Application of Cryogenic Coolants in Machining Processes
State-of-the-art Literature Study and Experimental Work on Metal Matrix Composite

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Abstract

Conventional cutting fluids are known for being expensive, polluting and a non-sustainable part of modern manufacturing processes. Global industrial trends are leaning towards environmental and health friendly technologies. Cryogenic cooling is an innovative and sustainable method, capable of replacing conventional oil-based cutting fluids under various conditions. The method has already proved to have a great potential in many different machining setups, performing equally or better than conventional cooling strategies in all criteria concerning machinability. Majority of research work published about cryogenic machining has revolved around turning operations most commonly in combination with steels, nickel-based alloys and titanium-based alloys. Other machining operations, e.g. milling and drilling, are less researched leaving the field with a great amount of unexplored areas. Although the technology has been developing for more than 60 years the general knowledge on the subject among machining specialists is relatively low. The room for improvement is large and further optimization is necessary before more generalization of the technique within the industry.

In the first part of this work a comprehensive state-of-the-art literature study is presented, with the main focus on turning, milling and drilling operations. Parallel to the making of the essay, a new search system within published work about cryogenic technology was designed and developed to create a database of knowledge for Sandvik Coromant in future cryogenic research. The second part of the essay covers the experimental work where tests were performed in drilling of metal matrix composite under different cooling strategies. The results revealed an advantage in the favour of CO₂ cryogenic cooling concerning precision and surface finish but an obvious need for further optimization of the process was evident as well.

Keywords: Cryogenic machining, Drilling, Milling, Turning, Manufacturing, Metal Matrix Composite, Sustainability, Cutting fluids
Sammanfattning


**Nyckelord:** Kryogenisk bearbetning, Borrning, Fräsnings, Svarvning, Tillverkning, Metal Matrix Composite, Hållbarhet, Kylvätskor
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1 Introduction

Cryogenics in the context of scientific sense is usually referring to events occurring at temperature -153°C or lower [1]. In the usual meaning of cryogenic liquids, chemicals such as liquid nitrogen, oxygen, helium, methane, carbon dioxide, ethane and argon are the area of interest. In this thesis work when referred to cryogenics, mainly only carbon dioxide (CO₂) and liquid nitrogen (LN₂) are within the interest zone.

The modern manufacturing world of producing and processing metals, offers a great variety of alternatives to produce a product demanded by the market. Turning, milling and drilling are among the most common methods exercised in order to shape and form metals to meet the requirements of the market. Myriads of factors affect the final outcome and productivity in manufacturing processes and higher demands are constantly forcing the industry to improve and optimize working methods [2].

Cutting fluids which are provided to the cutting zone in metal cutting are one of the most important elements in machining metal parts. The main purpose of cutting fluids is to provide cooling and lubrication in the cutting zone, workpiece, tool or the chip [3]. They are either classified as coolants, lubricants or a chemical formulation of cutting fluids which are designed to provide both cooling and lubrication. Coolants are usually water-based solutions or water emulsions and lubricants are usually oil-based fluids. Cooling-lubrication cutting fluids are most commonly oil-based and contain dozens of chemicals which can be hazardous for the environment [4, 5].

Environmental issues and sustainability demands are growing and have become an inseparable part of modern manufacturing. The industry is being forced to come up with innovative and sustainable solutions to sustain its level of competitiveness. Using cryogenic cooling liquids is an environmentally friendly method of providing cooling and lubrication to the cutting zone. Under certain parameters, cryogenic cooling has shown clear superiority over conventional oil-based coolants with pressure additives. E.g. the cooling efficiency is normally much higher and in some cases the conventional cutting fluids fail to provide desirable control of cutting temperature due to their lack of ability to penetrate sufficiently to the chip-tool interface [6].

Research and experiments with cryogenic gases as cooling and lubrication can be dated back to the 1950’s and is still being developed by scientists today [7]. The technique has not been fully adapted by the industry but has shown some great potential within certain combination of materials, cutting tools and machining methods [5]. Among the most common materials showing promising results associated with cryogenic cooling are difficult-to-machine materials such as nickel-based alloys, titanium-based alloys and hardened steels [8, 9].

In the criteria for machinability there are usually few factors involved in the judgment. The factors are:

- Chip form
- Magnitude of cutting forces
- Vibration of machining system
- Tool wear
- Surface finish
• Dimensional deviation [10]

These are all issues that have been proven to be influenced positively by cryogenic cooling.

1.1 Early History
Since the mid-19th century, examination of low-temperature technique has been developing. During that era, the fundamentals of thermodynamics started progressing and the first contributors to cryogenic science did their work between 1850 and 1900. In the beginning there was almost no practical use of the applications and the subject was only within the tight interest of scientists. The first challenges was simply to discover technique to reach temperatures low enough to liquefy gases like oxygen, nitrogen, hydrogen and helium [1]. The transfer of the liquefaction technology took place in the first half of 20th century. The first application in the production sector was the production of oxygen for the welding industry

![Figure 1 A timeline for early milestones in cryogenic technology][1]

The first reported machining using cryogenic CO₂ is from 1953 [11]. In 1961 W.S. Hollis stated that he could increase the life of carbide tools by using CO₂ as a coolant when machining titanium alloys [12]. In the 60’s, researcher at the Grumman Aircraft Manufacturing reported about increased material removal rates in machining titanium with LN₂ and CO₂ [13]. Uehara and Kumagai in 1970 experimented with cooling a titanium-alloy, carbon and stainless steels. Their observations concluded that we get different behavior for different metals and having various effects on tool life, surface roughness and flank wear [14].

1.2 Cryogenic technology
Several cryogenic liquids are available but for machining operations, CO₂ and LN₂ are almost exclusively used. To distinguish between liquid CO₂ and LN₂ we have to look into deeper the mechanism causing the low temperatures to occur.
1.2.1 LN$_2$

Figure 2 on the right shows the phase diagram for LN$_2$. The triple point, occurring at pressure 0.13 bar and -210°C, is the state where nitrogen can be found at all forms. LN$_2$ is nitrogen in a liquid state at a very low temperature and usually stored in isolated tanks at very high pressure. When the media enters the ambient temperature and the pressure drops (1.01325 bar), the nitrogen starts boiling at -196°C [15]. In cutting processes it absorbs the heat dissipated from the cutting process and evaporates into nitrogen gas and becomes a part of the air. It is safe non-combustible chemical and leaves no harmful residue to the environment since in becomes a part of the other 79% of nitrogen in the atmosphere [3, 16, 17]. However, in some cases when LN$_2$ comes in contact with hot surfaces it starts boiling and vaporizing, an insulating film of gas forms and surrounds the part, reducing the cooling effect [15].

1.2.2 CO$_2$

Figure 2 on the left shows the phase diagram of CO$_2$. At pressure from 0 to 5.2 bar and temperature from absolute zero (-273 °C) to -56.6°C, CO$_2$ can only be at solid or gaseous state. In order to get it on liquid form, CO$_2$ must be kept at pressure above 5.2 bar. Thus, CO$_2$ is often stored in a medium pressure tank (MPT) at pressure of 57 bar in liquid form at around 20°C (see Figure 2). In a cutting process it is provided through pressure-resistant pipes to guarantee the same phase of the chemical from the tank to the cutting zone. When the CO$_2$ exits the pipes and enters the atmospheric pressure, it experiences a major pressure drop, causing it to expand and cool down due to the Joule-Thomson effect [18]. This conversion of the physical state is called the process of sublimation [19]. The CO$_2$ cools to -78.5°C and transforms in 40% snow and 60% gas. The energy required for this transformation is taken from the surroundings in the form of heat. CO$_2$ is dry and after it has served its role as a cutting fluid the chemical sublimates to the air and leaves no residue. This characteristic makes it a suitable choice for machining materials which are incapable of using liquid coolants. [15].

1.2.3 Application of cryogenic cooling

The cryogenic liquid is supplied to the cutting zone through various ways and equipment. The liquid is stored in cylindrical or spherical shaped tanks including pressure control and vaporizer [20]. In the process of spraying the cryogenic cooling, the pressure in the tank itself forces the coolant to the cutting zone and no additional energy is needed for the application [17].
In this essay the main distinction is made between internal and external supply. The internal cooling is provided through a specially designed tool where the nitrogen or CO$_2$ enters the cutting zone in the nearest proximity to the tool-chip-workpiece interface. The external cooling can either be provided through a nozzle which is positioned to aim the coolant where needed (see Figure 4) or through a cap-like reservoir which can be used in turning operations where the reservoir is placed above the insert (see Figure 5) [14].

The most common way of taking advantage of cryogenic cooling is to deliver it to the cutting region, exposing it to the highest temperature in the machining process [17]. It can also be aimed specially at the workpiece seeking to change or improve material characteristics [22]. For the highest efficiency, having the spraying nozzle as close as possible to the contact area is essential [23, 24, 25]. The flow can be complicated to optimize when the spraying nozzle is placed far away from the cutting edge.
That usually results in much higher flow rate and simultaneously there is a need for preventing the cooling from being wasted to parts of the machine or nearby items where it’s unwanted. The extremely low temperature of cryogenic cooling can be harmful by changing the microstructure and mechanical characteristics of a material [15, 24].

Using external high pressure nozzles jets to apply the coolant is the most inaccurate one of these three already presented methods. It usually demands the highest flow rate of LN$_2$ or CO$_2$, where the cooling is applied in the tool-chip-workpiece interface. Most commonly the nozzles are placed and aimed to the cutting zone without any further help from the machining operator. However, there are examples where the operators are required to aim the nozzles manually which exposes him to various unnecessary risks.

![Figure 5 Photograph of tool holder and coolant delivery nozzle [26]](image)

The cap-like reservoir which is integrated into on top of the tool is an improvement from the external high-pressure nozzles, considering flow rate and accuracy. However, this method also require high flow rate so the coolant capable to penetrate fully to the cutting zone [27].

![Figure 6 Modified cutting inserts for turning for internal supply of LN$_2$ [21]](image)
When the cryogenic media is supplied via internal supply leading through the spindle, a distinction needs to be drawn between cooling with CO$_2$ and LN$_2$ when it comes to systems engineering. The LN$_2$ has significantly lower temperature than CO$_2$ and thus simple bearings and rotary feeds are not designed for such low temperatures. The spindle has to be equipped with a special vacuum-insulated conduit [15, 27] and a special rotary feed-through which allows for low temperatures has to be used to carry the nitrogen through the channels. Part of the nitrogen vaporizes on its way through the cooling channels, leading to cooling within the tool. [14]

1.3 Application of cryogenic cooling
Cryogenic cooling is known for being beneficial in many kinds of machining setups in terms of workpiece materials, tools material and tool geometry. The upcoming subchapters will cover the most notable ones.

1.3.1 Materials
Up till now, the main focus of application of cryogenic cooling has been associated with the so called difficult-to-machine materials. In that category among others are materials, often classified as aerospace materials or super-alloys, which are known for its high strength characteristics. Aerospace materials are very tough, resistant to corrosion and capable of sustaining strength in extreme conditions such as high temperature which make them to conform to strict safety regulations within the aerospace industry. High strength-to-weight ratio is also required to ensure the highest possible fuel consumption. [28]

The nature of aerospace materials make them very difficult to machine. The exceptionally low heat conductivity leads to high thermal tool load since only part of the heat is carried out with the chips. High friction leads to concentrated process heat at the tool-chip interface [8] Thus about 20-30% of extra thermal energy can be added on the cutting tool which increases the ductility and accelerates wear mechanism [8, 29]. The tool wear is often due to adhesion-dissolution-diffusion of tool material into the flowing chip at the chip-tool interface and also the chemical reaction between the tool and the chip [27, 30]. Scientists believe that the gross inhomogeneous plastic deformation in the chip limits the machining productivity [27]. For those reasons aerospace materials are machined at low cutting parameters and thus resulting in low productivity.

Materials classified as aerospace material in the everyday meaning e.g. alloys of steel, nickel and titanium. Research and experiments on cryogenic machining of these materials have shown promising results which is by most scientists considered to be attributed to lower temperature in the machining process. Other materials reporting about positive impact on cryogenic machining are materials such as tungsten carbide parts, low alloy steel AISI 4340, stainless steel and carbon steel [23, 29, 31].

1.3.2 Tools
Cutting tools in cryogenic cooling are of many kinds but the majority of studies involving cryogenic cooling have been performed with carbide tools, both coated namely with PVD and PCD. Tests have also been carried out with CBN, diamond and ceramic tools but it is hard find studies or trend for better efficiency with the more advanced and expensive tool materials [7, 23].
1.3.2.1 Tool geometry

For turning operations, several kinds of cutting inserts have been exercised. From the observations of this literature study, a diamond or square shaped cutting inserts are the most common ones, with 12mm length and thickness of 4,76 mm (see Figure 7). The radius is most commonly from 0,4 to 0,8 mm [10, 26, 30, 32, 33, 34, 35, 36, 37, 38, 39]. Triangular geometry [27] has also been tested but not as frequently.

![Figure 7 Carbide cutting inserts of common geometry for turning operations [40]](image)

Within drilling and milling operations, no remarkable trends in the employment of tools were noticed.

1.4 Process parameters

Process parameters are important in every machining operation. In order to get the highest efficiency of the selected combination of cutting tool and material, the process parameters have to be optimized. That can be a highly complex process but necessary to stay competitive. Whether it’s the flow rate of the coolant, the shape of the tool the cutting parameters, the slightest deviation can have massive impact on the process.

1.4.1 Flow rate and pressure of cryogenic supply

The flow rate of external supply of LN$_2$ has mostly been reported in combination with turning operations. The range is from 0,5 kg/min to 3,36 kg/min at pressure of 1,4-24 bars with the most common combination with flow rate less than 1 kg/min with pressure from 7,5-15 bars [5, 17, 22, 27, 34, 35, 39, 41, 42, 43, 44, 45]. Dhananchezian et al. [21] are the only one to report about pressure from internal application of LN$_2$ at pressure of 3 bar.

The only occasion, the flow rate was mentioned in an article concerning milling operation with LN$_2$ the flow rate was 4,2 kg/min [3].

For the flow rate of CO$_2$ the flow rate was rarely mentioned. Schaarschmidt et al. [46] and Machai et al. [8] performed tests with internal application of CO$_2$, where Schaarschmidt et al. milled with a flow rate of 0,48 kg/min and Machai et al. used a flow rate at 2,72 kg/min in a turning operation. Bermingham et al. [26] and Klocke et al. [39] used external CO$_2$ in turning operations at 8,2 and 6 bar pressure respectively.

1.4.2 Cutting parameters

The cutting speeds are highly dependent on the workpiece material. In turning operation on nickel-based alloys, the most common cutting speed tested was on the interval from 30 $V_c$=30-130 m/min [5, 15, 35, 42, 45, 47] although one experiment had cutting speeds up to 300 m/min [43]. The feed
rate were also quite low, from \( f = 0.05-0.25 \text{ mm/rev} \), most commonly from 0.05-0.10 mm/rev. The depth of cut was from \( a_e = 0.66-1.5 \text{ mm} \).

The titanium-based alloys allowed on average for higher cutting parameters than nickel-based alloys. Usually the cutting speed was tested from \( V_c = 70 - 150 \text{ m/min} \) with feed rate at \( f = 0.10 - 0.25 \text{ mm/rev} \) [8, 15, 21, 26, 27, 29, 38, 30, 39, 48, 44, 47]. Venkatesh et al. [11] and Dhananchezian et al. [21] are the two exceptions, testing at cutting speed \( V_c = 300 \text{ m/min} \) and \( V_c = 27 \text{ m/min} \) respectively. The Depth of cut was from \( a_e = 0.30 - 2.00 \text{ mm} \).

Only three studies reported about cutting parameters in drilling operations with cryogenic cooling. Only a handful of reports including cutting parameters for milling of other materials were available. Truesdale and Shinn [52] milled the nickel-based alloy Udime 720 with external LN\(_2\) at cutting speeds \( V_c = 90 - 180 \text{ m/min} \) and feed rate \( f = 0.04 \text{ mm/rev} \) coming to the conclusion that 120 m/min was the maximum cutting velocity allowed with acceptable surface finish. Klocke et al. [37] milled titanium-based alloy with external LN\(_2\) at cutting speed \( V_c = 100 \text{ m/min} \), at feed rate \( f = 0.03 \text{ mm/rev} \) and axial depth of cut \( a_e = 5 \text{ mm} \) and radial depth of cut \( a_e = 8 \text{ mm} \).

Wang and Pajurkar [41, 47] turned Ceramic at \( V_c = 133 \text{ m/min} \), feed rate \( f = 0.10 \text{ mm/rev} \) and depth of cut \( a_e = 0.50 \text{ mm} \). Franci Pusavec [22] made experiments with tungsten at cutting speeds \( V_c = 30 - 120 \text{ m/min} \), feed rate \( f = 0.04 - 0.10 \text{ mm/rev} \) and depth of cut \( a_e = 0.05 - 0.20 \text{ mm} \).

For milling operations few tests have been reported about the cutting parameters associated with cryogenic cooling. Schaarsschmidt et al. [46] performed tests on austenitic stainless and martensitic steel with internal application of coolant at cutting speed \( V_c = 320 \text{ and } V_c = 390 \text{ m/min} \), respectively. The feed rate was \( f = 0.40 \text{ mm/rev} \) and the depth of cut was radial \( a_e = 30 - 50 \text{ mm} \) and axial \( a_e = 3 - 4 \text{ mm} \). Nalbant et al. [3] end milled stainless steel with external application of LN\(_2\) at relatively lower cutting parameters with cutting speed at \( V_c = 80 - 200 \text{ m/min} \), feed rate \( f = 0.05 \text{ mm/rev} \), radial cut \( a_e = 15 \text{ mm} \) and depth of cut \( a_e = 0.5 \text{ mm} \).

Only a handful of reports including cutting parameters for milling of other materials were available. Dionne et al. [19] milled a carbon fiber reinforced polymer (CFRP) with CO\(_2\) cooling at cutting speed \( V_c = 120 \text{ m/min} \), feed rate \( f = 0.30 \text{ mm/rev} \), axial depth of cut \( a_e = 1.50 \text{ mm} \) and radial depth of cut \( a_e = 6.35 \text{ mm} \).

Only three studies reported about cutting parameters in drilling operations with cryogenic cooling. Dionne et al. [19] drilled CFRP-titanium stackup material with internal application of CO\(_2\) at cutting speeds \( V_c = 30 \text{ m/min} \) and feed rate \( f = 0.11 \text{ mm/rev} \). Dix et al. [53] modeled drilling operation with internal LN\(_2\) cooling at cutting speed \( V_c = 105 \text{ m/min} \) and feed rate of \( f = 0.21 \text{ mm/rev} \). Venkatesh et al. [11] performed drilling operation on titanium-based alloy with LN\(_2\) at cutting speed \( V_c = 10 \text{ m/min} \) and feed rate \( f = 0.10 - 0.40 \text{ mm/rev} \). Note, the there are no information about the application of the LN\(_2\) in this article.
1.5 Environment and ergonomics

The consumption of natural resources and pollution are leading to increasing pressure on politicians to make more strict regulations on manufacturers. Implementing sustainability principles in machining technology should result in improved environmental, economic and social performances (see Figure 8). Few of the actions the industry can strive to achieve, in order to move towards more sustainable production, is to:

- Reduce energy consumption in machining processes
- Minimize waste
- Utilize resources efficiently
- Improve management of cutting fluids, chips and oils
- Adopt life cycle assessment methods [17]
- Use renewable sources

![Figure 8 The three pillars of sustainability [17]](image)

In modern manufacturing, cutting fluids are an inseparable part of many machining operations. Oil-based cutting fluids are not only expensive financially but also a liability on the nature. Cutting fluids are often the main source of pollution from the machining industry. Identifying conventional oil-based cutting fluids as a major non-sustainable element of the process have led to implement alternate cutting fluid mechanisms. Cryogenic cooling is a sustainable alternative to conventional flood machining, as it evaporates to the atmosphere and leaves no residues. Oils which are hazardous to the nature are also extremely flammable and can cause serious danger within the laboratory [5, 17, 25].
1.5.1 Environment

Conventional oil-based cutting fluids include chemicals that cause water pollution, soil contamination [9, 10]. Chemicals like hydrocarbons, sulfur, phosphorus, chlorine and biocides are example of chemical that can be found in oil-based coolants and are harmful to the nature and can have severe effects on lakes, rivers and groundwater [5]. On the other hand, cryogenic cooling is a residual free and environmentally friendly machining method. The comparison of inputs and outputs of conventional oil-based machining and cryogenic machining is compared in Figure 10.
Cryogenic cooling is also capable of substituting infiltrants which are used to machine porous tungsten. The infiltrants are used to maintain the surface porosity in machining processes of the tungsten workpiece. However, the infiltrants are not environmentally friendly and cryogenic machining of porous tungsten appeared to be an alternative which can maintain acceptable surface porosity at similar or even higher cutting parameters [22].

CO$_2$ is by most researchers considered to be a greenhouse gas and one of the main chemical responsible for global warming [55]. With that fact in mind, a logical conclusion would be to state that machining with CO$_2$ cooling would not be environmentally friendly. However, the majority of CO$_2$ used for machining operations in Europe is processed through sources where the CO$_2$ serves as a waste product. If it wasn’t used for the machining purpose, it would otherwise find other paths to escape to the atmosphere and thus making the CO$_2$ machining process environmentally neutral [15].

In order to produce LN$_2$ used for machining, high energy is required for the process. If non-sustainable resources are used for producing the LN$_2$, a machining processes taking advantage of that specific coolant cannot be counted as environmentally friendly. In this case a trade-off can occur between the environmental burdens and higher energy consumption from the other alternative. However, the LN$_2$ can be produced through renewable energy resources giving it a head start concerning sustainability [17].

### 1.5.2 Personnel health

Oil-based mists have been revealed to be dangerous to human health. They can involve harbor bacteria and contain surfactants, biocides, chlorinated fatty, chelating agents and defoamers. Both surfactants and biocides are proven to impair lung functioning. Personnel are also exposed and vulnerable to these chemicals through dermal pathways [17, 56, 5]. In a chemical breakdown, an environmental pollution can occur especially at high temperature. The system often becomes a premium conditions for bacterial growth which can be dangerous to the operator. Due to that a lot
of space, equipment and time have to be spent making an effort in order to keep the system clean. The disposal cost of the hazardous materials is high and can raise the total cost significantly [33].

1.5.3 Chip disposal
Chips or swarf from machining operations can often be recycled in order to obtain higher resource efficiency especially in aerospace industries. In conventional oil-based machining the chip leftovers are covered in oil, making them unrecyclable unless it’s separated from the oil and shredded. That requires an extra process, wasting time, energy and presumably other natural resources. In cryogenic machining, the coolant, weather it is CO\textsubscript{2} or nitrogen, evaporates to the atmosphere after it has served its role as a coolant. Hence, the chips can be recycled directly after machining [5, 57].

1.5.4 Energy consumption
Manufacturing processes in general require high energy and few factors have to be considered when calculating to total energy cost. Cutting energy itself which changes with the cutting forces required to machine does not differ so much in the big picture of total energy consumption. Higher energy efficiency is obtained by increasing the material removal rate. Through that, the total energy consumption of a machine is reduced due to shorter process times in connection with basic functions of a machine e.g. energy for control, non-cutting time, flushing etc. However, higher cutting parameters are often joined with faster tool wear which might influence the big picture from an economical point of view [58, 59].
2 Operations
The focus of this literature review will be on three of the most common machining operations: Turning, milling and drilling. Although research work has been published about other machining operations, most notably grinding, in this thesis work we are limited to these three methods.

2.1 Turning
Turning is a machining process where a single-point tool removes material from surface of a rotating cylindrical workpiece. The tool is fed linearly in a direction parallel to the axis rotation of the workpiece [4]. The majority of research work on cryogenic machining has been made on turning operations. One of the reasons for that is the easy access of the cryogenic media to enter the cutting zone with an external nozzle in a single-point turning (see Figure 11) [7]. In the upcoming subchapters, cryogenic turning associated with different materials will be covered.

![Figure 11 A schematic of the economical cryogenic machining approach](image)

2.1.1 Titanium Alloys
F. Pusavec et al. [17, 32] made experiments and studies promoting sustainable production methods. They compared cryogenic LN₂ cooling with high pressure jet assisted machining (HPJAM) and conventional emulsion machining. In one of their studies [17] they compared the life cycle assessment in turning operations of the same product over a whole year between the three aforementioned coolant strategies. Their results, although being built on many assumptions, indicated that the environmental impacts from conventional emulsion and HPJAM are significantly higher compared to cryogenic cooling the when looking at the coolants exclusively.
Machai et al. [8, 38, 48] published 3 articles about the machining of β-titanium alloys which are known for being the most difficult to machine of all titanium alloys. The workpiece material they used was Ti-10V2Fe-3Al which offers the best combination of strength, fracture toughness and fatigue strength among all aluminum alloys. The tests were carried out on a CNC-lathe with cemented carbide tools, both coated with (Ti,Al)N-TiN and uncoated. CO₂ was applied through the tool holder via a nozzle integrated above the cutting insert. According to them, cemented carbide tools with a sharp cutting edge should be used for turning β-titanium alloys in order to achieve the highest tool life, both for flood emulsion and cryogenic cooling (CO₂).

Figure 12 shows SEM-pictures of cemented carbide’s cutting edge condition after different cutting lengths. The pictures to the left reveals notch wear forming during emulsion machining. On the rake face of the tool, for both emulsion and CO₂ machining, workpiece material has started welding. Hence, in this case, the CO₂ is not managing to penetrate to the cutting zone fully to suppress the chemical reactivity of the workpiece material. However, the cooling of the CO₂ maintained the hardness of the tool and reduced friction at the flank face. The development of flank and notch wear on the coated tool was highly reduced. The analysis revealed that the coating was removed on and beneath the minor and major cutting edge but occurred much slower compared to flood emulsion.

![Figure 12 SEM images of the coated cutting tool (a) with oil-based conventional cooling and (b) with CO₂ snow [8]](image)

The tool life increased for all tested tools at a cutting speed of \( v_c = 100 \text{ m/min} \) with cryogenic cooling. Especially tools with rounded cutting edge benefitted due to reduction of friction occurring at the flank face because of the lower temperatures and less deflection of the machined workpiece surface. The coated tool with sharp cutting edge offered the longest tool life for both cryogenic and emulsion cooling.

Less lubricating properties and regular removal of built-up-edge would lead to small notches at the workpiece surface. Figure 13 show burrs formed at the depth-of-cut line reduced in size when CO₂ coolant was applied and the tendency to form notch wear at the major cutting edge was highly reduced.
The CO₂ cooling offered longer tool life presumably due to lower temperature in the tool and the workpiece. Formation of white layers and micro-structural changes were prevented due to these advantages of cryogenic cooling (see Figure 14).

In the conclusion, they state that tool life is highly dependent on cutting conditions and microstructure of the material. The heat treatment of the workpiece plays an important role concerning tool wear, especially for which kind of wear mechanism occur. At cutting speeds \( V_c = 100 \) m/min or higher, they claim that tool wear increases rapidly due to the inability of the coolant to penetrate to the tool-chip-workpiece interface. Their opinion is that the fast tool wear occurring at higher speeds is the main reason why the cryogenic technology has not been adapted by the industry.
Klocke et al. [29, 39] studied the effect of high-pressure lubricant supply and cryogenic cooling using LN\textsubscript{2} and CO\textsubscript{2} in a longitudinal external turning of Ti-6Al-4V and Inconel 718 with cemented carbide and whisker-reinforced ceramics as cutting materials. They evaluated tool wear, tool temperature, chip form, cutting force and specific tool load.

There was a clear improvement concerning tool wear between conventional flood cooling and cryogenic cooling (see Figure 15). The LN\textsubscript{2} has a little edge over CO\textsubscript{2} and the flank wear forms at very slow rate while turning with LN\textsubscript{2}. The flank wear in cryogenic turning is predictable and uniform compared to conventional machining. The reduced tool wear, which made the tool life up to five times longer compared to high-pressure oil-based coolant, can mainly be explained by lower temperature in the cutting zone.

![Figure 15 Comparison between conventional oil-based, CO\textsubscript{2} and LN\textsubscript{2} cooling during turning of Ti-6Al-4V](image)

Mon et al. [27] performed tests turning titanium alloys with Ti-Al-N coated carbide. The experiments were done at three different cutting speeds for cryogenic cooling and one test of conventional cutting fluid for comparison.
The cooling affected the chips in the manner of making them more brittle and thus making it brake earlier without causing excessive brittleness in the workpiece or cutting tool material. Also the high pressure helped to blow away the chip from the cutting zone. With cryogenic cutting fluids, the flank and crater wear was almost none (see Figure 16) and the surface roughness proved to improve with higher cutting speed. In Figure 17, crater wear and chipping is evident in the insert machined with conventional oil-based cutting liquid. The insert which was used in the cryogenic turning has traces of titanium workpiece material welded on the rake face, seen there as the white layer in the picture to the right. When compared to conventional machining the flank wear and crater on the insert was reduced dramatically and surface roughness improved from 0.43 µm to 0.13 µm. No information can be found in the article if the surface roughness values are measuring $R_a$ or $R_z$.

Venugopal et al. [30, 60] published two articles in 2007 about turning titanium alloys with carbide inserts under cryogenic cooling. In both their experiments Ti-6Al-4V was turned under dry, wet and cryogenic cooling. LN$_2$ was used as cryogenic coolant which was supplied through jets, impinged on the tool rake and flank surface using a specially designed nozzle.

In their observations, the crater wear had tendency to be narrow compared to when machining of steels (see Figure 18) independent of which cooling strategy was used. That implies a short chip-tool contact [61]. The shorter the contact length is, the machining temperature rises and enhances the adhesion-dissolution-diffusion wear between the chip and the rake face of the tool. Flaking occurred on the rake surface just at the end of the crater wear region under both wet and cryogenic machining condition. This was caused by the higher thermal gradient at the end of crater wear contact.
Dhananchezian et al. [21] performed tests turning Ti-6Al-4V with PVD TiAlN coated tungsten carbide inserts under conventional wet and cryogenic cooling. The tests were carried out at different cutting speeds and constant feed rate (0.159 mm/rev). LN$_2$ was used as the cryogenic cooling and supplied internally via the tool, aimed directly to the tool-chip interface.

Their results indicated that the reduction in temperature in the cutting zone was reduced by 61-66% when comparing the cryogenic cooling to wet machining. The main cutting force and feed force was reduced by 35-42%) and surface roughness was improved by 35-39%.

Bermingham et al. [26] performed experiments, turning Ti-6Al-4V under dry and cryogenic conditions. The cutting speed was kept constant at $V_c = 125$ m/min and tests were carried out at different feed rates and depth of cut. LN$_2$ was as the cryogenic medium and it was delivered through the tool holder, providing rake cooling and through an external nozzle placed above the insert (see Figure 19).
Their results revealed a clear benefit of cryogenic cooling over dry machining with improved tool life in all their tests. However, the most influential factor in tool life is the feed rate which should be minimized to maximize the tool life.

The chip-tool contact length is reduced in the cryogenic machining, which reduces the frictional heat generated on the rake face. Thus, the heat which is generated during primary shear band deformation is less likely to pass on to the tool because the interface area is decreased. As Figure 19 shows, the delivery of LN$_2$ is both provided to rake and flank in this case. The cryogenic coolant does not only extract heat from the cutting zone but also the coolant delivered through the rake nozzle is likely helping to mechanically lift the chip away from the tool.

The cryogenic coolant delivery reduced the main cutting force, due to the lubricating effect of LN$_2$ on the flank face, but the thrust force got higher and the feed force stayed the same. Note that the main cutting force only reduced when the coolant was provided to both rake and flank.

Stoll et al. [15] performed tests turning titanium alloy Ti-6Al-4V with coated carbide inserts. Their purpose was to find the best combination of cutting speed and cooling parameters while other parameters were kept constant. The cooling strategies used were high-pressure jet, cryogenic CO$_2$ cooling, aerosol dry lubrication in combination with CO$_2$ at different flow rate. Both CO$_2$ and high-pressure jet were aimed at the rake face through the tool.

With so many cooling strategies there were different advantages involved in all of them. For Ti-6Al-4V, CO$_2$ and aerosol resulted in reduced tool life values. The tools failed due to chipping of cutting edge. That happened because of strong crater wear due to insufficient cooling.

University of Nebraska-Lincoln [62] made tests in turning Ti-6Al-4V with cemented carbide inserts under cryogenic cooling. The common advanced cutting tool materials did little to improve the material removal rate of titanium alloys and high speed machining had been attempted with little success. Using LN$_2$ coolant for turning resulted in less tool wear and better surface roughness.
compared to other cooling methods and dry machining. Compared to oil, the tool wear decreased significantly. They reduced temperatures in the cutting zone with LN$_2$ and thus reduced chemical reactivity between workpiece and tool.

2.1.2 Tungsten

F. Pusavec [22] executed experiments to study machining of porous tungsten. The surface porosity is a highly demanded characteristic of the tungsten but frequently during machining processes, smearing occurs on the surface causing the porosity to reduce or vanish. The traditional solution to that problem is to use infiltrants of any kind in machining processes to maintain the surface porosity. However, the infiltrants which are often made of polymers are not environmentally friendly. Carbide, ceramic, CBN and diamond tools were compared in order to find the best cutting grade for improving surface porosity levels. The cutting forces, porosity in terms of number of pores, pore size, surface roughness and tool flank wear were measured and analyzed.

Both methods, cryogenic and conventional infiltrant machining, performed similarly but the plastic-infiltrated sample had a little edge over cryogenic due to less smearing on the surface. On the other hand, the cryogenic cooling surpassed the conventional machining in other areas such as greatly reduced cycle time, environmental characteristics and no possibility of contamination. As tests of this type have been performed seldom it is a quite reasonable to assume a large room for improvement is available for optimizing the cutting parameters.

PCD tools produced parts with sufficient surface porosity and less tool-wear compared to other tools. Cryogenic cooling is the first method to return satisfying industry standards of machined porous tungsten without infiltrants. Adapting the technique could result in more environmental friendly machining, lower costs, less power consumption, reduced waste, enhanced operational safety and improved personnel health.

2.1.3 Steels

Pusavec et al. [32] researched the effects of cryogenic cooling on stability within the machining system. Chatter is known to affect surface integrity, cutting tool wear and noise. In their tests they compared dry and cryogenic machining and compared parameters of cutting depth, feed rate and cutting tool radius. Also in their evaluation, they calculated three specific force coefficients, cutting direction, feed direction and radial direction.
Figure 20 Example of feed force time series and corresponding NCER for cryogenic and dry machining at machining parameters $f = 0.15 \text{ mm/rev}$ and $v_c = 180 \text{ m/min}$ [32]

Their results revealed that cryogenic cooling offered more than double depth of cut within the desirable stability frame compared to dry cutting. Regardless of direction the results were always in favor of cryogenic cooling. In Figure 20 the NCER scale is a function of depth of cut, $a_p$. The NCER is a nonlinear characteristic of signal regularity and predictability. The blue line, representing cryogenic machining, is able to stay out of the chatter region for higher $a_p$ value than the red line, representing dry machining.

Bicek et al. [36] performed tests turning normalized and hardened bearing steel AISI 52100 with CBN cutting inserts. The tests were carried out to compare conventional oil-based cutting fluid, cryogenic cooling and dry turning in combination with this workpiece material. Productivity, chip formation, induced constant specific force and mean arithmetic roughness value were evaluated in these experiments. LN$_2$ was provided through external nozzle to the cutting zone in the cryogenic processes.

Surface roughness reduced in the turning process of AISI 52100 normalized steel with cryogenic cooling. Micro-hardness increased by 10-15% which prolongs fatigue life of the mechanical element in turning, which is popular in the mechanical industry. For the hardened bearing steel AISI 52100 the surface roughness was similar for all cooling methods and the micro-hardness also stayed similar. Figure 21 and Figure 22 show SEM pictures of metallographic structure of normalized and hardened steels in the heat affected zone after cryogenic turning. Note that the white line in Figure 22 is a consequence of edge polishing and not a white layer. Figure 23 and Figure 24 are pictures of the same surfaces as Figure 21 and Figure 22 but taken through optical microscopy which is vital in order to view white layers. No white layers can be seen on these pictures.
Figure 21 SEM picture of metallographic structure of normalized AISI 52100

Figure 22 SEM picture of metallographic structure of Hardened AISI 52100
Excessive vibration at the beginning of cryogenic turning of normalized bearing steel seemed to cause highly unfavorable tool geometry causing material brittleness of the insert. Presumably cryogenic machining of hardened AISI 52100 with CBN inserts would result in longer tool life if the vibrations were eliminated. These results imply that tool geometry and cutting edge preparation of these tests could have been more optimized in the case of cryogenic machining. Despite these problems, the cryogenic cooling enabled longer tool life and about 15% benefit in cut volume for hardened bearing steels.

Dhar and Kamruzzaman [10] carried out tests turning AISI-4037 steel with coated carbide inserts. The experiments were performed at four different cutting speeds and feed rates while the depth of cut was kept constant. For comparison they performed tests under dry, wet and cryogenic cooling. LN$_2$ was supplied through an external nozzle which was fixed beside the cutting tool to provide cooling at the rake surface in the cryogenic cooling.
The results indicated that increased feed rate causes higher interface temperature which often can cause higher surface roughness. The process had to be optimized within the cutting speed and feed rate parameters. The cryogenic cooling provided an improvement in surface roughness which could mostly be attributed to reduction in auxiliary flank wear. The reduction in temperatures improved the tool-chip interaction making the cryogenic cooling slow tool wear development, resulting with better surface finish and higher dimensional accuracy compared to the other two methods [63].

Dhar et al. [34] performed tests turning carbon steel using carbide insert. Tests were carried out at different speed and feed rates and a constant depth of cut. For comparison they made the tests dry and with cryogenic cooling. LN$_2$ was used as the cooling liquid and was provided through and external nozzle aimed to the cutting zone along the main and the auxiliary cutting edge. A FEM analysis was made to predict the temperature distribution at the tool chip interface (see Figure 25).

In the process of new chip forming, first it interacts with the rake face and remains at low temperature. At the interface a friction occurs, generating heat, but in that time period the chip has moved to the middle of the chip-tool interface. Normally the chip-tool contact goes from being plastic to elastic and the heat flux reduces when the shear stress is less in the elastic region than that in the plastic region. Therefore the maximum temperature occurs in the mid-section. Figure 25 explains where the highest temperature is generated in the cutting process. Number 10 represents the area where the highest temperature occurs while 1 represents the lowest. For the higher efficiency of the cooling, the medium has to be capable to penetrate as close as possible to the zone where the highest temperature occurs.

Khan et al. [49] did a study on turning stainless steel SUS 304 with a tool, AC 2000 graded, coated with TiCN. The tests were carried out at different cutting speeds, feed rate and depth of cut. They compared machining stainless steel with cryogenic and conventional flood cooling. In cryogenic cooling, LN$_2$ was supplied through a specially modified insert (see Figure 26).
The tool which was modified for supplying the cryogenic coolant very close to the cutting edge turned out to be an effective strategy. LN$_2$ was passed into the threaded hole 4 of the tool body 5 (see Figure 26). The tool life could be increased by more than four times and the cooling was even more effective at higher cutting speeds. When moving towards higher feed rate the chip thickness increased and the plastic deformation in the shear zone occurred at faster rate, thus generating more heat. The intimacy of the spray nozzle to the cutting edge, made the LN$_2$ extra effective at higher feed rate rather than higher depth of cut. Almost no flank wear was observed on the tool at low cutting speeds in cryogenic turning (see Figure 27). At higher cutting speeds the cutting edge suffered from micro-cracks and some minor flank wear.

Dhar et al. [33] performed tests in turning AISI 1040 and E4340 steel with two different kinds of carbide inserts (SNMG and SNMM). The tests were performed under different cutting speed, feed rate, depth of cut under dry and cryogenic conditions.
At higher cutting speeds, they assume that the cryogenic coolant is not able to penetrate fully to the chip-tool contact zone and thus not shoring up fully expectations of temperature reduction. That is because the chip goes fully plastic and makes full contact with the tool rake face, preventing the fluid from entering the chip-tool interface. At lower cutting speed, when the chip-tool contact was partially elastic where the chip left the tool, the LN$_2$ was dragged in that elastic contact zone in small quantity by the capillary effect (ability of a liquid to flow in narrow spaces without the assistance) resulting in more efficient cooling.

![Dry machining, 25min](image1)
![Cryogenic Machining, 30min](image2)

Figure 28 SEM pictures of worn out insert of SNMG (upper) and SNMM (lower) inserts after machining AISI E4340C steel under dry and cryogenic conditions [33]

In the case of AISI 1040 steel the effect of cryogenic cooling showed significant improvement in reducing the average flank wear, notch wear and auxiliary flank wear. Tool life improved with cryogenic cooling from 25 minutes to beyond 50 minutes for SNMG inserts and from 17 to beyond 50 min of SNMM inserts. For AISI E4340C steel the cryogenic cooling also provided better results and also a little better for the SNMG for both the flank wear and auxiliary flank wear (see Figure 28). Results suggested that surface quality was correlated with the growth of auxiliary flank wear. Cryogenic cooling improved the surface finish through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation. The results suggest that cryogenic machining of steels with carbide inserts reduces flank wear due to less abrasion and notching and thermal sensitive wear at the flanks was almost non-evident.

2.1.4 Nickel-based alloys
Stoll et al. [15] performed tests turning Inconel 718 with coated carbide inserts. Their purpose was to find the best combination of cutting speed and cooling parameters while other parameters were
kept constant. The tests were carried out under high pressure jet, cryogenic CO$_2$ cooling and aerosol dry lubrication in combination with CO$_2$ at different flow rate. Both CO$_2$ and high-pressure were aimed at the rake face through the tool.

With so many cooling strategies there were different advantages involved in all of them. When turning Inconel 718 the maximum tool life occurred at a low cutting speed 50m/min using the high-pressure cooling with 80 bar. That can be attributed to less frequent chip breaking which is considered being responsible for tool wear.

Pusavec et al. [5] did a study to review the sustainable machining technologies, environmental factors, cost, quality, etc. In their observations they researched the option of machining Inconel 718 using conventional flood, high-pressure jet assisted machining, cryogenic LN$_2$ using carbide cutting tool. Tool lifetime was measured and the processes were evaluated in terms of sustainability principles.

Kranjik et al. [43] performed experiments to research the effects of cryogenic cooling on system stability of high-speed machining. In their tests they turned Inconel 718 with mixed Al$_2$O$_3$ ceramic inserts and compared tests using dry and cryogenic machining. The cooling medium they used was LN$_2$ which was provided externally via jet. In their analysis they used ANOVA quantified by ODR.

In their experiments, the cutting stiffness while using cryogenic cooling increased due to stronger interaction of the process. The structural damping within the machining system made the interaction of the process with machine tool structure stronger, resulting in a stiffer process.

2.1.5 Ceramic

Wang and Pajurkar [41] performed tests, turning ceramic material, reaction bonded silicon nitride (RBSN), with two different CBN tools (VC734 and VC722). They compared dry machining with cryogenic cooling under the same cutting parameters, measuring the flank wear at a regular interval. For determining the heat distribution in the cutting zone, they used FEM analysis. LN$_2$ was provided to the cutting zone in the cryogenic tests through a cap installed above the tool.

The tool life of VC734 doubled and was roughly five times better for VC722 with the cryogenic cooling. This can mainly be attributed to the reduction of maximum cutting temperature occurring in the cutting zone, from 1153°C to 829°C.

University of Nebraska-Lincoln [62] made tests in hard turning RBSN under cryogenic cooling. The common advanced cutting tool materials did little to improve the material-rate removal of titanium alloys and high speed machining has been attempted with little success. Using LN$_2$ coolant for turning RBSN resulted in less tool wear and better surface roughness compared to other cooling methods and dry machining.

Compared to oil, the tool wear decreased significantly. The PCBN insert, which was used in the trials, had a clear trend of increasing temperature due to growing tool wear after every cut performed with conventional coolant. Also the process became more stable under cryogenic turning.

2.2 Milling

Milling is an operation in which a workpiece is fed through a rotating cylindrical tool with multiple cutting edges. The axis of rotation of the cutting tool is perpendicular to the direction of feed. The
orientation between the tool axis and feed direction is one of the features which distinguish milling from drilling [4, 64]. Milling with has not been researched as extensively as turning operations. That is mainly due to the difficulties of gaining access for the cryogenic coolant to the cutting zone compared to turning. Modifying tools and inserts may require further development of machining systems and might retard the adoption of the industry.

2.2.1 Titanium alloys
Klocke et al. [29] performed tests in end milling TiAl6V4 with cemented carbide inserts and studies comparing the effects of high pressure conventional oil-based cutting fluid (HP-lubricoolant) and cryogenic cooling on tool wear, chip forms and cutting temperature in milling of titanium alloys. LN2 was supplied through an external nozzle in the cryogenic tests.

![Figure 29 Tool wear development in milling Ti-6Al-4V with conventional oil-based (left) and LN2 (right) cooling [29]](image)

The tests revealed less tool wear with cryogenic cooling (see Figure 29). Adhesion was reduced and only scratches on the coating were visible after the same machining time as a tool had worn out with conventional cooling [37].

2.2.2 Steels
Nalbant et al. [3] performed experiments of milling AISI 304 stainless steel in a 3-axis machine. Tests were performed under both dry and cryogenic conditions and in different cutting directions (up- and down milling) at four different cutting speeds. LN2 was supplied externally to the cutting zone in cryogenic cooling. Forces in the milling process were analyzed under dry and cryogenic conditions.

Their statistical analysis suggested that the maximum cutting force and torque were higher in cryogenic milling. With higher cutting speed the cutting forces increased as well, but the maximum torque reduced. At lower cutting speeds chipping or frittering started occurring around the tool nose in climb milling (see Figure 30). The frittering tended to be more serious with cryogenic cooling due to the thermal shocks around the insert nose. In conventional milling, dry and cryogenic cooling
performed similarly. Their conclusion is that cryogenic cooling in these conditions showed no remarkable advantage over dry machining.

![Cryogenic climb milling vs Dry climb milling](image)

*Figure 30 Comparison between cryogenic (left) and dry (right) climb milling. (a) 80 m/min (b) 120 m/min (c) 160 m/min (d) 200 m/min [3]*

Schaarshcmidt et al. [46] investigated the influences of different coolant strategies on the wear behavior, flank wear, as well as the temperature in the workpiece and tool cutting edge during machining. In their tests they milled a steam turbine blade made of X12CrNiWTiB16-13 under five different cooling strategies: Dry machining, MQL external, Aerosol dry lubrication internal, Aerosol dry lubrication internal + CO2 as cryogenics external and Compressed air internal + CO2 as cryogenics external.

The flank wear between those 5 different methods varied little between the methods when milling just one part. Looking at the development after milling of 3 parts, the compressed air + CO2 resulted with the least flank wear.

They also performed other tests for their new two-channel through coolant system which they built in combination with Starrag AG. The aim of the investigation was to determine the influences on tool life, workpiece quality and chip formation. In these tests they compared dry machining with CO2 in combination with compressed air. After machining identically, one dry and one with CO2 cooling, the flank wear reduced drastically (from 0.16mm to 0.06mm) with the usage of CO2. With cutting speed 25% higher and increasing the feed rate from 0.40 to 0.55 they were able to achieve a similar flank wear to the dry machining with lower parameters. Figure 31 illustrates surface quality which improved with CO2 and compressed air despite performing at higher cutting parameters. Due to high process temperatures parts of the chips tend to weld on the surface in dry machining while that development is suppressed by cryogenics.
Figure 31 Comparison of surface quality for milled surface of Martensitic steel with dry machining and CO₂ cooling [46]

2.2.3 Nickel-based alloys
Truesdale and Shin [52] performed tests to examine the effects of cutting velocity on the microstructure in the milling process of Udimet 720 with coated carbide inserts. The tests were carried out at different cutting speeds and constant feed and depth of cut using both up and down face milling processes. LN₂ was supplied through an external nozzle directed first to the workpiece just before the milling started. After the workpiece had pre-cooled the nozzle was directed to the tool for the cryogenic milling. For comparison, milling was also performed with conventional emulsion cooling.

For Udimet 720, the material’s microstructure is essential for the final outcome. Thus, if the machining process deforms the microstructure by smearing and plucking, the material loses its value. Through microstructural analysis it was detected that smearing and plucking increased as a function of cutting velocity. When machining with emulsion it was rather the microstructural deformation than the tool wear which was limiting the cutting speed. The maximum speed to machine Udimet 720 with conventional oil-based cutting fluid was only 10 m/min. The cryogenic cooling could allow a maximum cutting speed of 120 m/min with acceptable microstructure.

2.2.4 Carbon fiber reinforced polymers
When end milling Carbon fiber reinforced polymers (CRFP) the challenge is to achieve non-abrasive surface. High temperature generated by the milling process can soften binders of the resin. Liquid CO₂ can provide sufficient cooling to limit the temperature in the binders and thus preventing the deforming of the material.

Dionne et al. [19] made tests in composite milling carbon fiber reinforced polymers using CVD coated end mill. The milling process was carried out under dry and cryogenic conditions. The CO₂ was
supplied externally in combination with dry air to the cutting zone in cryogenic milling. The maximum temperature was reduced from 200°C to 99°C for dry and cryogenic CO₂ milling respectively.

2.3 Drilling
Drilling is a cutting process used to cut or enlarge a round hole in a workpiece. Very limited work has been reported about drilling with cryogenic cooling. Similar to milling, the difficulties in applying the coolant to the cutting zone compared to turning operations are likely the reason for limited research on the subject.

Dix et al. [53] were able to create highly realistic model for drilling assisted by cryogenic cooling. According to their conclusion the tool geometry and particularly the position of the cooling channel outlets are crucial for temperature distribution during the process.

Figure 32 depicts how the LN₂ runs through the shrink-fit chuck, drill shank, and drill tip. A pre-cooling stage for 540 seconds is necessary for this drill and at t=0 the LN₂ reaches the drill tip. A significant cooling occurs in all parts of the drill and especially the drill tip. The temperature peak occurring at t=20 is due to a cyclical escape of gas. Despite the best insulation, heat conduction occurred in the supply lines and also formation of gas, which reduced the cooling effects [53].

![Figure 32 Temperature distribution at the drilling tool when integrating a cryogenic cooling using LN₂](image)

2.3.1 Titanium
Venkatesh et al. [11] performed tests drilling and titanium alloy, Ti-6Al-4V, with a coated carbide. The cutting speed was kept constant but the tests were carried out at different feed rate.
Figure 33 and Figure 32 depict the precision of holes drilled with conventional and cryogenic cooling, respectively. Better roundness was achieved through cryogenic drilling and the diameter of the drilled hole had higher accuracy. Improvements in surface finish, cylindricity were also evident. Note
that the report lacked information about the supply of cryogenic cooling and the type of cryogenic media.

2.3.2 Cast iron
Neugebauer et al. [58] performed tests to compare drilling of cast iron dry and with emulsion, MQL, CO\textsubscript{2} and dry. Their results showed no significant difference between the cooling methods at lower cutting speed and feed. As they increased the cutting parameters the effects of cryogenic cooling and MQL on tool life showed superiority over dry machining. With the increased cutting speed from 160 m/min to 210 m/min and feed rate from 0.25 mm/rev to 0.33 mm/rev, the CO\textsubscript{2} cooling performing better than MQL and at least eight times better than dry machining. Although the cryogenic cooling provided the best results, the emulsion tests were not far behind concerning tool life.

Although they use more energy with higher material removal (MRR) parameters, they achieved significantly higher efficiency using CO\textsubscript{2} compared to the other methods.

![Comparison of energy consumption, tool cost and total cost in drilling for different cooling strategies as a function of material removal rate](image)

According to the authors, the low consumption and low investment cost compared to wet machining for the system, makes the alternative of cryogenic cooling a method which provides a high performance cutting.

2.3.3 Composite stackup
The usage of composite material and composite stackups of titanium and aluminum has been growing within automotive and aerospace industry. Compared to using aluminum stackups, the weight of the aero planes can be reduced by 20%. One of the most challenging problems facing engineers and scientists is drilling efficiently holes through layers to install fasteners and other components. The trend today is to use carbon-fiber-reinforced polymer (CFRP) in combination with high strength titanium based materials. As already described, titanium based materials are difficult to machine. CFRP have a very low heat conductivity and storage properties. On top of that the materials are very abrasive and can easily delaminate on the exit site of the drilled hole. Due to the low thermal conductivity of titanium, the warmth tends to spread to the CFRP resin and cause damages on the material. With conventional coolants such as water and oil, an optimal cooling for the stackup materials are seldom reached which often result in a poor hole surface quality of out of tolerance dimension. By using CO\textsubscript{2} cryogenic medium both layers are protected.
Usually it is the composite which is drilled in first. After that the titanium is drilled and the chips pass through the composite. By using traditional emulsion coolants it is very tough to create the optimal cooling, resulting in poor surface quality and holes made out of the dimensional tolerance.

Dionne et al. [19] performed tests to drill through the stack up made of titanium alloy and carbon fiber reinforced polymer with coated carbide drills. The tests were carried out under cryogenic and conventional oil-based emulsion. CO$_2$ was provided through the tool in the cryogenic drilling. In their results the temperature was reduced by 27°C in the composite material and by 20°C in the titanium in the cryogenic drilling.

Manufacturers have been able to increase the tool life, quality, accuracy and decreased the time per part manufactured part significantly. According to the results presented in the article, productivity, tool life, surface finish, cleanliness and energy savings can be improved with cryogenic drilling.

2.4 Innovations in cryogenic machining technology
The new innovations today are mostly focused on tools capable of providing the cryogenic media through the tool itself, and also combining it with other cutting fluids like MQL, conventional emulsion or air through either internal or external supply.

![Figure 36 Cryo-tec copy milling cutter F2334R with channels for two different media [46, 65]](image)
Walter AG and Starrag AG together have developed a CO\textsubscript{2}-based cryogenic cooling method to produce turbine blades on a production scale [65]. The CO\textsubscript{2} is provided through the tool and directly to the tool-workpiece interface. They claim to be able to machine up to 70% faster than with dry machining and increase the tool life if cutting parameters are held the same. They have also developed a two channel coolant system (Cryo-tec F2334R), with one channel designed for CO\textsubscript{2} supply and the other one for compressed air, aerosol or emulsion [46](see Figure 36 and Figure 37). They are currently developing a three channel system as well and their future step is to develop a three channel rotary feed which should be able to use conventional cooling, MQL and cryogenic medium as well as their combination.

MAG is developing a new tool with a coolant from tool through [31], [66]. They claim that the new tool will be able to combine LN\textsubscript{2} with MQL in order to reduce friction and adhesion. They also state the new tool is suitable for machining titanium-based, nickel-based and nodular or compacted graphite iron (CGI). The main focus will be on milling and drilling tools in the future and they hope for an increase of 60% in cutting speed in milling of CGI with carbide tool and up to quadruple speed with PCD.

MAG [67] has also developed a low flow cryogenic titanium machining process of the Lockheed Martin F-35 Lightning II stealth fighter. By applying this technique, the productivity and efficiency in machining was improved by 25%. They have used LN\textsubscript{2} with highly optimized flow rate to improve the cutting tool life and material removal rates. They offer cryogenic tool cooling technology on a range of new machines including five-axis machines and turning systems.

In cooperation with the German ISF (institute for metal cutting and manufacturing), Walter AG wants to work in a project of machining high-tensile bainitic steels. With that said, the focus will be on investigation on the cryogenic lathe machining of titanium and nickel-based materials and to develop the tooling systems further [68].
3 Summary and conclusion of literature study

Although the technique of using cryogenic cutting fluids for machining has been developing for over 70 years, the industry has still not fully adapted it. As many have reported, cryogenic cooling has great technological and economic potential. Some state that technique is profitable compared to more common cooling methods while others have doubts. Every case is individual and needs to be analyzed privately in every case [37].

The success of applying cryogenic cooling is highly depending on many parameters such as workpiece material, cutting tool material, the design of the tool and process parameters. In machining processes of hard-to-machine materials, usually the cooling is aimed directly to the cutting zone while for ductile material the cooling is sometimes directed to the material. The great majority of presented and reported results about machining cryogenic cooling have been positive in terms of tool life, wear development and surface finish.

Most research in the past has been about turning operations with titanium alloys and steel as workpiece material and LN$_2$ cryogenic cooling [11, 69]. Milling operations have also had its share while very little work has been done on drilling and other machining operations. The main reason why scientists on the subject have mostly concentrated on turning operations is most likely due to the easy and clear access for the cutting fluid to the cutting zone without any modification of the tool. In milling and drilling, it can be essential for process to have an internal application of the cryogenic cutting fluid for it to have any effects. That could result in adjustments and changes of the machine systems which can take long time to develop. In external application of cryogenic cooling to milling and drilling operations, higher pressure and flow rate could be required for the coolant for it to have any effects. The cryogenic coolants are expensive and not reusable after applying it like many oil-based coolants and thus in may be repulsive to make experiments with external application of cryogenic cooling in milling and drilling.

For this literature study, 78% of the articles which involved testing and experiments covered turning operations, 20% about milling and 10% about drilling. Note that the sum of these percentages is over 100% which can be explained by the fact that some articles covered more than one type of machining operation.

The common choice of LN$_2$ over CO$_2$ could be involved with the fact that CO$_2$ is a greenhouse gas even though normally the machining with CO$_2$ is not causing additional emission to the environment [27].

As a selection for cutting tools in cryogenic machining, standard tools can be used although cemented carbides are the choice of today for titanium alloys [65]. Still it is preferable to use tools with high thermal conductivity, making the cryogenic coolant functioning as a heat absorber [37].

Why the industry hasn’t fully adopted the cryogenic technology is a question asked by many and has been answered with various theories. This is a highly relevant question, especially due to the fact that almost all results reported have been positive while hardly any mainstream manufacturer is using the technique in notable volume. Schaarschmidt et al. [46] claim that the difficulty of handling nitrogen as well as the need for thermal insulated media supply in the machine and the cutting tool is repulsive to the industry. Machai et al. [48] who experienced fast tool wear at higher cutting speeds
in their experiments of turning titanium alloy, stated that the lack of performance at higher cutting speeds might be the reason for slow adaptation by the industry. Other theories have been surrounding the slow update of standards and regulations within industries such as aerospace industry. Cryogenic cooling has shown great results and benefits with the most common aerospace materials but still the technique is not being used. This industry is regulated with standards which are not changed over a night.

After reading science articles concerning cryogenic cooling, the picture painted of cryogenic cooling technology is almost strictly positive, leaving you stunned why the technique is not being practiced more. An explanation could be that scientists are often not presenting negative results they achieve in their lab-work. Opposite to all the positive research covered in this essay, there might be myriads of unsuccessful trials with cryogenic cooling which we are unfamiliar with.

Few of the disadvantages which might be holding back the adoption of the industry:

- Lack of tools specially designed for cryogenic cooling, in terms of geometry, substrate and coating
- Lack of machine – tool interface designed for cryogenic machining.
- Lack of knowledge of tool manufacturers and end-users
- In some cases it is necessary to pre-cool the workpiece in order to prevent thermal shocks
- High initial cost
- High complication level of optimizing the flow and pressure
- Relatively high price of LN$_2$ and CO$_2$
- Cutting fluid is not reusable as it is in some case of conventional machining
- The machine tools builders are too conservative
4 Experimental investigation
For study of the setup and results of experimental work see Appendix A which is a part of Sandvik Coromant confidentiality.
Bibliography


[70] Rolander, Ulf. *Analysis of IP related cutting tools used for machining with cryogenic cooling*. u.o.: NDA between MAG and Sandvik Tooling, 2011.


Appendix A

Sandvik confidential information