD analysis and reported the best inlet pressure of 0.6 MPa and liquid/gas volume fraction of 90%.

Ayed et al. [97] suggested higher pressure and flow rate is suitable for better machinability performance. However, to improve the cooling efficiency of the LN₂ delivery setup, Pusavec et al. [128] have emphasized the significance of the LN₂ phase during machining. For which they employed phase separator and methods to identify the phase of cryogen.

Table 6
Heat loss due to different modes of heat transfer.

Attributes	Remark
Heat loss due to radiation	$q_{\text{radiation}} = \frac{\sigma A (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$
Heat loss due to convection	$q_{\text{convection}} = hA(T_{\text{internal surface}} - T_{\text{surrounding surface}})$
Heat loss due to conduction	$q_{\text{conduction}} = -kA \frac{dT}{dx} \approx kA \frac{T_1 - T_2}{l}$

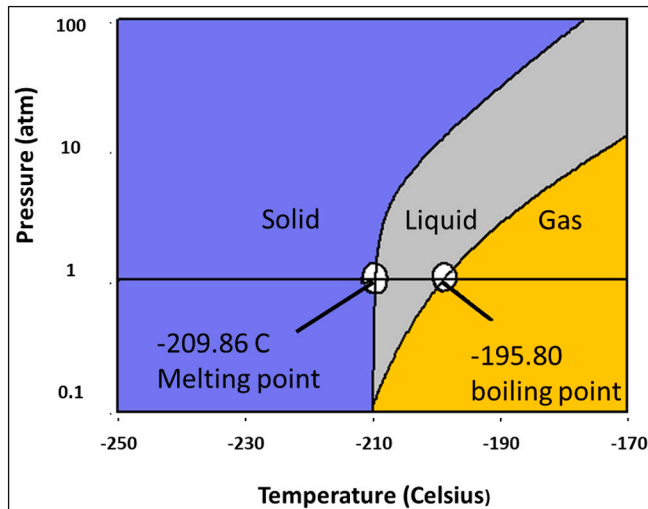


Fig. 17. N₂ phase diagram.

Therefore, to make an efficient delivery system, optimum pressure is critical to get the desired flow of cryogenic fluid in the liquid phase. In this setup, a Dura pressure of 0.6 MPa is selected for experiments based on a literature survey [199].

In past studies, the flow rate from 0.5 to 3 L/min is used to perform LN₂ machining. In these setups, approximately 1 L/min of LN₂ is consumed during experiments using a mono-jet. Moreover, during the dual jet and multi-jets machining experiment LN₂ is consumed at a rate of 1.5 L/min and 2.5 L/min respectively, for a stable flow of LN₂.

5.1.5. Development of fixtures for LN₂ machining setups

Fixtures are developed to retrofit the LN₂ delivery setup to existing machine tools. Mono and dual-jet LN₂ setups are developed for cryogenic turning and retrofitted with conventional lathe and CNC turning centre as shown in Fig. 18. The LN₂ machining setup with its variants is presented in Fig. 19.

5.2. LCO₂ machining setup

LCO₂ can exist at atmospheric temperature but it has to be stored at high pressure (Approximately 6 MPa). Hence, insulation is not required to restrict the loss as seen in the LN₂ case. For performing machining LCO₂ condition, a siphon (dip) tube was inserted into the cylinder storing CO₂ at 6 MPa. Siphon tube help CO₂ to come out of the pressurized cylinder without evaporation. When CO₂ is supplied from a nozzle to the cutting zone through a nozzle. It expands and evaporates due to the Joule-Thomson sublimation effect due to a drastic pressure drop and absorbs heat from the cutting zone.

5.3. Hybrid machining setups

5.3.1. CUAT setup

CUAT technique is a hybridization of cryogenic turning and ultrasonic-assisted turning (UAT) (refer to Fig. 20a). In-house developed UAT and LN₂ setups are retrofitted with the conventional lathe to get CUAT setup. UAT setup enabled ultrasonic vibrations to the tool in a direction parallel to the cutting velocity. These vibrations are generated with the help of a high-frequency generator and transmitted using a high-frequency cable to piezoelectric rings, which are mounted on the horn. Piezoelectric rings convert electrical energy into mechanical vibrations and transfer the generated vibrations to the cutting tool. For

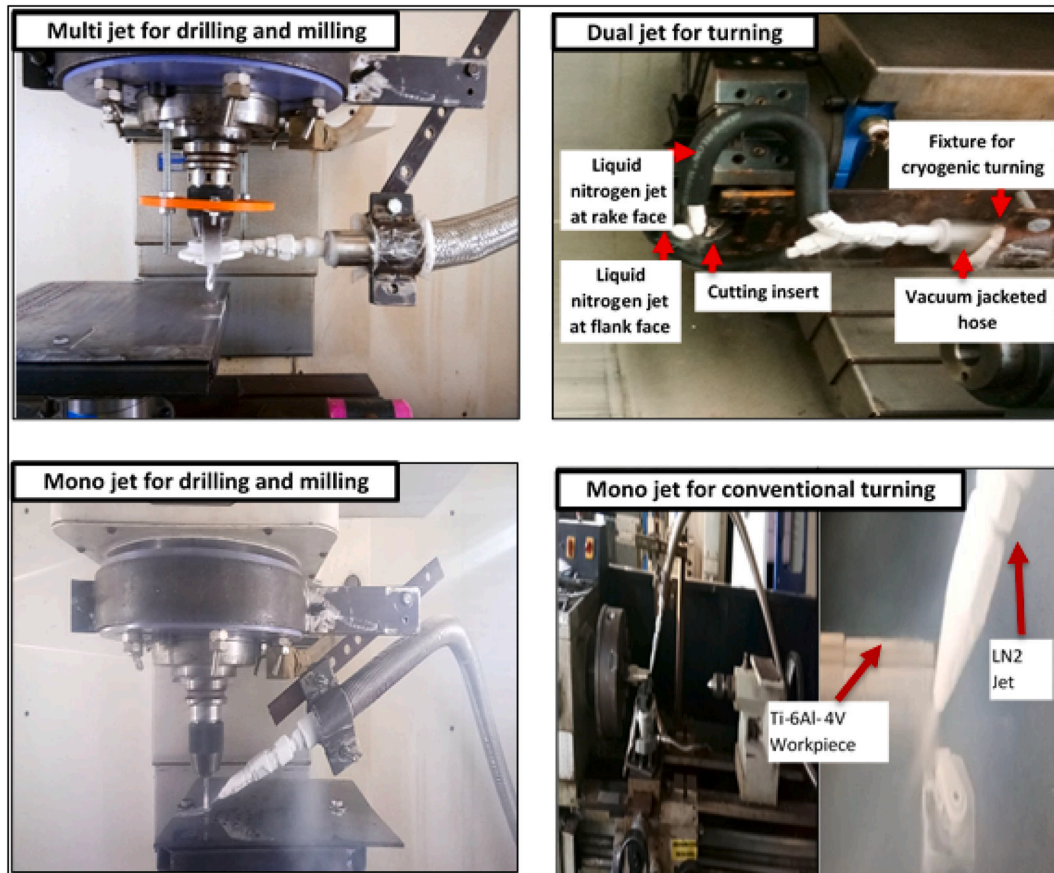


Fig. 18. Fixtures to retrofit cryogenic delivery setup to existing machine tools (Copyrights reserved) [33,188,200].

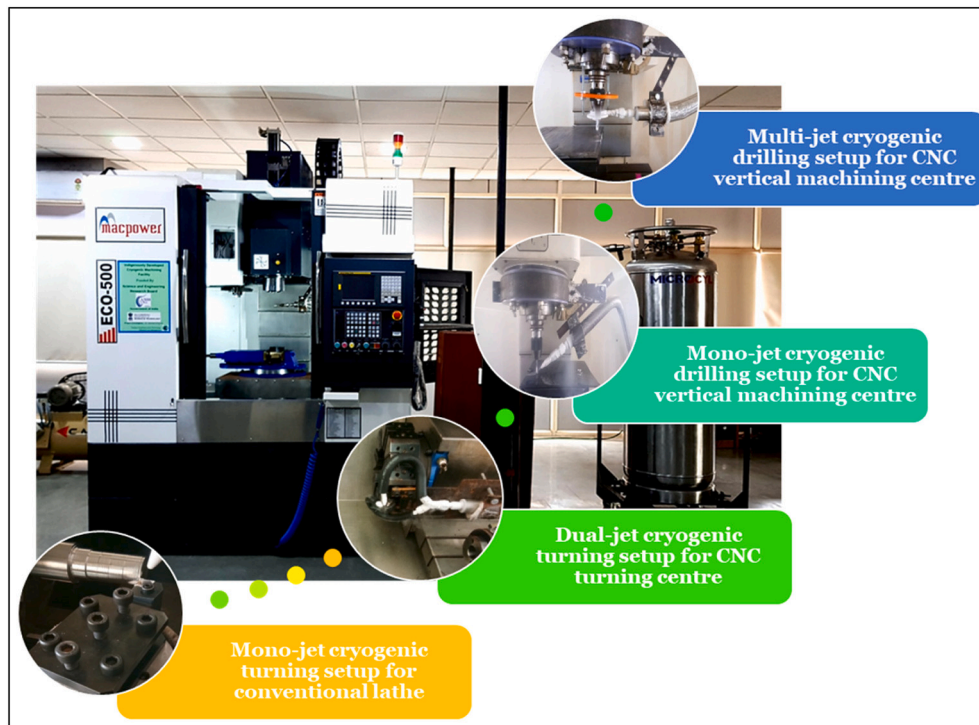


Fig. 19. In-house developed cryogenic machining facility.

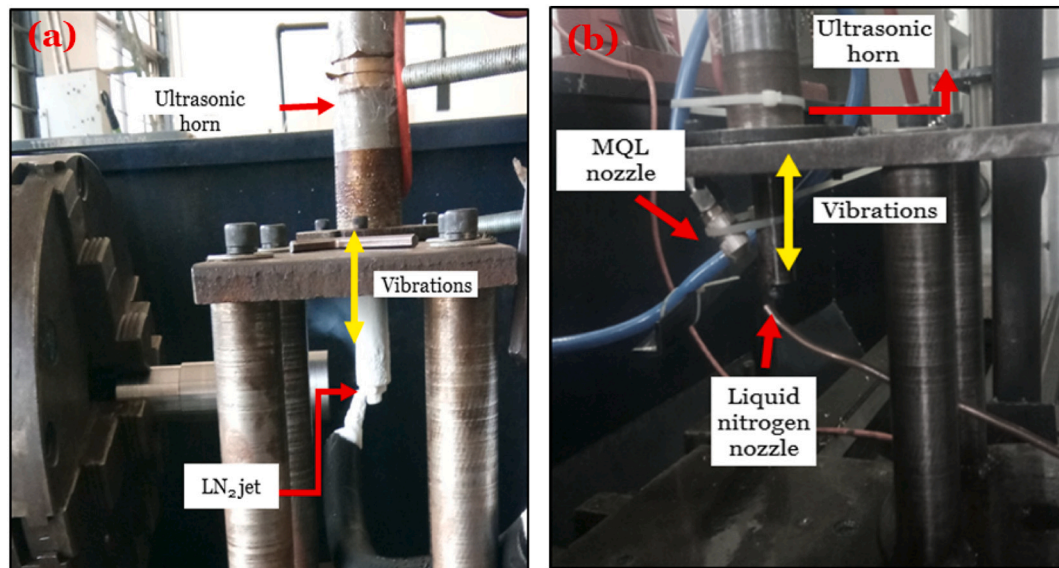


Fig. 20. (a) CUAT; (b) CUMQLAT setup (Copyrights reserved) [112].

UAT, cutting speed must be less than critical cutting speed (refer to Eq. (1)). This is because above critical speed UAT act as conventional turning [201]. For this UAT setup, the amplitude and frequency of vibrations are used at 10 μm and 20 kHz.

$$V_{critical} = 2 \times \pi \times \text{amplitude} \times \text{frequency} \quad (1)$$

5.3.2. CUMQLAT setup

CUMQLAT technique is a hybridization of CUAT and MQL assisted turning (refer to Fig. 20b). In-house developed CUAT and MQL setups are retrofitted with a conventional lathe to get CUMQLAT setup. For MQL setup, compressed air is transported from the compressor to the cutting zone through the FRL unit. FRL unit enabled mixing of compressed air

with oil. Oil consumption and pressure is controlled and monitored using gauges attached to the FRL unit. In this setup, oil mist was sprayed at rake face 0.6 MPa using a 2 mm nozzle. at the rake face from a stand-off distance of 20 mm at an angle of 75° from perpendicular to cutting speed vector.

6. Challenges and future trends

Despite the unquestionable advantages of cryogenic machining regarding the machinability of many low machinability materials, this technique's large-scale use still faces some barriers in all aspects of the triple bottom line to supports its sustainable implementation. The first

barrier is regarding the social aspect, dictating that more knowledge about the technique must be spread, to make companies believe in this green technology and implement it on the shop floors. The second point is regarding the environment, since the scientific literature about the overall sustainability of the process is scarce, with missing papers considering the impacts of the production of the cryogenic coolants on the environment. The third aspect is regarding the delivery system that is rarely industrialized. Most of the delivery systems are homemade that seems inexpensive. Few studies are focusing on the costs of implementing or adapting this technology in the industries. From a more technical and scientific point of view, one of the main challenges is to deliver cryogenic coolants at even higher pressures. The techniques currently covered are divided into those that use the natural expansion of the cryogenic fluids stored at high pressure and those that use heating based on electrical resistances to generate the pressure increase. Both techniques result in pressures generally below 1 MPa and not maintaining this pressure long enough to be safely applied on an industrial scale. Although many patents have been applied in recent years, cryogenic machining still lacks designs that allow for better efficiency and less waste in delivering the coolant.

The use of cryogenic cooling in the machining of low-machinability materials remains the main research trend. Since it is well known that the technique improves the tool life, the research trends are now shifting to the surface and especially the sub-surface integrity. The focus on sub-surface integrity is especially aimed at heat-treated alloys (such as hardened steels and precipitation-hardened materials), or materials that may show phase changes with increasing temperature generated during machining as the shape memory alloys. The number of studies on the effect of the technique in polymers and composites' machinability indicates that this is also a trend. The effects of cryogenic cooling on the chip and burr formation, surface integrity, and fibre orientation near the cutting zone are future research trends. Hybridization of cryogenic machining processes with other sustainable manufacturing processes can also provide a new direction to researchers.

7. Conclusions

As the modern manufacturing industry strives to achieve more sustainability, cryogenic and hybrid machining techniques stands out as one of the most promising methods. This paper reviewed the current state-of-the-art cryogenic and hybrid setups intended for difficult-to-machine alloys and composites to help in that goal. Machinability aspects and problems discussed in recent investigations for titanium-based alloys, nickel-based alloys, ferrous alloys, composites, and other difficult-to-cut alloys are reviewed. Design and development aspects of in-house developed cryogenic and hybrid machining setups are discussed. This review article also discusses the sustainability aspect of machining techniques, as it is an important asset for this technology to be implemented on a larger scale. Following are the main conclusion drawn from this study:

- Most of the literature's patents discuss different solutions to deliver cryogenic fluids to the cutting zone. However, the development of efficient delivery systems to carry out hybrid machining can lead to further improvement in the machinability of difficult-to-cut alloys and composites.
- Sustainability assessment of different cryogenic and hybrid machining techniques remain relatively less explored. More investigations in this direction could help industries to adopt these technologies.
- For titanium alloys, based on literature, it can be noted that there is still no consensus regarding the best cryogenic delivery methods for machining the aforementioned materials, which impairs the large-scale implementation of this technique. Further hybridization of cryogenic machining techniques with near dry machining techniques

such as MQL, EMQL, and nano-MQL can be beneficial for titanium alloys' machinability improvements.

- For nickel-based alloys, machinability improvements of very few alloys such as Inconel 718 and Nimonic 90 were explored using cryogenic machining techniques. Exploration of machinability improvements of other alloys of nickel using cryogenic and hybrid machining techniques can be beneficial. Moreover, research work is needed to understand cryogenic drilling and milling of nickel-based alloys as most of the studies have focused on cryogenic turning. As the cutting mechanics of turning operation is different from drilling and milling operations.
- For cryogenic machining of ferrous alloys, machinability improvements were observed in chip breakability, white layer formation, and tool life. However, the hybridization of cryogenic machining with near dry machining techniques can improve the economic aspect of sustainability of the process.
- For composite materials, very few studies have focused on machinability improvements of metal matrix composites using cryogenic machining. Hence, more studies are needed to understand the machinability of different particulate metal matrix composites and fibre reinforcement plastics under cryogenic and hybrid machining techniques.
- The possibility of machinability improvements for few other alloys such as NiTi shape memory alloys and tungsten are explored in the past. However, the work done in this direction is also very limited. More work is needed to realize the full potential of cryogenic and hybrid machining techniques in machining these alloys.

Cryogenic and hybrid machining techniques must be encouraged because of their importance to sustainable manufacturing, and companies need to endeavour efforts towards developing industrial cryogenic and hybrid machining systems at affordable prices. Further integration of the cryogenic machining technique with various MQL, ultrasonic, and laser-assisted techniques can improve machining techniques' efficiency. Moreover, the application of Industry 4.0 in cryogenic and hybrid machining techniques can lead to effective control of input process parameters and coolant delivery parameters.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

The work presented in this paper is, to the best of my knowledge and belief, original, except as acknowledged in the text, and the material has not been submitted, either in whole or in part, for a degree at this or any other university. There is no conflict of interest to declare.

Acknowledgement

The authors would like to thank the SERB-DST, Government of India, for the financial support given under the Make-in-India project (ECR/2016/000735), titled "Design and Development of Energy Efficient Cryogenic Machining Facility for Heat Resistant Alloys and Carbon Fibre Composites".

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