LN2 FOR MILLING PROCESSES

DAMRC

INDEX

1. This project is made in collaboration with:

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2. Executive Summary

This technical report investigates the potential of substitution of traditional coolant with Liquid Nitrogen (LN2) in milling operations. The study comprises an extensive literature review and a series of experiments aimed at comparing the productivity and stability of the milling process using liquid nitrogen as a coolant. Two different delivery systems are evaluated: an external delivery system tested on Aluminum, SuperDuplex, and Cast Iron, and an internal delivery system utilizing a commercial tool holder for coolant delivery through the tool over Aluminum.

The evaluation focuses on multiple productivity metrics, including tool wear, power consumption, chip shape inspection, and noise levels. Simultaneously, the stability of the process is evaluated through measurements of geometric and dimensional tolerances, as well as surface roughness.

Throughout the experiments, encouraging results were obtained, particularly concerning productivity factors such as noise, power consumption, chip analysis, and tool wear. However, challenges emerged related to the geometry and configuration of the delivery systems, affecting the overall stability of the milling process. These findings highlight the importance of considering not only the positive impacts but also the potential limitations and issues associated with LN2 coolant replacement in milling applications. The report concludes with recommendations for optimizing the delivery systems and further avenues for research in order to enhance the feasibility and effectiveness of LN2 as a milling coolant.

3. Introduction

As part of the machining process of metals, coolants and lubricants are often used. These coolants and lubricants ensure cooling of workpiece and cutting tools, while at the same time lubricating the cutting process whereby increased tool life can be achieved relative to dry machining. The problem with conventional coolants and lubricants is that these are oil-based and thus an environmental burden, just as they are a nuisance to the working environment and can have negative health effects.

Based on a wide range of different reasons, including environment, climate, working environment, personal health, and economy, it is desired to find an alternative to the conventional coolants and lubricants (including emulsions and crude cutting oil). One of these alternatives is “cryogenic coolants”, where the conventional coolants and lubricants are replaced by cryogenic liquids such as Liquid Nitrogen (LN2) and Liquid or Super Critical Carbon Dioxide (LCO2 & scCO2). However, most of the work done in this topic are at an academic level, e.g., (Suhaimi et al., 2018) with the scope to investigate and demonstrate the applicability of cryogenics as coolants. The challenge with this research is that it is often very academically focused and not at a Technology Readiness Level (TRL) ready for direct deployment in the industry – both due to challenges regarding system construction and due to process understanding.

Through previous projects, DAMRC has been involved in work on cryogenics as coolants. Together with the University of Bilbao, milling tests using LCO2 vs conventional flood coolant have been compared for 5 materials. Tests in stainless steel concluded increases in tool life of 125% while tests in the other materials showed up to 40% increase in tool life. In another project, DAMRC investigated the use of LN2 for turning applications. That project searched to document if LN2 could replace crude cutting oils for long-turning processes. These tests showed significant improvement in chip formation and breaking, without disrupting the part geometry and quality.

Based on these existing insights this project is to investigate and demonstrate the applicability of Liquid Nitrogen cooling as an alternative to emulsion-based coolants in CNC milling. The choice of LN2 over LCO2 is based on the safety aspects – as CO2 is denser than air it will stay at ground level, potentially posing a risk of displacing oxygen, leading to loss of consciousness and potentially death if concentrations are too high.

Via the project, DAMRC will develop, test, and set up a supply system for the supply of LN2 as a coolant to the cutting zone. In a first stage, the system is based on an external supply setup, to reduce the risk of freezing bearings and to reduce the barriers for potential industry adoption. Using the LN2 supply system, machining tests are conducted- and test results analysed, to qualify the positive and negative effects of using LN2 as coolant media for milling processes. In a second stage of the project, the applicability of an internal delivery system originally designed to deliver coolant trough internals passages in the tool is tested to try to improve the control of the amount and impact area of the LN2.

3.1 Success Criteria

It is expected that using LN2 as cooling in CNC machining (milling) a greater process stability can be achieved compared to emulsion-based coolant. With increased process stability, we expect to achieve increased tool life, improved chip breaking, and reduced power consumption, while maintaining or improving machining quality. The expectation is thus increased productivity, resulting in a reduction of cycle time per part and thereby fully or partially contributing offsetting the expected additional costs involved in the use of liquid nitrogen.

4. Pre-analysis and Literature search

As the start of the project existing literature and articles have been reviewed to base the project on existing state-of-the-art knowledge and insights.

4.1 Characteristics of gaseous and liquid nitrogen

Liquid nitrogen and liquid carbon dioxide have been used as media for new cooling strategies. The reason for using these kinds of medias for cooling is their increased cooling abilities, combined with improved environmental and health aspects. Specifically, their ability to evaporate (transform from liquid to gas) at atmospheric pressure, helps them extract heat from the cutting region – together with their general low temperatures (Khanna et al., 2021).

For liquid nitrogen the phase diagram can be found in **Error! Reference source not found.**. From this, the l iquid phase can be seen. Depending on the given pressure of the nitrogen, its phase transition temperature from liquid to gas ranges from -196°C at 1 bar (≈ 1 atm.) to -178°C at 5,4 bar and -169,4°C at 10 bar (TheEngineeringToolbox, n.d.-b).

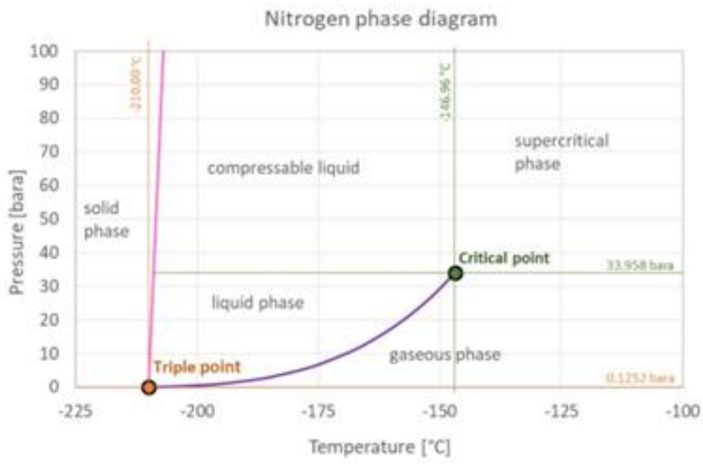


Figure 1 - Phase diagram for nitrogen (TheEngineeringToolbox, n.d.-c)

To take advantage of this knowledge, it is possible to expand the "operating window" within which it is possible to cool the cutting zone with nitrogen on liquid form by increasing the pressure. However, as stated by (Khanna et al., 2021), too high pressure can increase the level of turbulence which limits the performance of the liquid nitrogen.

One of the reasons that the liquid phase is sought over the gaseous phase is the difference in thermal conductivity.

Table 1 specifies the thermal conductivity for nitrogen at various pressures and temperatures for the gas and liquid phase, together with water and air. As can be seen water has the most superior thermal conductivity of ≈600 mW/m K in liquid phase. However, when changing to gas the conductivity drops significantly – which is a known phenomenon that happens in machining. As can be seen conductivity of liquid nitrogen ranges between liquid water and gaseous air, nitrogen & water. Due to the larger temperature difference, nitrogen is effective at removing the heat of the process.

Temperature	Pressure	Thermal Conductivity	State
[°C]	[bar]	[mW/m K]	
-210.0	1	173.3	Liquid nitrogen
-195.9	1	145.0	Liquid nitrogen
-195.9	1	7.174	Gaseous nitrogen
-193.2	1	7.443	Gaseous nitrogen

-210.0	10	173.6	Liquid nitrogen
-169.4	10	92.74	Liquid nitrogen
-169.4	10	11.67	Gaseous nitrogen
-133.20	10	14.00	Gaseous nitrogen
-190.0	1	7.82	Atm. Air
-150.0	1	11.69	Atm. Air
0.0	1	24.36	Atm. Air
100.0	1	31.62	Atm. Air
300.0	1	44.41	Atm. Air
20.0	1	598.0	Liquid water
99.6	1	677.0	Liquid water
100	1	24.57	Gaseous water
200	1	33.43	Gaseous water
500	1	66.58	Gaseous water

Table 1: Thermal Conductivity vs. temperature and pressure for nitrogen, atmospheric air, and water (TheEngineeringToolbox, n.d.-b, n.d.-d, n.d.-a)

4.2 Cryogenic supply systems

An important aspect of cryogenic cooling techniques is the delivery system and infrastructure of the cryogenic coolant. This is well visualized by

Table 1, from which it is clear that the supply of cryogenics must happen at extremely low temperatures, and that the temperatures within hoses must be kept below a critical value to avoid phase transition until the cooling media reaches the cutting zone. This also challenges the ability to adapt the cooling method to CNC machines using "traditional" methods, by simply adding the cryogenic supply to existing external and internal coolant supplies. Thus, most literature on LN2 and cryogenic coolant have used special adapted systems for coolant delivery.

To supplement this, the choice of delivery system might also be affected by the application of the cryogenics coolant. Typically, it is seen that cryogenics are used in three ways (Khanna et al., 2021). Namely:

- **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** It is a method of improving the wear resistance of tools by cryogenically treating them before the machining process.
- **Cryo-processing of the workpieces** is a method where the workpiece is treated under cryogenic conditions to change thermal and mechanical properties to improve the machinability.

Some experience in supply system design has been gained from previous projects and tests carried out by DAMRC. In the turning project using LN2 as coolant, LN2 was supplied through an armoured flexible steel hose insulated with standard commercial pipe insulation PE foam, to reduce convection. The hose was connected to a steel turning tool holder with internal cooling channels to allow direct and precise delivery of LN2 (see Figures 2 and 3 for illustrations). Through this configuration, it was observed that the system needed more than 30 minutes to cool, so the supply would be liquid nitrogen and not gaseous. This follows the general rule given by Linde that to reduce the temperature from 20°C to -196°C between 0.5 and 1.0 liters of liquid nitrogen pr is needed. kg. metal (Linde-gas, 2022).

Figure 2 - First iteration LN2 supply system for LN2 turning project.

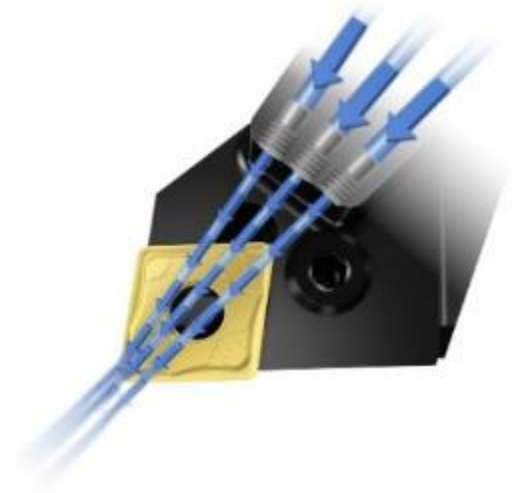


Figure 3 - First iteration LN2 supply system for LN2 turning project.

With the goal to review the state of the art about delivery system of LN2, in Figure 4 three examples on cryogenic supply systems can be seen. As is seen, some variation exists from system to system, however, some several similarities can be pointed out:

- Vacuum jacketed pipes/hoses are often used to reduce temperature change and phase transformation.
- Solenoid valves are used to automatically activate/deactivate the coolant supply and to control the flow.
- Pressure indicators are used to monitor the pressure.
- Phase separators are used to ensure that only liquid nitrogen is fed to the spray zone.
- Some systems use flow meters to monitor the use of nitrogen.

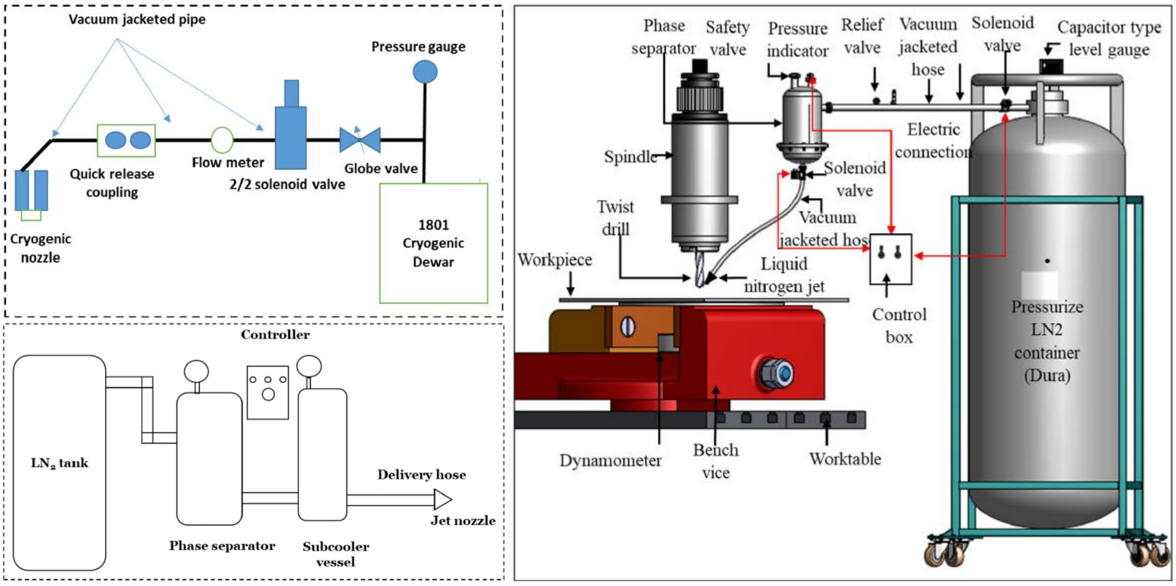


Figure 4: Examples on different system designs for cryogenic supply systems (Khanna et al., 2021)

Other more industrialized cryogenic systems also exist on the market, mostly of them use to working with CO2 or are also very expensive. Some examples are 5S, Cool Clean Technologies, BeCold, Industrial Cryogenic Technologies, Cryofab and Fusion Coolant Systems. See example on the ChilAire system design from Cool Clean Technologies in Figure 5.

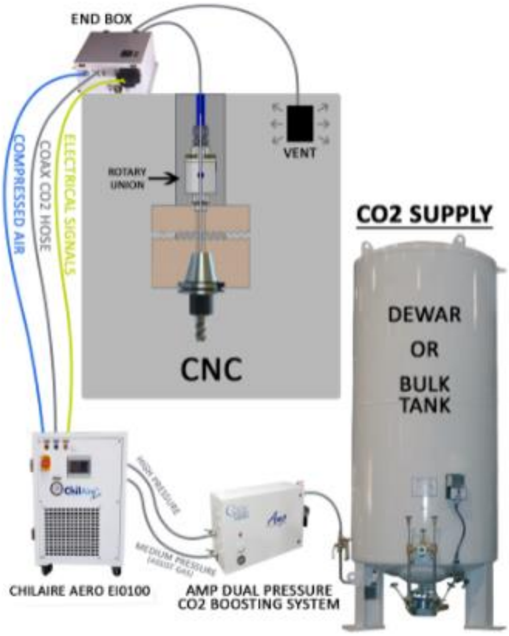


Figure 5: System design for Cool Clean Technologies, ChilAire CO2 coolant system (CoolCleanTechnologies, n.d.)

Beyond the supply system design, several studies and suppliers have worked on delivering the best possible coolant supply to the cutting zone.

For external supplies (Khanna et al., 2021) presented two different solutions. A “Mono jet solution for drilling and milling” (Figure 6 - left) and a “Multi jet solutions for drilling and milling” (Figure 6 - right).

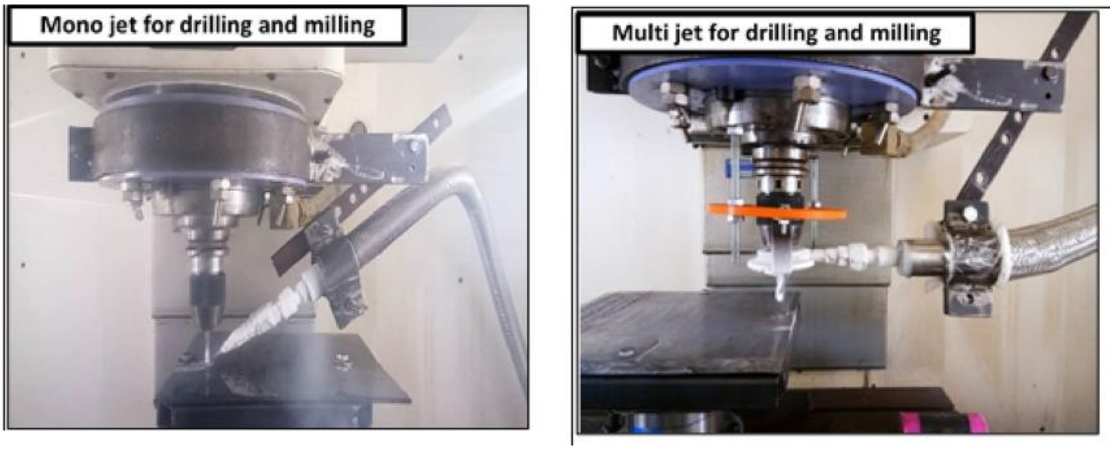


Figure 6: A Mono- and Multi jet nozzle solution for external supply of cryogen coolants (Khanna et al., 2021)

(Pereira et al., 2015) presented a special designed nozzle for combining cryogenic fluids and MQL (minimum quantity lubrication). This nozzle sprays LCO2 from four sides, trapping the MQL oil in the middle, carrying it to the cutting zone (see Figure 7). An interesting feature of the nozzle design is the convergent-divergent outlet design, which, due to compressible fluid dynamics, increase the outlet speed of the cryogenic (LCO2). (Song et al., 2020) presented a similar concept about trapping MQL in a flow of cryogenic LCO2. The reason for designing these special nozzles for hybrid cryogenic cooling with MQL is, that if each media (the cryogenic gas/liquid and the MQL) are applied separately, e.g., from each side, the oil mist are not able to enter the cutting zone due to the spraying pressure from the cryogenic (see Figure 8).

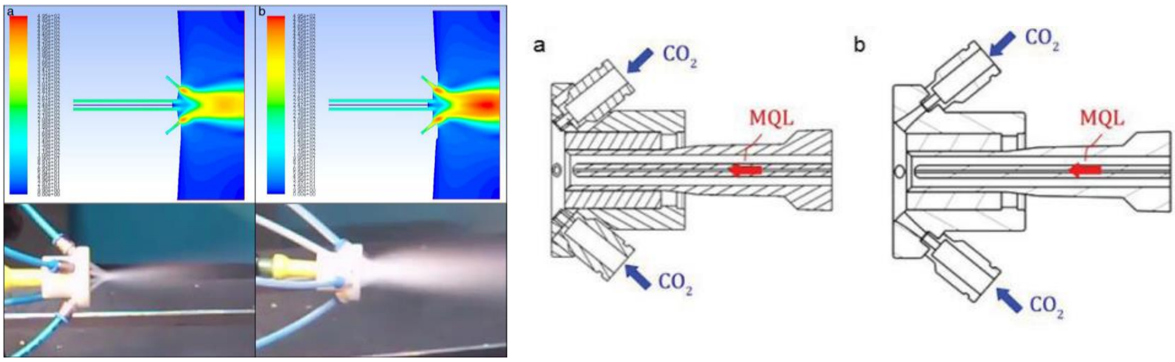


Figure 7: Two nozzle designs. Design B (right side design) has convergent-divergent outlets to increase fluid speed which is obtained due to compressible fluid dynamics (Pereira et al., 2015).

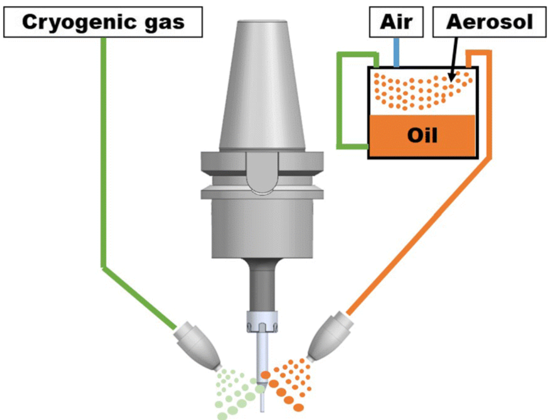


Figure 8: Cryogenic gas and MQL oil applied separately to the cutting zone (Song et al., 2020)

One of the industrial solutions, the ICEFLY solution from Industrial Cryogenic Technologies LLC, proposes one of the most unique solutions to the nozzle and hose system. Just like the DAMRC turning project they use the "hose-in-hose" principle for the end supply of LN2.

"We use that pressure to move the nitrogen from the source to the end of line. There are no pumps in our system.
We then deliver the LN2 over any long distance (1M to 6M) through vacuum jacketed lines that we produce ourselves. At any shorter distance we use insulated lines." (Knopf, n.d.)

"With such a configuration, the first portion of the cryogenic fluid flows through the inner tube while a second portion flows through an annulus between the inner tube and outer tube. By maintaining the annulus at a lower pressure than the inside tube, the liquid in the annulus can provide a refrigeration duty to the liquid inside the inner tube (e.g., such as by boiling), such that the inner liquid is cooled and stays in a saturated liquid state. This feature is critical for supply of either a saturated liquid nitrogen stream or for preparation of a low temperature gaseous nitrogen product." (Knopf, n.d.)

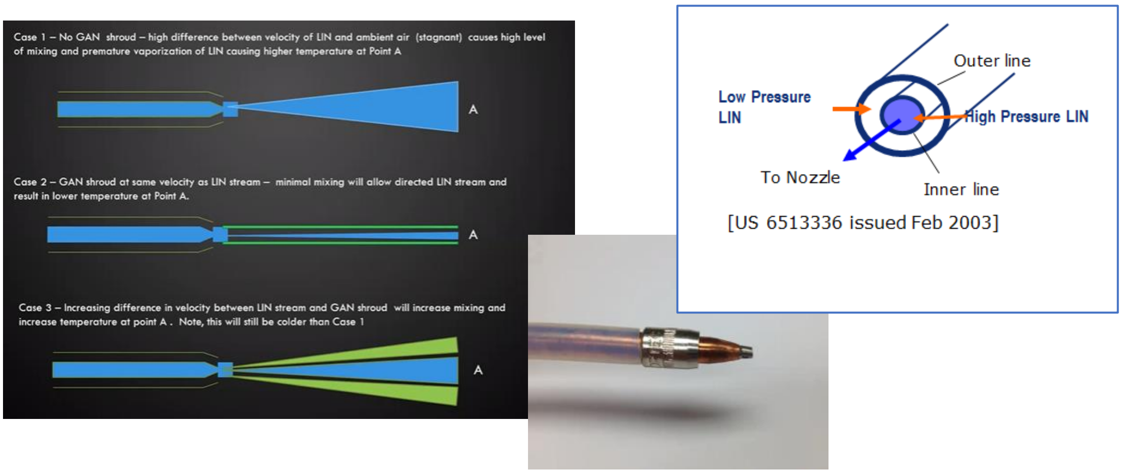


Figure 9: ICEFLY CryoCut Low-Flow Cryogenic Delivery System (Knopf, n.d.)

However, one extra attribute that the ICEFLY system incorporates is the outlet nozzle. Where the gaseous nitrogen in the outer hose just evaporated in the DAMRC turning project, this gas/liquid is actively used in the ICEFLY nozzle. "*We also have a nozzle that runs liquid nitrogen through the center with gaseous nitrogen running along the outside. By adjusting the flow of each (liquid vs. gas) you can control the temperature coming out of the nozzle."* (Knopf, n.d.). According to (Damir et al., 2019) the ICEFLY external nozzle has a diameter of 2,2mm with a flow of 0,5 L/min at 0,55MPa.

For internal cooling systems, special tool holders have been developed and used. These holders work via an inlet mechanism on the side of the holder, via which the coolant media is feed into the tool (Park et al., 2015). Various variants of these holders exist. However, the general working principle remains the same. Some examples of the identified suppliers of these are; *CFT Systems, Industrial Cryogenic Technologies LLC, Coventry Engineering Limited*.

A main benefit of these systems is their ability to deliver the coolant exactly at the cutting zone, allowing for optimal cooling – independent of the positioning of the tool relative to the coolant supply and the workpiece.

This makes these solutions great for drilling and larger tool diameters. Further, the holder and coupling system is easy to retrofit into existing CNCs.

The main disadvantage is that several kg of metal needs to be pre-cooled, just like it is impossible to insulate the holder, why it must be expected that operating costs will increase for these methods. According to Linde Gas, each kg of metal requires 0,5-1L of liquid nitrogen to be cooled from 20 °C to -196 °C (https://www.linde-gas.dk/da/processes_ren/cooling/index.html). However, the usage is most likely higher when the nitrogen only passes by.

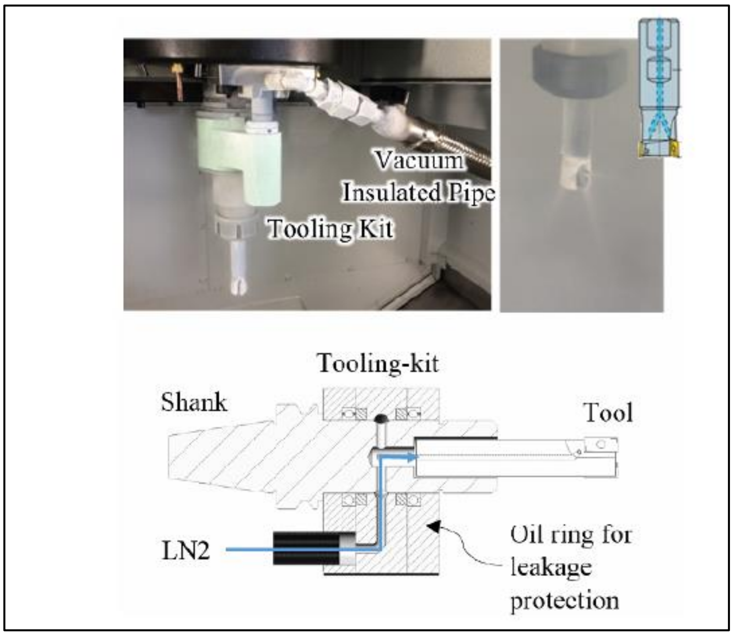


Figure 10: Custom designed tool holder for internal cryogenic coolant supply (Park et al., 2015)

4.3 Performance of liquid nitrogen in milling processes

Beyond the health and cleanliness aspect of LN2, the governing argument for introducing this media as a coolant is to improve machining performance – i.e., part quality, tool life, productivity, etc.

The performance of LN2 relative to LCO2 and conventional refrigerants in milling applications is summarized below.

The general impression is that most studies include not only LN2 or LCO2, but also combines the cryogenic with MQL to compensate for the missing lubrication.

(Park et al., 2015; Suhaimi et al., 2018) studied the effect of external and internal cooling with LN2, the effect of internal cooling with LN2 combined with Nano-MQL, and the effect of indirect cooling with LN2 and Nano-MQL. This cryogenic cooling methods were compared with tests using flood coolant and Nano-MQL. The tests were made using a solid carbide endmill machining Ti6Al4V (grade 5 Titanium).

The cutting forces from each method can be seen in Figure 11. During their study they observed strong adhesion of titanium to the tool for external and internal cooling with LN2. However, for the other cooling methods, the cutting forces stayed somewhat unchanged throughout their study.

This indicates a strong need for lubrication when using LN2 on endmills. However, a former study by Park showed high machining performance without strong adhesion. In this study an indexable endmill with a small depth-of-cut was used with internal and external LN2.

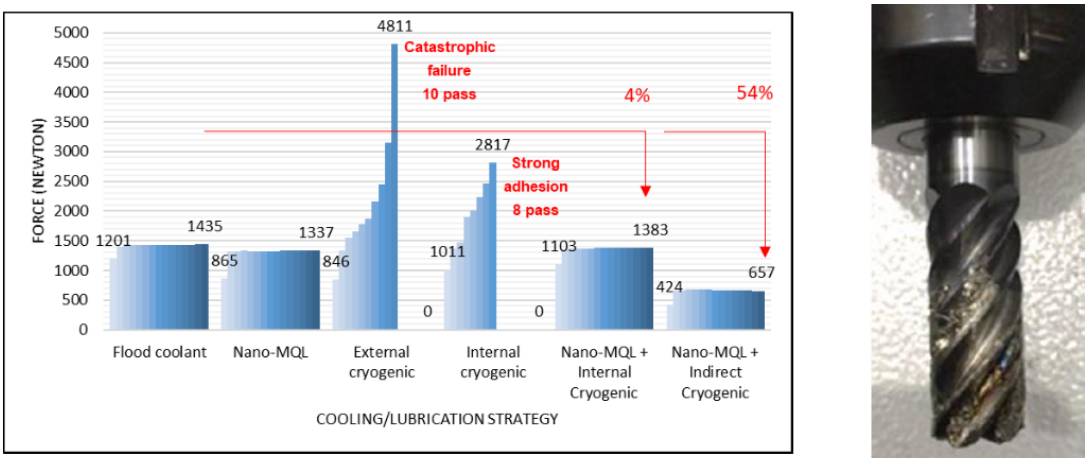


Figure 11: Cutting forces for all lubrication strategies (left) and tool use for the tests (Suhaimi et al., 2018)

On the wear side, they found that when you add MQL to the LN2, wear can be reduced. For the case where indirect cryogenic coolant is used, the wear size dropped by 90% at the end of the milling tests. This method facilitates cooling and cryogenic hardening of the tool, without affecting the workpiece hardness (and thus cutting resistance) (Khanna et al., 2021). Further, the risk of thermal shocking of the cutting edges is reduced.

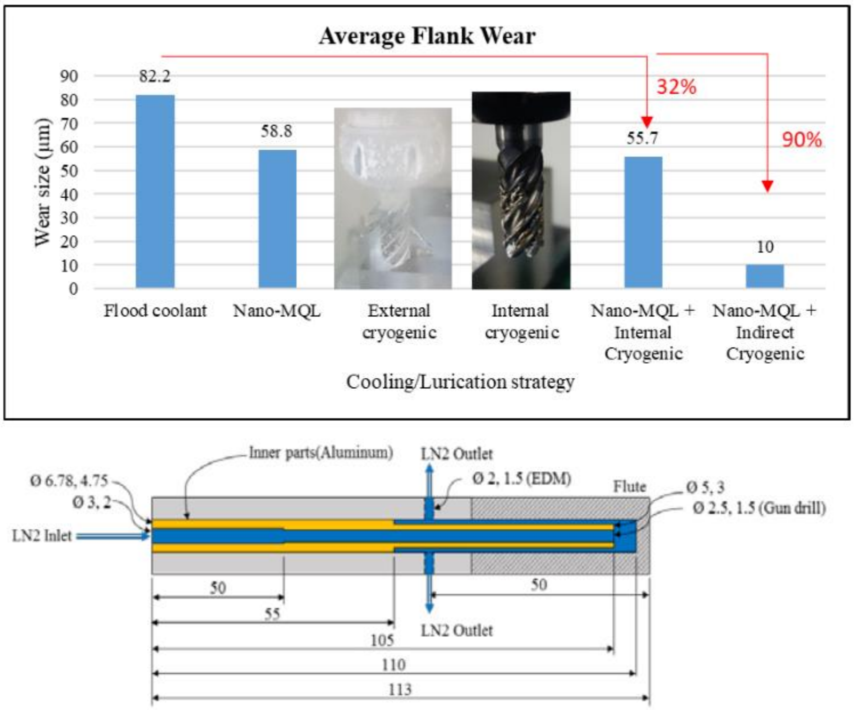


Figure 12: Average flank wear (upper) and tooling design for indirect cryogenic cooling (Suhaimi et al., 2018)

(Khanna et al., 2021) reviewed existing literature on cryogenic milling. One of the studies compared dry, LCO2, LN2, MQL, LN2MQL, and LCO2MQL. The study found that the hybrid solutions LCO2MQL and LN2MQL resulted in improved tool life (up to 50%) and up to 30% higher cutting speeds, compared to dry machining.

Other results summarized by (Khanna et al., 2021). In Ti6Al4V following results were found:

- LN2 was compared with flood and dry milling of Ti6Al4V. A nozzle was placed 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%).
- Higher residual compressive stress and fewer surface defects under a cryogenic environment. However, it was observed that the surface morphology has generally deteriorated using cryogenics.
- Reduced surface roughness and increased cutting force using LN2MQL technique compared to the flood technique.
- Improved surface integrity and a fourfold increase in tool life using high flow rate and high pressure of LN2.
- 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.

In nickel alloys:

- A 40% decrease in surface roughness of machined component under LN2 condition compared to dry condition.
- Improvement in tool life (93.5%) when using the LCO2MQL combination instead of dry machining.
- Plasma heating was used 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%), cutting force (30–50%) and improvement in tool life (170%) using the modified cutting conditions.

In difficult to cut ferrous alloys:

- In machining AISI 1060 steel under cryogenic cooling, the result shows better surface finish and tool life compared to wet and dry machining.
- The effect of cryogenic cooling on AISI 4140 steel found improvements in tool wear, dimensional deviation, and surface roughness.
- In AISI 52100 a significant decrease in white layer formation was observed using ICEFLY's delivery system for LN2. However, residual stresses are increased, which can generally contribute to fatigue life in comparison to dry machining.
- Both lubrication and freezing of chips are required during the machining of low machinability ferrous materials. Therefore, cryogenic is suggested to upgrade to cryoMQL.
- Cryogenic machining of EN24 material, hardened to 45 HRC, showed an increase in tool life up to 38.60%, a decrease in tangential cutting force up to 15.42% and an improved surface finish in comparison with conventional flood cooling.
- Milling performance of austenitic steel (SS 304) under LCO2MQL and flood conditions were studied. They reported an increase in tool life (324%) at higher process parameters using LCO2MQL milling compared to flood milling. Moreover, surface roughness, microstructural changes, residual stress, and micro-hardness were comparable for both milling techniques.

The 5ME (a system supplier for LN2) could achieve a tool life increase of ten times for compacted graphite iron, three times for titanium, and a 40% increase for diverse composites. With the 5ME cryogenic machining it is possible to run two to five times faster for hard-to-machine materials than with conventional cooling. For compacted graphite iron a five time increase in finishing cutting speed, for titanium a two times increase in semi-finish cutting speed, and for steel alloys a 1.6 times increase in semi-finish cutting speed could be realized with the LN2 cryogenic system compared to conventional flood cooling (Wohlfeil, 2015).

(Song et al., 2020) compared performance of DRY, cryoCO2, MQL, cryoCO2MQL machining Ti6Al4V. They found that spraying of cryogenic CO2 refrigerant was more effective than dry machining but not as effective as the remaining methods in reducing tool wear. Further they found that tool wear initiated from material adhesion to the rake face of the tool.

It was found the MQL was more effective than cryogenic gas in decreasing tool wear when externally supplied. In addition, the combined CryoCO2MQL nozzle, which is a hybrid cryogenic gas-MQL method, maintained an almost constant low level of tool wear. This method was analysed to be most effective among the external supply methods. Figure 13 visualizes the effect on cutting forces and tool wear as function of cutting volume, and coolant method. Further they found that by increasing MQL supply from ≈20 to ≈60 ml/hr., tool wear could be decreased significantly.

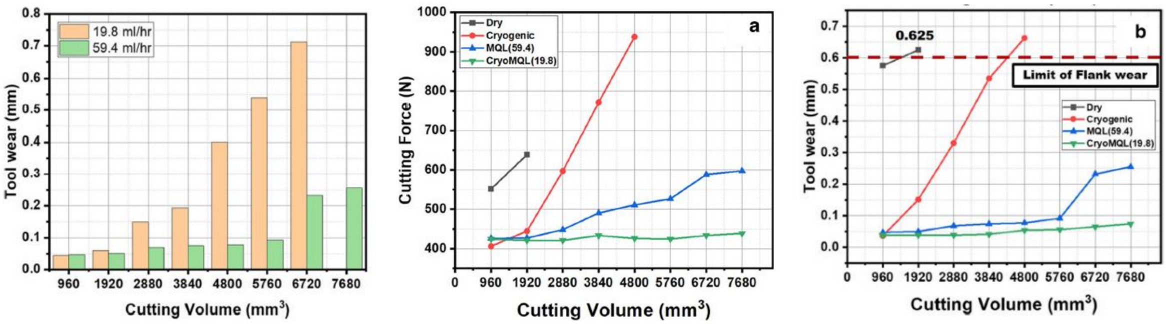


*Figure 13: **Left**: Effect on MQL-flow supply on tool wear. **Middel**: Cutting Forces and **Right**: Tool wear using different coolant methods* (Song et al., 2020)

Softer materials is another material group that benefits from cryogenic machining (Jacobs, 2020). These materials are soft and ductile, which makes them prone for melting or/and adhering to the tool or workpiece. By using cryogenic cooling targeted for the workpiece, these materials are made more brittle. This often means that the cut will look better, which translates into shorter and better controlled chips, a lower surface roughness (Ra) and a tool with less material adhesion.

Figure 14 visualizes the cryogenic effect of cooling workpiece. When doing this, the aim is to change the material characteristics from “rubbery” to the region of “tough” and “cold flow” by controlling the temperature of the workpiece. Neither “Rubbery” or “Glassy” characteristics are desired.

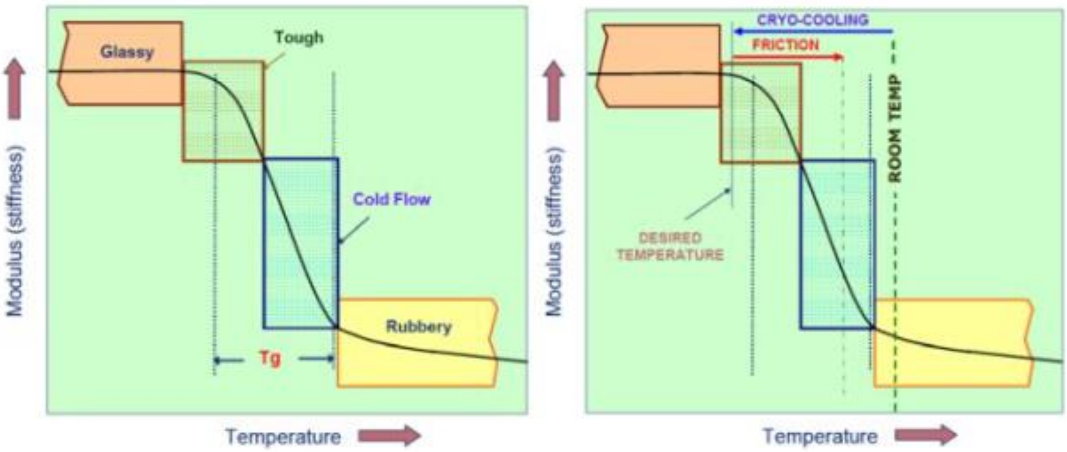


Figure 14: Visualization of change in stiffness (ductility) as result of reduced temperature (cryogenic treatment) (Jacobs, 2020)

In addition to all the above aspects, literature research tells us that cryogenic coolant has an impact on another very important characteristic of the milling process which is the shape and breakability of the resulting chip.

From Bahattin Y, Et al.(2020), we have that the surface quality of the part is affected by the behaviour of the chip resulting from machining, and can convey important information about the process. The dimensional shape of the chips depends not only on the ductility, resistance, and the crystalline structure of the workpiece, but also on the cutting parameters, the coolants used and the tool geometry. Chip formation in machining is classified into continuous, discontinuous, and built-up edge.

Continuous chip formation is the result of machining ductile steels at high speed and low feed rate, while built-up edge chips is continuous, but formation is the result of slow speeds, where heat dissipation is also slow, and therefore part of the chip is welded on the tool tip. On the other hand, the discontinuous shape is due to excess stress in the chip because of chip bending. Chip formation begins with the first chip bending and breaks when the acquired radius is such that the stress on the outside of the chip is greater than the ultimate strength of the material.

It is important to know that if we have a continuous chip, it can be easily accumulated from the workpiece negatively affect operator safety, quality surface and tool wear due to the less capability of heat dissipation. Chip build-up in the cutting zone leads to heat accumulating on the cutting tool and the workpiece instead of being removed. At high temperatures, the tool and the chip will chemically diffuse, causing the tool and chip to combine into other compounds, this reducing tool hardness and toughness until reach the collapse of the tool.

Continuous chip occupying the cutting zone impedes the cutting fluid from making its way into the cutting zone, and also increases the power used in the operation. These undesirable outcomes involving continuous chip formation increase operational cost and make that the majority of the different research achieve the conclusion that chip breaking must be employed, like is the same that say that in the machining process is necessary to reduce the radio of the chip to make the break of it.

The use of coolants, delivered to the cutting zone at specific pressures, is an alternative solution on the problem of chip breaking where it has been determined by researchers that increased pressure reduced chip curvature radius which resulted in broken chips with smaller dimensions. Independently of the pressure of the fluid coolant, the kind of methodology used to cool down the process have direct impact in the chip breaking. Bahattin Y, Et al.(2020) mention that several scientific studies have analysed the effect in this propriety's for different cooling methods like dry, wet, MQL, MQIL plus cooled air and cryogenic. These studies determined that the cryogenic processing provide the best result in terms of chip formation, and this could be attributed to the fact that the material increases its breakability when it is cooled to temperatures below the ductile-brittle transition temperature, increasing the embrittlement of the chip.

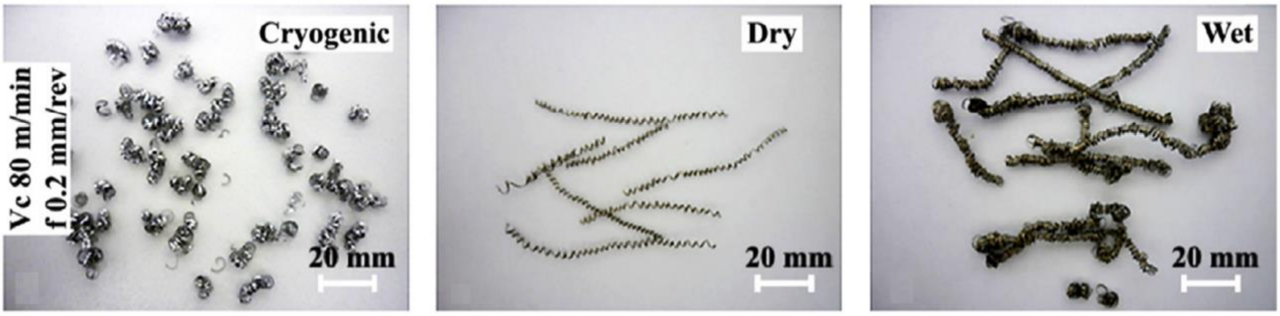


Figure 15 - Effects of various cooling methods on chip breaking Bordin A, Et al(2017)

5. Design of experiments and test parts

In this section the reflections about design of the experiments and test part are presented. The goal of the project is to test and demonstrate what effect has the use of cryogenic LN2 on the machining performance and workpiece characteristics compared to conventional cooling to evaluate to then evaluate the industrial relevance of the application.

We can separate the test into two different fields, one related to the part resulting, where the stability of the parts is analysed, take measurements of machining parts using conventional and cryogenically coolant, whose parts are defined to contemplate the main and more used operations into the milling process. In This analysis different geometrical dimensions and roughness are measured. And other part related to productivity where the different parameters of the process like tool wear, power consumption of the machine, chip inspection and particle concentration in the air are analysed.

5.1 Choice of materials for the test

To make these tests three different materials are used, and each one of them will be machining using conventional and cryogenic coolants, given place to 6 different experiments. The materials to use are Aluminium AW6026-LF-T6, Cast Iron EN-EJS-500-7C and Stainless-steel Super duplex SAF 2507 and are shown in Figure 16 - Test samples materials - AW6026 in the left, EN-EJS-500-7C in the middle, SAF 2507 in the right..

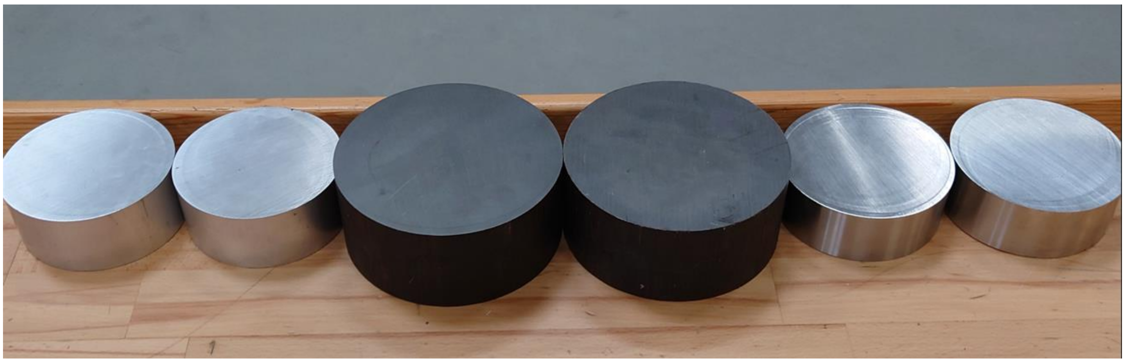


Figure 16 - Test samples materials - AW6026 in the left, EN-EJS-500-7C in the middle, SAF 2507 in the right.

In the application for this project, tool steel was a part of the selected materials, but after consulting some of DAMRC members it was decided to change tool steel out with cast iron as these materials are widely used in the Danish Industries, are particularity difficulties to be machining due their hardness and mechanical characteristic and to have wider range of different steel types in this project.

In table 2 their main mechanical proprieties can be appreciated:

MATERIAL	MODULUS OF ELASTICITY (Mpa)	YIELD STRENGTH (Mpa)	TENSILE STRENGTH (Mpa)	ACHIEVED HARDENESS
Aluminum AW6026-LF-T6	71130	300	370	95 HB
Cast Iron EN-EJS-500-7C	210000	305	500	220 HRC
Super duplex SAF 2507	200000	550	760	260 HB

Table 2 – Mechanical proprieties.

5.2 selection of geometry for the experiments

The materials presented are milling with the goal of obtaining different machining parts where the main operations using in the industry can be studied under the effect of conventional and cryogenic coolant, these operations, can be classifieds in Face milling, Pocket milling, Side milling and Slot milling. In addition, an optional test is established for Super duplex where the grooving operation is included because this process is sensitive for milling tool wear (It is decided to perform the grooving milling test only on Super duplex because there will be a higher wear of the tools used for this test, compared to Aluminium, and cast iron), so if the tool wear cannot be appreciated in the first three tests, this optional test is executed. In figures 15,16,17 and 18 the different parts of machining can be appreciated. All geometries are made in collaboration with DAMRC members, to make the geometry's as close as possible to what is used in the Danish industry.

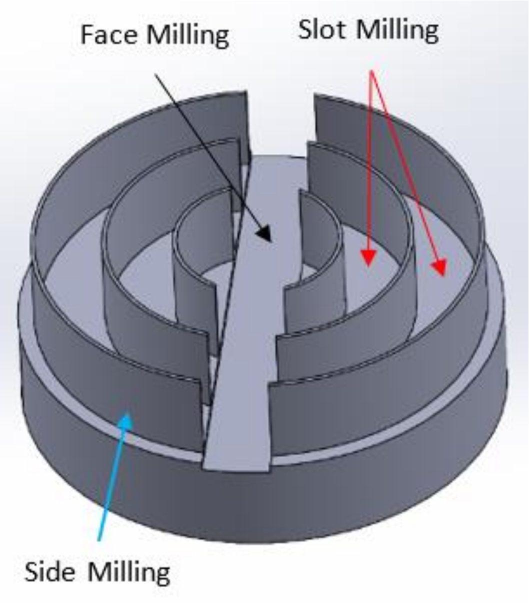


Figure 17-Workpiece to be machined in Aluminum AW6026-LF-T6

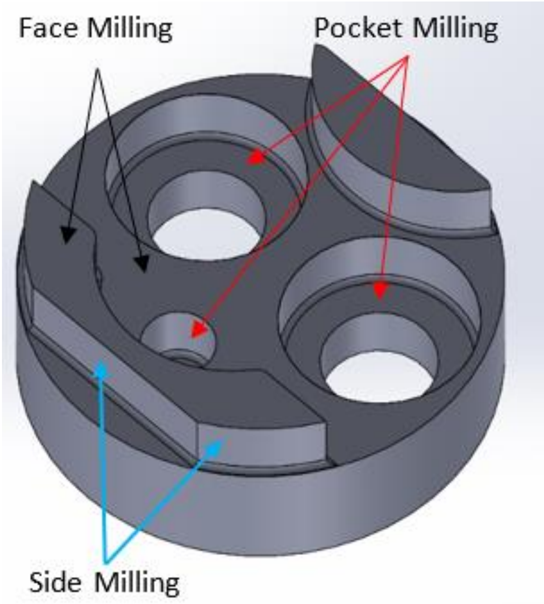


Figure 18-Workpice to be machined in Cast Iron EN-EJS-500-7C.

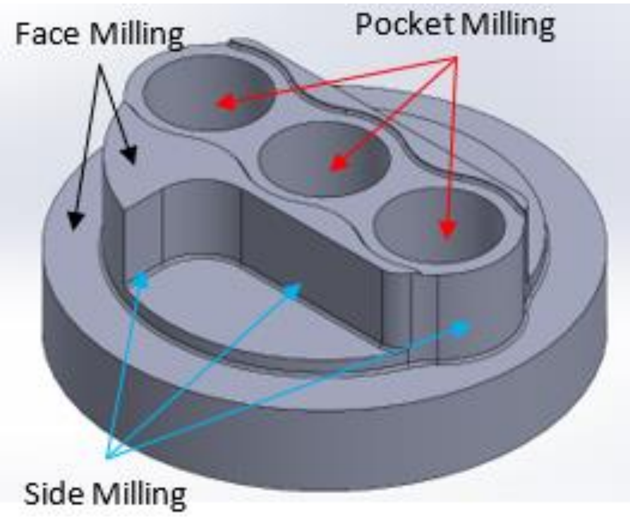


Figure 19- Workpiece to be machined in Super duplex SAF 2507

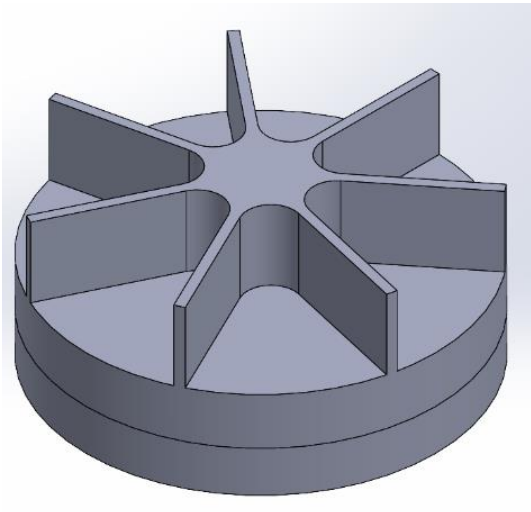


Figure 20- Optional Workpiece to be machined in Super Duplex SAF 2507.

5.3 Selection of machine and tools for the test.

5.3.1 Machine

Alle the parts are machined in a 5-axis vertical machining center (DMU80T), with a 12,000-rpm spindle and the piece is clamped into a three-jaw Diesella Lathe Chuck Self-centering fixture. It is shown in Figure 21.

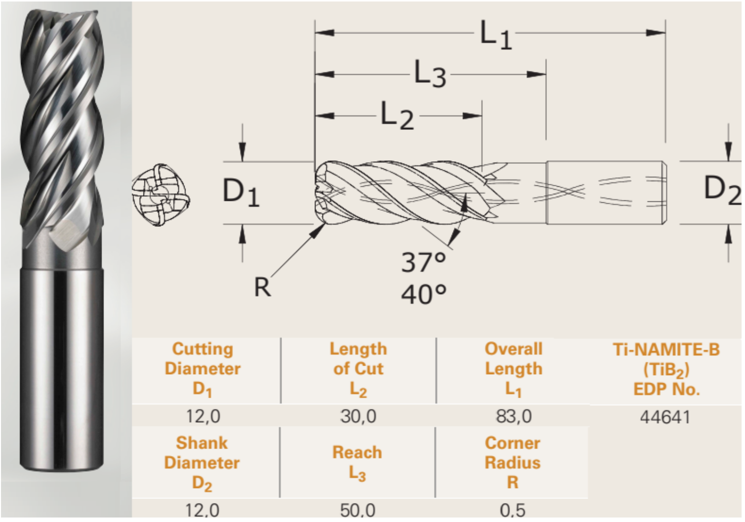
Figure 21- 5-Axis vertical machining center (DMU80T).

5.3.2 Tools

The difference in the mechanical properties of the different material that have been chose to make the tests carry out the necessity of used different tools to machining the mentioned workpieces in order to be the more close that is possible to the real daily industry work conditions. With this goal, Kyocera, experimented company in the machining field provided to DAMRC the tools and made the following guidelines about the indicated tools and parameters to machining the parts.

For **Aluminum AW6026-LF-T6** the milling tool chosen is a SGS 43MAPF (#44641) ø12 R0,5 Z4 TL83 – APMX30. This tool is mounted in a 12mm bushing 393.CG-200852 with cooling through the spindle to by fitted in the spindle by a tool holder from Erickson denominated Hydro Force DV40HCTHT20070M. The milling tool, bushing and tool holder can be appreciated in Figure 22, Figure 23 and Figure 24 respectively.

In **Cast Iron EN-EJS-500-7C,** the same Bushing is used, one drilling tool holder S40-DRV390M-3-11 with SCMT110406-CA415D-E and SCMT110410-PR1535-I inserts is used and it is shown in Figure 25. Milling tool holder MEC 25-S25-11T-4 with BDMT11T331 ER-JT PR1210 insert is used to semi-finishing machining and it is shown in Figure 26.



Cutting Diameter D_1	Length of Cut L_2	Overall Length L_1	Ti-NAMITE-B (TiB_2) EDP No.
12,0	30,0	83,0	44641
Shank Diameter D_2	**Reach L_3**	**Corner Radius R**	
12,0	50,0	0,5	

Figure 22 - Aluminium milling tool - SGS 43MAPF (#44641) ø12 R0,5 Z4 TL83 – APMX30

Figure 23 - 12mm bushing 393.CG-200852.

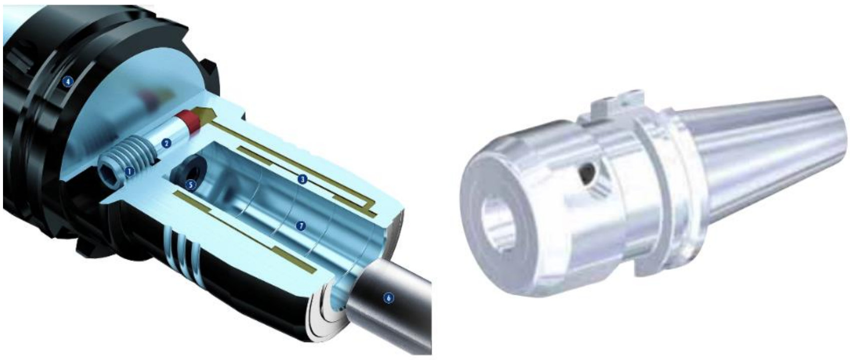


Figure 24- Erickson Hydro Force DV40HCTHT20070M.

Figure 25 -Drilling tool holder S40-DRV390M-3-11 with SCMT110406-CA415D-E and SCMT110410-PR1535-I inserts

Figure 26- Milling tool holder MEC 25-S25-11T-4 with BDMT11T331 ER-JT PR1210 insert

To machining Stainless Stell **Super duplex SAF 2507** a 393.CF-20 08 50 Bushing is used and three different tools holders with their respectively insert are defined. To High Feed roughing a MFH 20-S20-03-4T tool holder with LOGU030310ER-GM CA6535 insert is selected, then to finishing a Z-Carb-HPR (#47018) ø12 R0,76 Z5 TL83-APMX26 tool is used, and finally a S32-DRV270M-3-09 ø 27 3Xd tool with SCMT090405-CA520D-E and SCMT090405-PR1535-I inserts is used to drilling. These tools with their respective insert are shown in Figure 27, 28 and 29 respectively.

Figure 27 - MFH 20-S20-03-4T tool holder with LOGU030310ER-GM CA6535 insert.

Figure 28 - Z-Carb-HPR (#47018) ø12 R0,76 Z5 TL83-APMX26 tool.

Figure 29 - S32-DRV270M-3-09 ø 27 3Xd tool holder with SCMT090405-CA520D-E and SCMT090405-PR1535-I inserts.

These tools are configurated with the cutting parameters shown in Table 3.

Tool	Diameter of the tool ø (mm)	Cutting speed Vc (m/min)	Feed per revolution Fn (mm/r)	Feed per tooth Fz (mm/z)	Axial depth of cut Ap (mm)	Radial depth of cut Ae (mm)	Comment.
SGS 43MAPF Z3	12	200	---	0,05	6	12	Aluminum – Slotting.
		300	---	0,1	30	1	Aluminum – Finishing.
S40-DRV390M-3-11	39	160	0,13	---	---	---	Cast Iron – Drilling.
MEC 25-S25-11T-4	25	180	---	0,15	5	7,5	Cast Iron – Milling.
S32-DRV270M-3-09	27	120	0,1	---	---	---	Super Duplex - Drilling
MFH 20-S20-03-4T	20	140	---	0,4	0,3	10	Super Duplex - High Feed roughing
Z-Carb-HPR (#47018) ø12 R0,76 Z5 TL83-APMX26	12	190	---	0,017	26	1,2	Super Duplex - Finishing

Table 2- Cutting parameters.

Where the variables indicated means the following:

- **Cutting speed Vc**: Linear speed in the cut diameter.
- **Feed per revolution Fn**: Linear distance that the cutting-edge travels during a single spindle rotation.
- **Feed per tooth Fz**: Chip thickness that each tooth of the milling cutter removes from the material as it passes through it.
- **Axial Depth of cut Ap**: Length that the tool engages a workpiece in its axis direction as it moves perpendicular to it.
- **Radial depth of cut Ae**: Distance a tool is stepping over into a workpiece in radial direction.

These parameters are using with the toolpaths shown in Figure 30, 31 and 32 for each material:

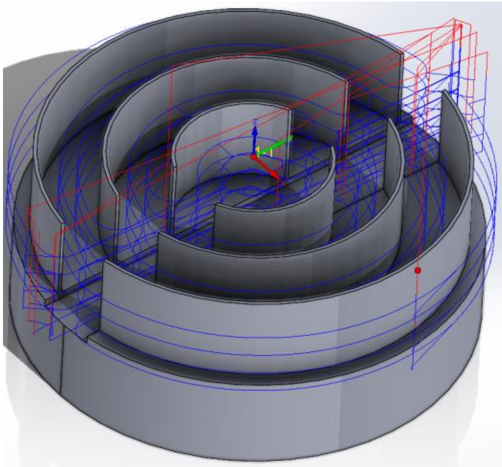


Figure 30 – Toolpath for Aluminum.

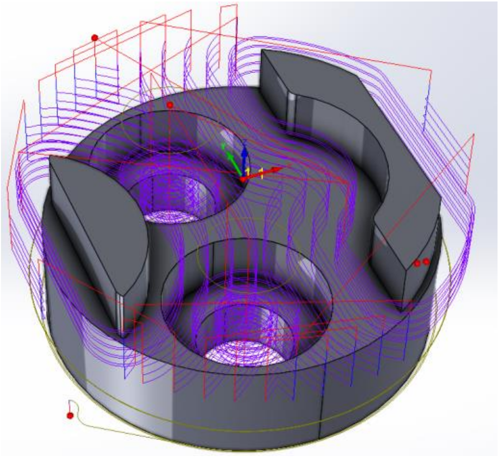


Figure 31 – Toolpath for Cast Iron.

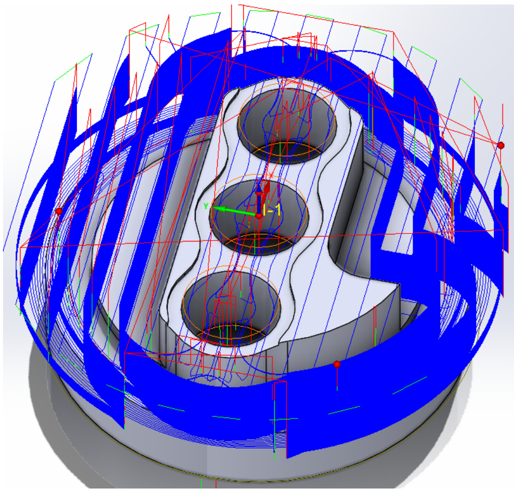


Figure 32 – Toolpath for SuperDuplex.

Regarding to the conventional coolant to use in the test, a Quaker Houghton Danmark – Hocut 4940 is selected and the levels of concentration the oil in water is measured in each of the test. The delivery system integrated in the machine is used to transport the coolant to the work area as is shown in Figure 33.

Figure 33 – Conventional coolant delivery system.

Regarding the LN2 delivery system, the project can be divided into two different sections where the feasibility of two different systems is tested. On the one hand, the tests where the comparison between conventional refrigerant and LN2 is performed (that is, the milling of three different materials with both refrigerants) is carried out with an external delivery system as we describe below. On the other hand, with the idea of improving performance and avoiding some problems related to the external delivery system, such as being able to have more control of the area where the LN2 makes contact and having more control over the flow and temperature of the process, an internal delivery system is tested. This system is composed of a tool holder originally used for MQL, a liquid gas chamber to improve system efficiency, and a circuit composed of instruments and insulated hoses.

For the tests where the **external delivery system** is used, the LN2 it´s fed from a XL-50 Taylor-Wharton vessel across a house system isolated by special Foam is proposed. To reduce heat loss via convection and conduction, plastic hoses are used. Due to the low temperature a specially selected polymer - “perflouralkoxy” (PFA) is used due to its properties to function at temperatures down to -240°C. Beyond changing to a polymer hose, a principle inspired by vacuum hoses is used, where a Ø6/Ø4mm hose for liquid nitrogen supply, is fitted into a Ø12/Ø9 hose. However, instead of creasing vacuum between the two hoses, the larger hose is supplied with gaseous-liquid nitrogen, to act as a “membrane” between the LN2 supply and the environment, just as the cooling effect of the phase transition is used actively to keep the temperatures low. On the outside of the Ø12mm PFA hose, pipe insulation PE foam and aluminium tape is used. On the end of the hoses, a low-pressure “Solid Stream” nozzle (Lechler type 544.320.16.CA) was fitted. Via this system design, the pre-cooling time is reduced to ≈5 min, opposite to the 30 min mentioned in the literature. The general supply system, and the cross-section of gas and liquid "separator" is visualized in Figure 34.

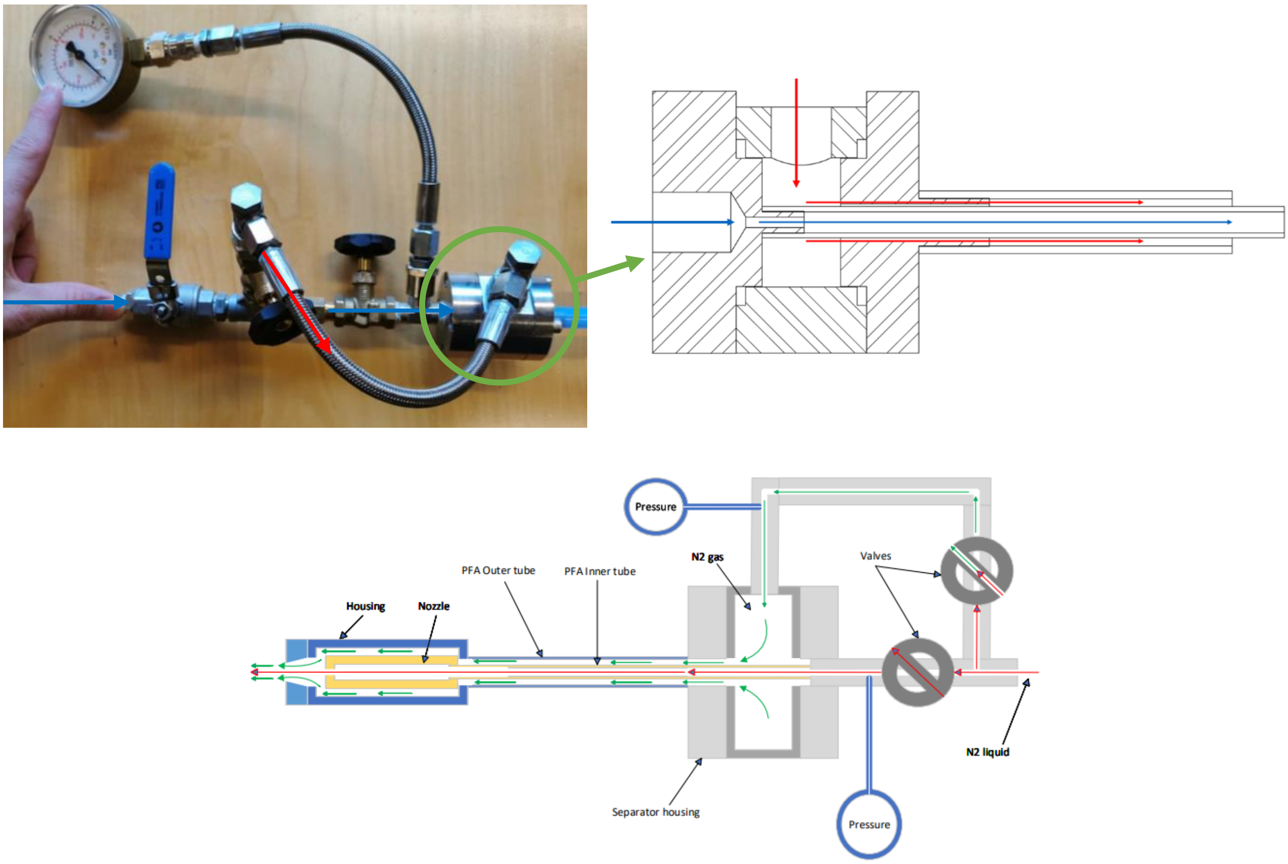


Figure 34: The general system design, and the block to separate gaseous and liquid nitrogen. Red arrows indicate the flow of gaseous nitrogen. Blue arrows indicate the flow of liquid nitrogen.

To fit the house to the spindle and guarantee the correct incidence angle and position of the nozzle, a support clamp for the CNC machine is used and installed with the hardware shown in Figure 35. Also, the Nitrogen liquid Dewar XL-50 acquired is shown in Figure 36.

Figure 35 - Liquid Nitrogen delivery system.

Figure 36 - Liquid Nitrogen Dewar.

In the context of the **internal delivery system**, we employ a SK40xER32x100-AD tool holder to facilitate the distribution of LN2 within the coolant circuit of our tools, ensuring that the flow of LN2 specifically impacts the cutting edge during the milling process. This system utilizes the same hoses, valves, instruments, and chamber for separating the liquid and gas phases as in the previous configuration. However, there is a significant departure from the previous setup in that, instead of terminating in a nozzle, the system is directly connected to a plug that interfaces with the internal circuits of the tool holder.

Additionally, we have introduced a medium-term plastic hose between the end of the system and the tool holder. This hose serves as a safeguard, acting as a fuse if any components within the system become blocked during operation. This proactive measure helps prevent damage to other interconnected systems while maintaining the efficiency and integrity of our LN2 delivery process. We can observe a picture of this circuit in Figure 37.

Figure 37: Internal Delivery system for LN2.

6. Validate, analyse, and quality assurance.

The evaluation of the test process with the two different coolants is divided into two groups, one related to the part resulting where the stability of the parts is analysed and the other related to the effect on the productivity of the two different coolants. These groups contain the following measurements process:

Validation of coolant effect on part stability:

- Measurement of geometric and dimensional tolerances in the resulting parts.
- Roughness measurements in the parts.

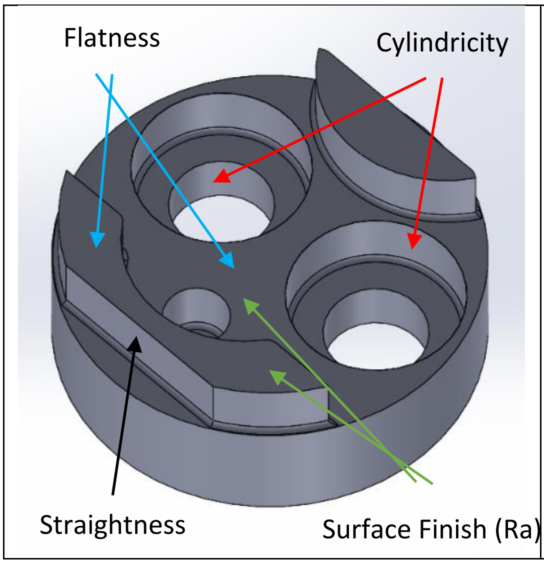
Validation of coolant effect on productivity:

- Tool wear inspection.
- Power consumption analysis.
- Chip shape inspection.
- Noise

The **stability or quality of the test parts** is evaluated by measuring separate **dimensions of the parts and surface roughness**. The geometric measurements are made on a TESA MICRO-HITE 3D CMM surveyor. The surface roughness measurements are made with a hand-held Mahr MarSurf PS1 roughness meter. Both devices are shown in Figure 38 respectively.

Figure 38: Left, TESA CMM surveyor. Right, Mahr roughness mete

The following illustration (Figure 39) shows an example of the type of measurements to be taken in the different geometry for the experiments. The results of the measurements are discussed in section 5.



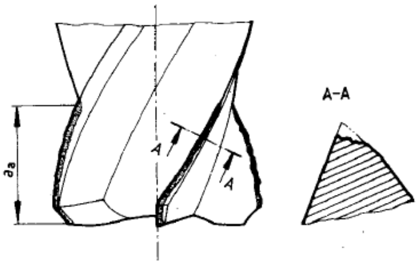
- **Straightness** —
- **Flatness** ▱
- **Cylindricity** ○
- **Surface finish** √

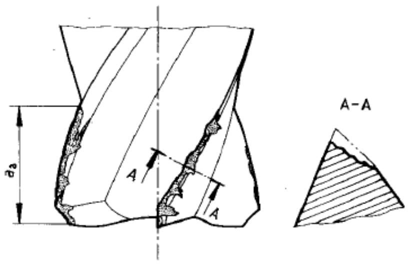
Figure 39- Illustrations of some of the measurements that will be made in this project.

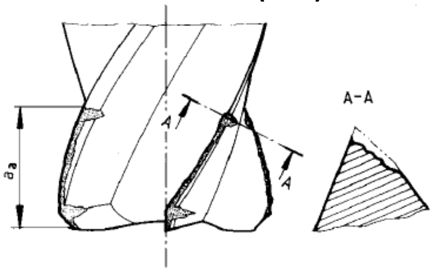
Regarding the validation of the **coolant effect on productivity**, different concepts are evaluated. First, the **tool wear** is analysed by visual inspection and high-resolution imagines, where the experiments are designed so that the cutting time is so long that it is expected that a certain degree of tool wear will be recorded.

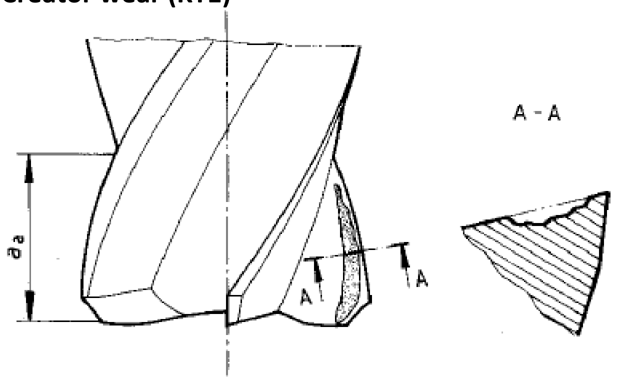
For assessment and classification of tool wear, including which type may occur, ISO 8688-2 "Tool Life testing in milling" is taken as a starting point, which includes contains several different classifications.

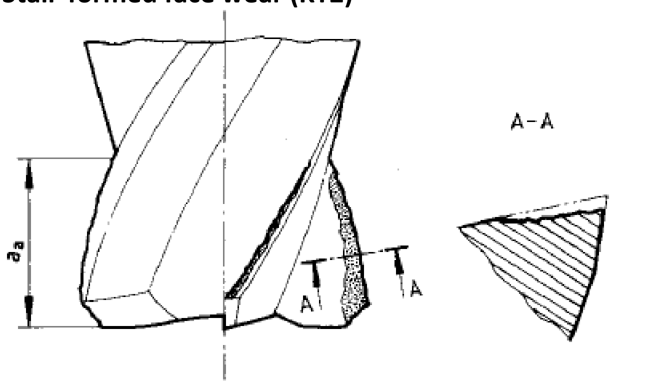
Different wear tools are shown in Table 3 and Table 4 according to ISO 8688-2:

<table>
<tr><td colspan="6">Flank wear (VB): Loss of material from the tool flanks during cutting which results in the progressive development of a flank wear land.</td></tr>
<tr><td colspan="2">Uniform flank wear (VB1)


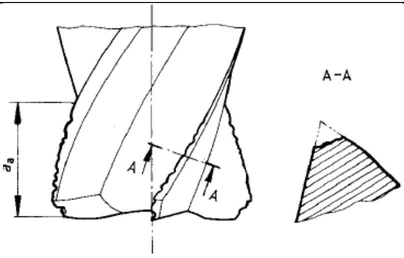
Wear land which is normally of constant width and extends over those portions of the tool flanks adjoining the entire length of the active cutting edge.</td><td colspan="2">Non-Uniform flank wear (VB2)


Wear land which has an irregular width and for which the profile generated by the intersection of the wear and the original flank varies at each position of the measurement</td><td colspan="2">Localized flank wear (VB3)


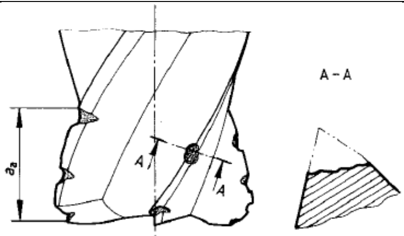
Exaggerated and localized form of flank wear which develops at a specific part of the flank.</td></tr>
<tr><td colspan="6">Face wear (KT): Gradual Loss of tool material from the tool facing during cutting.</td></tr>
<tr><td colspan="3">Creator wear (KT1)


Progressive development of a crater oriented approximately parallel to the major cutting edge and with a maximum depth some distance away from the major cutting edge.</td><td colspan="3">Stair-formed face wear (KT2)


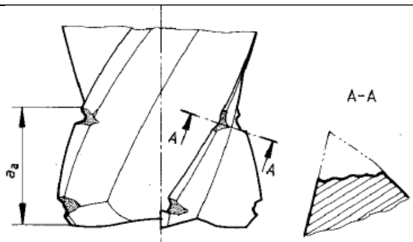
Form of wear in which the maximum depth of the wear scar, measured perpendicular to the tool face, occurs at the intersection of the wear with the tool's major flank.</td></tr>
<tr><td colspan="6">Chipping (CH): Edge deterioration where parts of the edge break away.</td></tr>
<tr><td colspan="2">Uniform chipping (CH1)</td><td colspan="2">Non-uniform chipping (CH2)</td><td colspan="2">Localized chipping (CH3)</td></tr>
</table>



Loss of tool fragments of approximately equal size along the cutting edges significantly influences the uniformity of the width of the flank wear land.

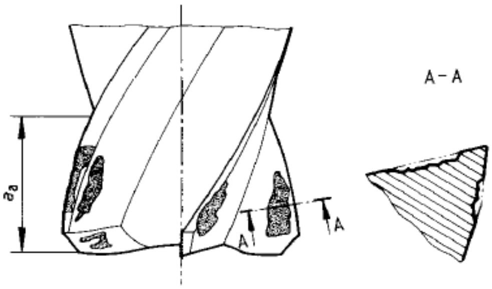


Chipping occurs mostly in connection with cracks at a small number of positions along the active cutting edges but with no consistency from one cutting edge to another.

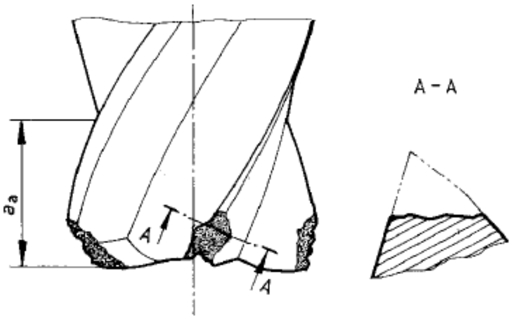


Chipping which occurs consistently at certain positions along the active cutting edge

Flaking (FL): Loss of tool fragments in the form of flakes from the tool surfaces. This phenomenon is most frequently observed when coated tools are used but may also be observed with other tool materials.

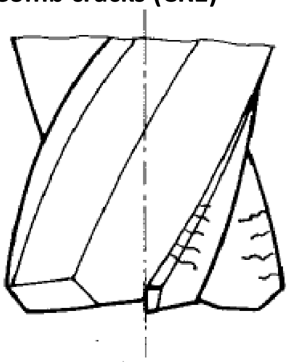


Catastrophic failure (CF): Rapid deterioration to complete failure of the cutting part.

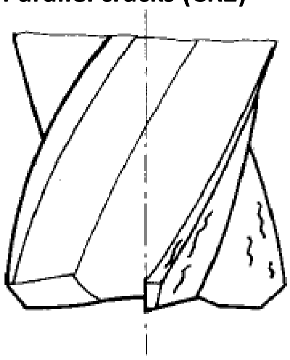


Cracks (CR): Fracture of the cutting tool material which does not immediately cause loss of tool material

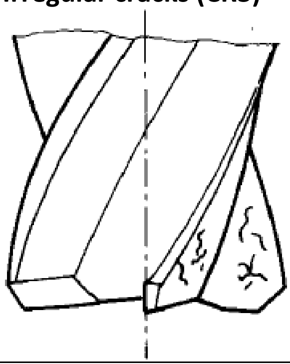
Comb cracks (CR1)



Parallel cracks (CR2)



Irregular cracks (CR3)



Cracks that appear on both the tool face and the tool flank and are oriented approximately perpendicular to the major cutting edge	Cracks that appear on the tool face or the tool flank and which are oriented approximately parallel to the major cutting edge	Cracks that sometimes appear on the tool face and the flank and which are irregularly oriented

Table 3 -Tool wears according to ISO 8688-2.

Tool Damage Form		Cause	Countermeasure
Flank Wear		· Tool grade is too soft. · Cutting speed is too high. · Flank angle is too small. · Feed rate is extremely low.	· Tool grade with high wear resistance. · Lower cutting speed. · Increase flank angle. · Increase feed rate.
Crater Wear		· Tool grade is too soft. · Cutting speed is too high. · Feed rate is too high.	· Tool grade with high wear resistance. · Lower cutting speed. · Lower feed rate.
Chipping		· Tool grade is too hard. · Feed rate is too high. · Lack of cutting edge strength. · Lack of shank or holder rigidity.	· Tool grade with high toughness. · Lower feed rate. · Increase honing. (Round honing is to be changed to chamfer honing.) · Use large shank size.
Fracture		· Tool grade is too hard. · Feed rate is too high. · Lack of cutting edge strength. · Lack of shank or holder rigidity.	· Tool grade with high toughness. · Lower feed rate. · Increase honing. (Round honing is to be changed to chamfer honing.) · Use large shank size.
Plastic Deformation		· Tool grade is too soft. · Cutting speed is too high. · Depth of cut and feed rate are too large. · Cutting temperature is high.	· Tool grade with high wear resistance. · Lower cutting speed. · Decrease depth of cut and feed rate. · Tool grade with high thermal conductivity.
Welding		· Cutting speed is low. · Poor sharpness. · Unsuitable grade.	· Increase cutting speed. (For ANSI 1045, cutting speed 260 SFM.) · Increase rake angle. · Tool grade with low affinity. (Coated grade, cermet grade)
Thermal Cracks		· Expansion or shrinkage due to cutting heat. · Tool grade is too hard. *Especially in milling.	· Dry cutting. (For wet cutting, flood workpiece with cutting fluid) · Tool grade with high toughness.
Notching		· Hard surfaces such as uncut surface, chilled parts and machining hardened layer. · Friction caused by jagged shaped chips. (Caused by small vibration)	· Tool grade with high wear resistance. · Increase rake angle to improve sharpness.
Flaking		· Cutting edge welding and adhesion. · Poor chip disposal.	· Increase rake angle to improve sharpness. · Enlarge chip pocket.

Table 4 -Tool wears according to ISO 8688-2.

A significant part of the machine is about the chips, as these can tell us about what happened during the machining process. In this evaluation, the focus will be particularly on the following aspects:

1. The chips have dent marks,
2. Size and bend of the chip

In the literature, analysis is possible to see that the desirable condition during the machining is that the chips cut themselves in short pieces to avoid several problems regarding power consumption, undesirables' effects in the finish condition, problems extracting heat from the work areas, and other problems related to the chip. Duo to that, the following analysis is made over the chips resulting in the process:

- Visual inspection over the chips to try to identify any dent mark (Direct correlation with problems in the surface finishing) comparing similar pieces to different coolant methods.
- For the same material and geometry, the chip bending radius should be smaller in the case where more heat is extracted if it is considered that the temperature would be related to the local shrinkage of the chip. In addition, chip breakage is given by the achievement of a minimum critical radius so, the size and radius of curvature of the chips have a direct correlation with the heat extraction from the working zone given by the coolant. To make an analysis on this topic the chips resulting from the two different coolant methodologies are placed on a scale grid to make a visual inspection with high-resolution images.

Finally, the power consumption during the process is measured using a Tiny Tag data logger from Gemini Data loggers (TinyTag TV-4804) and it´s shown in Figure 40, which is mounted directly on one of the phases from the main cable of the processing center (previous tests have shown that the current for each of the 3 phases is approximately the same, including the distribution of consumption during processing).

Figure 40: Tiny Tag Data logger with a current clamp.

The logger measures the current (I) through the machine power cable and is set to measure once per second (max value) in milliamps (Ma).

To calculate the Kw consumption (P), the following formula is used, under the conditions below. $P[kW] = (I * U * \sqrt{3} * \cos(\phi))/1000$, where:

- In [A]: The power consumption. I = average current consumption on the phase(s).
- U [V]: The voltage. An average voltage of 400V is expected.
- Φ (phi): Power loss. An expected power loss of 20% is expected.

The conversion from power consumption (Kw) to energy consumption (kWh) is calculated by:

kWh=Kw*h, where:

t [hours]: time specified in hours.

Test process.

To ensure that the collected data of the experiments can be comparable between different materials and coolant used, a test process data sheet have been designed to structure the tests. In the following, the test process data sheet for Aluminium is presented in Figure 41.

DAMRC
Danish Advanced Manufacturing Research Center

TEST PROCESS - DATA SHEET

PROJECT	P1001-4-1 LN2 Milling	
TEST LEAI	G.CARRILLO	gca@damrc.com
TEST DATI	13/03/2023	
INT / EXT	INT	ID 4
TEST PLA(	DAMRC FACILITIES	

PROCESS NAME

MILLING OF ALUMINUM WITH LN2

MATERIAL TO PROCCES AND TOOLS TO USE	QTY
Aluminum AW6026-LF-T6 50mm x 120mm diam.	1
5-axis vertical machining center (DMU80T)	1
SGS 43MAPF (#44641) ø12 R0,5 Z4 TL83 – APMX30	1
TinyTag TV-4804	1
MarSurf PS1	1
XL-45 TAYLON WHARTON LN2 VESSEL.	1
Digital sound level meter	1

PROCESS DESCRIPTION

BEFORE

- Use the necessary personal protection elements
- Setting up current meter
- Setting up noise meter
- Take photos during all the setup process.
- Setting up video Camera.
- Calibrate the tip of the LN2 nozzle so that the bottom of the hose at the tip is higher than the bottom of the tool by a distance equal to the height of the workpiece plus 5mm. The tipo of the nozzle have to
- Check de correct conection of the LN2 delivery system, operate pressure of the system from LIQUID valve on the LN2 container, calibrate the correct pressure with the machine door closed.

DURING

- Take measurements of the noise.
- Take measurements of the current.
- Re-calibrate the position of the LN2 nozzle in each tool change to achieve the condition of Figure 1.
- Take photos of the process in different stage of the milling.
- Collect chips during each change of tool.
- Record all the process with the video camera

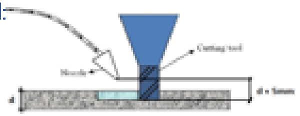
AFTER

- Take measurements of the noise.
- Take measurements of geometrial dimensions on the base of documentantion attached in technical
- Take measurements of dimentions on the base of documentantion attached in technical report
- Take measurements of roughness on the base of documentantion attached in technical report P1001-
- Take measurements of hardness on the base of documentantion attached in technical report P1001-

DATA RECORDED DURING THE PROCESS

ADDITIONAL DATA - OBSERVATIONS

Figure 1:



START TIME		TIME OF TEST	

Danish Advanced Manufacturing Research Center
Sandagervej 10
DK – 7400 Herning
(+45) 2154 5054
mail@damrc.com

Figure 41: Test process data sheet for Aluminium milled with LN2.

Then, to test the feasibility of the internal delivery system, the test process data sheet used during the test is showed in Figure 42.

DAMRC Danish Advanced Manufacturing Research Center	TEST PROCESS - DATA SHEET	
	PROJECT	P1001-4-1 LN2 Milling
	DAMRC CP	Ronnie Manley Petersen rmp@damrc.com
	TEST DATE	xx/10/23
	SUPPLIER	Internal process
	TEST PLACE	DAMRC Technology Center.

PROCESS NAME

TEST PROCESS - Internal delivery system Test.

MATERIAL/TOOLS TO BE USED/PROVIDED BY DAMRC	QTY
Machine: DMG DMU-80T. **Tools:** Tool Holder SK40xER32x100-AD assembled with O-rings and Anti-leak parts / R390-016A16-11L With Insert 1040R12 / End mill SGS-W28987 / LN2 Delivery system with measure intruments and valves. **Materials:** LN2 5 Bar Tank / Two Aluminum AW6026-LF-T6 blocks of 120mmøx50mm / Block of Super duplex SAF 2507 of 120mmøx50mm.	

PROCESS DESCRIPTION

Set Up Internal Delivery systm

1) Close the main valve and the Gas/Liquid Valves of the LN2 delivery system, then open the valve of the LN2 vessel. Wait in this condition for 5 minutes.
2) Open main valve of the LN2 delivery system, after that open gradually the LN2 Gas valve until reach 1.5 Bar in the correspondent manometer. Wait for 5 minutes. Simulatanaly run the spindle of the DMU at 300RPM and control temperature of the cast.
3) Open the LN2 Liquid valve of the delivery system until reach 1.5 barand wait until have Liquid nitrogen flowing out from the holes of the tool. Then close the gas LN2 valve.

Aluminum AW6026-LF-T6 Milling.

1) Facing one milimeter of the Aluminium block, then make a grove of 10mm of deep across the hole diameter.

Super duplex SAF 2507 - Milling.

1) Facing one milimeter of the Aluminium block, then make a grove of 10mm of deep across the hole diameter.

DATA RECORDED DURING THE PROCESS

Stop the proccess after each milling operation and take chips in both materials **Aluminum AW6026-LF-T6 Milling** and **Super duplex SAF 2507 - Milling.**

ADDITIONAL DATA - OBSERVATIONS

	SUPPLIER´S SIGNATURE

DATE OF RECIPT		RETURN DATE	

Figure 42: Test process data sheet for Internal delivery system.

7. Test results

In this section the results of the different tests carried out are discussed. In a first battery of tests, as mentioned in the last section, three different materials were tested using conventional refrigerant and LN2 using an external supply system to provide the cryogenic refrigerant at the work surface. Then, based on the previous result and with the aim of improving the control over the test parameters, a new experiment has been designed using a conventional tool holder with the ability to deliver fluid inside the tool to provide the coolant on the work surface regardless of the operation used. The result of both types of experimenters is discussed below.

7.1 First battery of test – External delivery system of LN2.

7.1.1 Chips and tool wear analysis.

Cast Iron, Aluminium and Stainless-Steel super duplex were milled in different geometries using LN2 and conventional coolant. During the process measurements about the level of noise, current consumption by the whole machine, were taken. After the milling process pictures of the chips, tools and parts resulting were taken to post analysis. In the end analysis about geometrical and dimensional stability and surface roughness was made. The results of the experiments are showed below and then conclusions and future steps proposal are discussed.

7.1.1.1 Aluminium - Oil Water

PROCESS

Figure 43: Aluminium – Oil Water process.

CHIPS

MACRO VIEW **MICROSCOPIC VIEW**

FINISHING

Figure 44: Aluminium – Chips –O/W - Finishing Macro View.

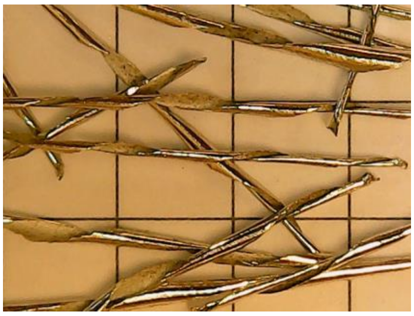


Figure 45: Aluminium – Chips –O/W- Finishing Microscopic View.

SCRUB

Figure 46: Aluminium – Chips –O/W- Scrub Macro View.

Figure 47: Aluminium – Chips –O/W- Scrub Microscopic.

TOOLS

Figure 48: Aluminium – Tools - O/W – Scrub.

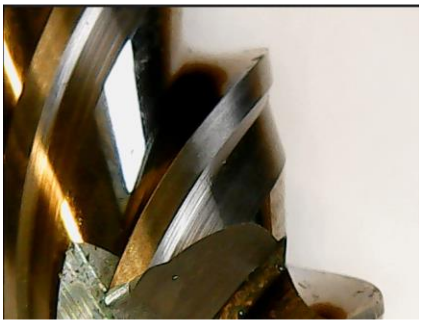


Figure 49: Aluminium – Tools - OW – Scrub.

Figure 50: Aluminium – Tools - OW – Scrub.

7.1.1.2 Aluminium - LN2

PROCESS

Figure 51: Aluminium – LN2 process.

Figure 52: Aluminium – LN2 process.

CHIPS

MACRO VIEW **MICROSCOPIC VIEW**

FINISHING

Figure 53: Aluminium – Chips – LN2 - Finishing Macro View.

Figure 54: Aluminium – Chips – LN2 - Finishing Microscopic View.

SCRUB

Figure 55: Aluminium – Chips – LN2 - Scrub Macro View.

Figure 56: Aluminium – Chips – LN2 - Scrub Microscopic View.

TOOLS

Figure 57: Aluminium – Tools – LN2 – Scrub.

Figure 58: Aluminium – Tools – LN2 – Scrub.

Figure 59: Aluminium – Tools – LN2 – Scrub.

7.1.1.3 Cast Iron - Oil Water.

PROCESS

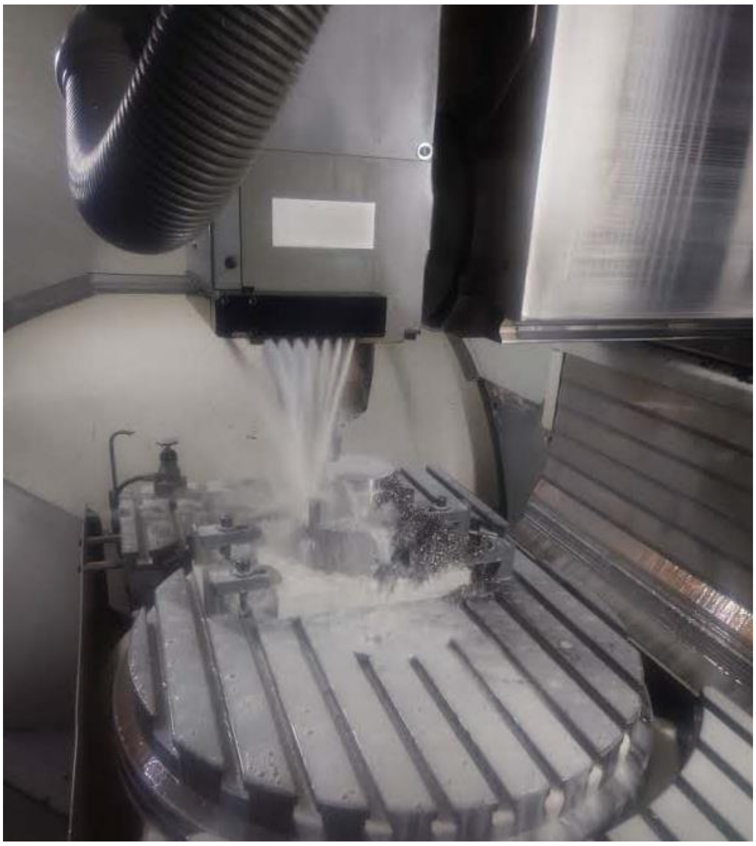


Figure 60: Cast Iron – O/W - Process.

CHIPS

MACRO VIEW **MICROSCOPIC VIEW**

DRILLING

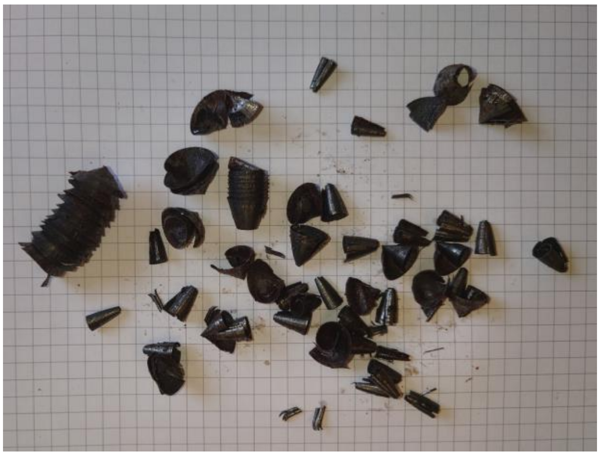


Figure 61: Cast Iron – Chips –O/W - Drilling Macro View.

Figure 62: Cast Iron – Chips –O/W - Drilling Microscopic.

MILLING


Figure 63: Cast Iron – Chips –O/W - Milling Macro View.


Figure 64: Cast Iron – Chips –O/W - Milling Microscopic.

TOOLS
DRILLING

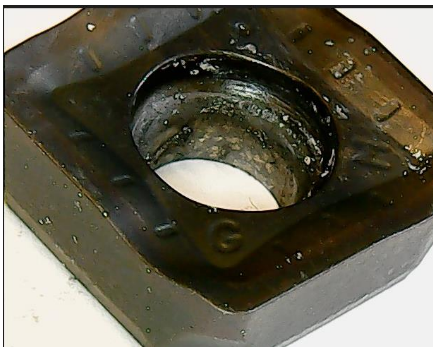


Figure 65: Cast Iron – Tools – O/W – Drilling.

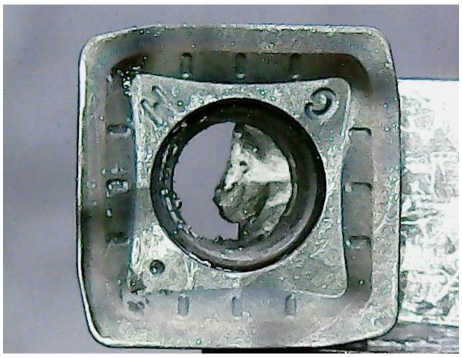


Figure 67: Cast Iron – Tools – O/W – Drilling.

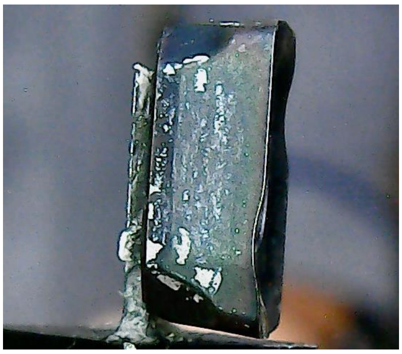


Figure 68: Cast Iron – Tools – O/W – Drilling.

SCRUB

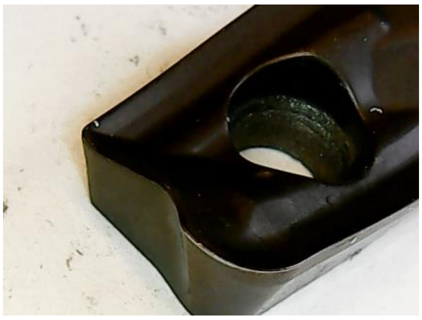


Figure 69: Cast Iron – Tools – O/W – Scrub.


Figure 70: Cast Iron – Tools – O/W – Scrub.

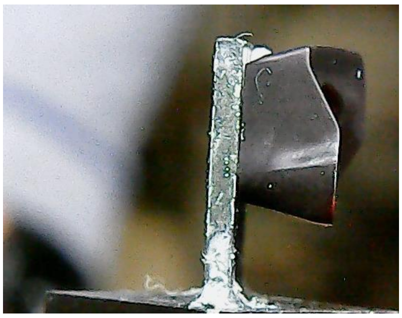


Figure 71: Cast Iron – Tools – O/W – Scrub.

7.1.1.4 Cast Iron - LN2

PROCESS

Figure 72: Cast Iron – LN2 - Process.

CHIPS

MACRO VIEW **MICROSCOPIC VIEW**

DRILLING

Figure 73: Cast Iron – Chips –LN2 - Drilling Macro View.

Figure 74: Cast Iron – Chips –LN2 - Drilling Microscopic

MILLING

Figure 75: Cast Iron – Chips –LN2 - Milling Macro View.

Figure 76: Cast Iron – Chips –LN2 - Milling Microscopic

TOOLS
DRILLING

Figure 77: Cast Iron – Tools – LN2 – Drilling.

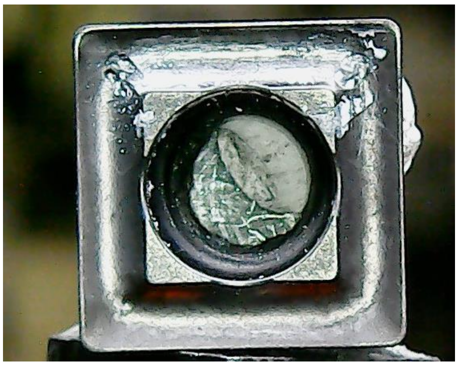


Figure 78: Cast Iron – Tools – LN2 – Drilling.

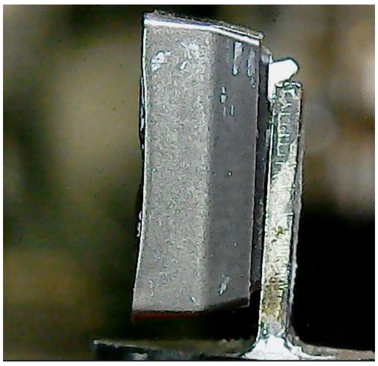


Figure 79: Cast Iron – Tools – LN2 – Drilling.

SCRUB

Figure 80: Cast Iron – Tools – LN2 – Scrub.

Figure 81: Cast Iron – Tools – LN2 – Scrub.

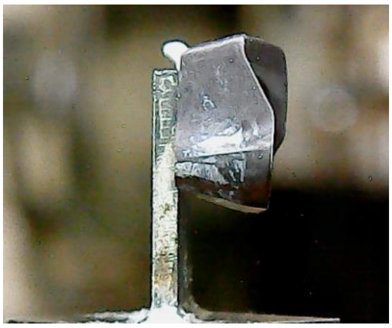


Figure 82: Cast Iron – Tools – LN2 – Scrub.

7.1.1.5 Super Duplex - Oil Water

PROCESS

Figure 83: Super Duplex – O/W - Process.

CHIPS

MACRO VIEW **MICROSCOPIC VIEW**

FINISHING

Figure 84: Super Duplex – Chips – O/W - Finishing Macro View.

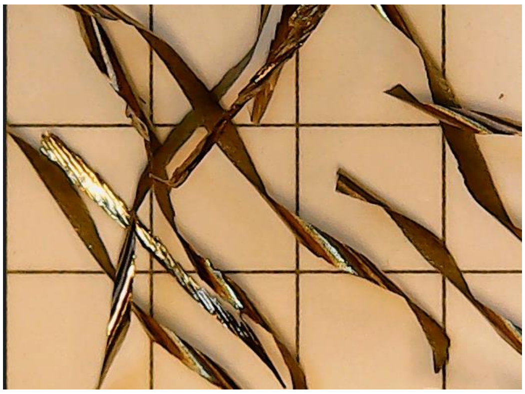


Figure 85: Super Duplex – Chips – O/W - Finishing Microscopic

DRILLING

Figure 86: Super Duplex – Chips – O/W - Drilling Macro View.

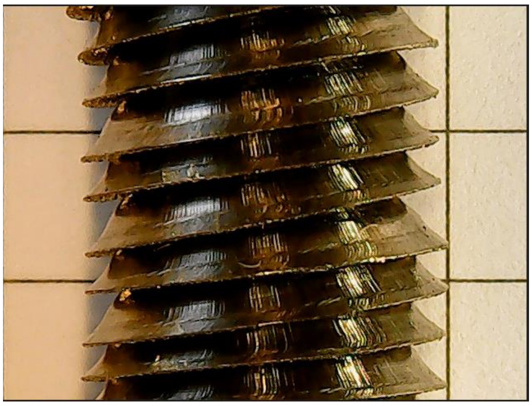


Figure 87: Super Duplex – Chips – O/W - Drilling Microscopic.

SCRUB

Figure 88: Super Duplex – Chips – O/W - Scrub Macro View.

Figure 89: Super Duplex – Chips – O/W - Scrub Microscopic.

TOOLS

FINISHING

Figure 90: Super Duplex – Tools – O/W – Finishing.

Figure 91: Super Duplex – Tools – O/W – Finishing.

DRILLING

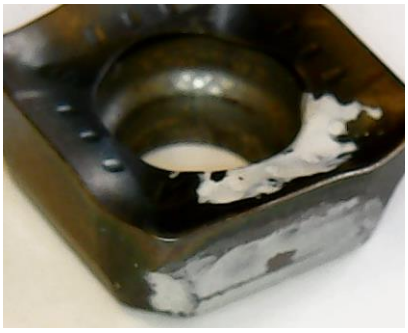


Figure 92: Super Duplex – Tools – O/W – Drilling

Figure 93: Super Duplex – Tools – O/W – Drilling

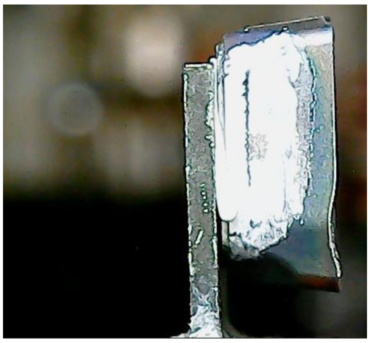


Figure 94: Super Duplex – Tools – O/W – Drilling

Figure 95: Super Duplex – Tools – O/W – Drilling

Figure 96: Super Duplex – Tools – O/W – Drilling

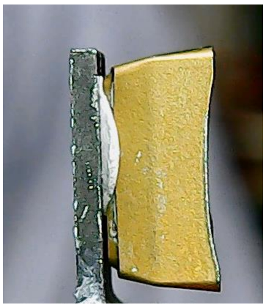


Figure 97: Super Duplex – Tools – O/W – Drilling

SCRUB

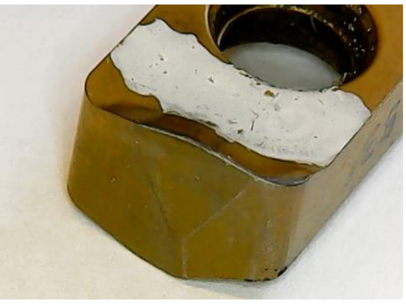


Figure 17

Figure 98: Super Duplex – Tools – O/W – Scrub

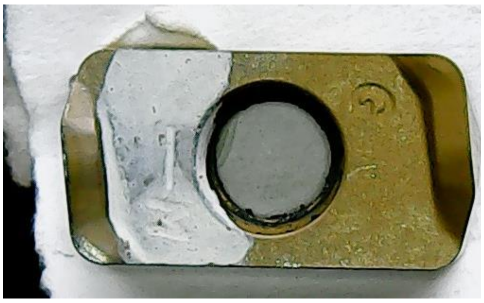


Figure 99: Super Duplex – Tools – O/W – Scrub

Figure 100: Super Duplex – Tools – O/W – Scrub

7.1.1.6 Super duplex – LN2.

PROCESS

Figure 101: Super Duplex – LN2 – Process.

CHIPS

MACRO VIEW **MICROSCOPIC VIEW**

FINISHING


Figure 102: Super Duplex – Chips – LN2 – Finishing Macro View.


Figure 103: Super Duplex – Chips – LN2 – Finishing Microscopic

DRILLING


Figure 104: Super Duplex – Chips – LN2 – Drilling Macro View.


Figure 105: Super Duplex – Chips – LN2 – Drilling Mircroscopic.

SCRUB


Figure 106: Super Duplex – Chips – LN2- Scrub Macro View.


Figure 107: Super Duplex – Chips – LN2- Scrub Microscopic.

TOOLS

FINISHING


Figure 108: Super Duplex – Tools – LN2 – Finishing.


Figure 109: Super Duplex – Tools – LN2 – Finishing.

DRILLING


Figure 110: Super Duplex – Tools – LN2 – Drilling.

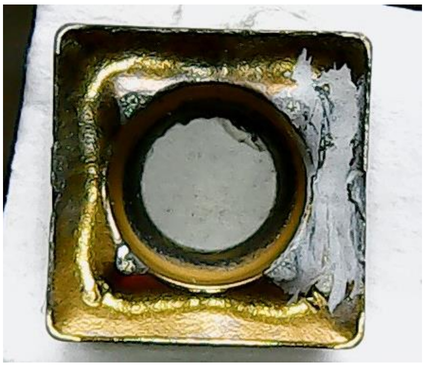


Figure 111: Super Duplex – Tools – LN2 – Drilling.

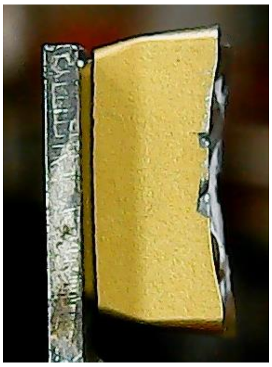


Figure 112: Super Duplex – Tools – LN2– Drilling.

Figure 113: Super Duplex – Tools – LN2 – Drilling.

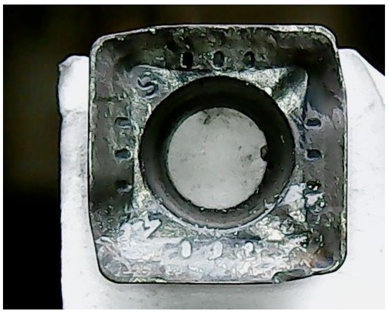


Figure 114: Super Duplex – Tools – LN2 – Drilling.

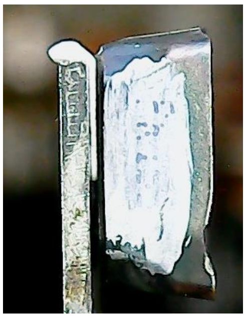


Figure 115: Super Duplex – Tools – LN2 – Drilling.

SCRUB

Figure 116: Super Duplex – Tools – LN2 – Scrub.

Figure 117: Super Duplex – Tools – LN2 – Scrub.

Figure 118: Super Duplex – Tools – LN2 – Scrub.

7.1.2 Geometrical and Dimensional Tolerance analysis.

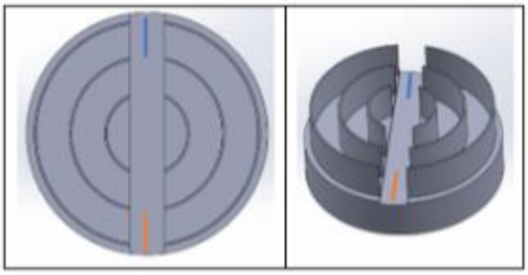
This section shows the result of the geometric and dimensional tolerance analysis. The measurement to quantify these values is carried out using a TESA MH3D-DUAL coordinate measuring machine "The MH3D-DUAL CMM". Different geometric parameters are evaluated for the different geometries corresponding to each material to draw conclusions about the effect of LN2 in terms of dimensional and geometric precision.

7.1.2.1 Aluminium – O/W

Measurement points for: Aluminum (AW6026-LF-T6)

Material:	Aluminium	**LN2:**		**Conventional coolant:**	**X**	**ID:**		**Date**	28/08/23

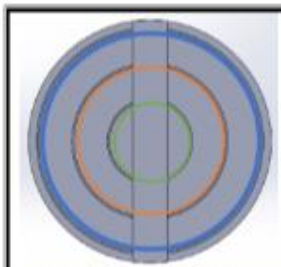
Surface measurement:



Measuring points for surface roughness:

Blue: 0,760 Ra 5,07 Rz	Orange: 0,550 Ra 3,11 Rz

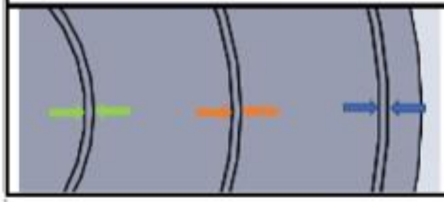
CMM- measurement.



Circularity:

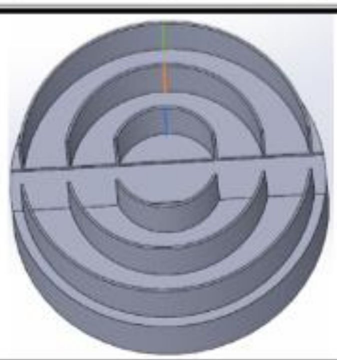
Circularity 2-3 mm below surface (inside the circle)

Blue: diam109,8553
Orange: diam74,8616
Green: diam39,8705mm



Wall thickness of Rib: 3-5 mm under top surface

Blue: 1,1184
Orange: 1,1061
Green: 1,1443mm



Straightness:

Straightness on wings, from bottom to top (one of each wing) With five point

Blue: 0,0192
Orange: 0,0082
Green: 0,0088

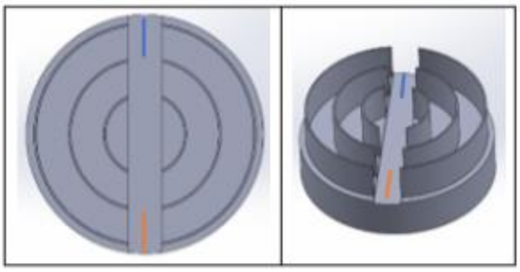
Figure 119 – Geometrical and Dimensional Tolerance measurement – Data sheet Aluminium-O/W.

7.1.2.2 Aluminium – LN2

Measurement points for: Aluminum (AW6026-LF-T6)

Material:	Aluminium	LN2:	X	Conventional coolant:		ID:		Date	28/08/23

Surface measurement:



Measuring points for surface roughness:

Blue: 1,008 Ra 5,11 Rz	Orange: 1,078 Ra 5,70 Rz

CMM- measurement.

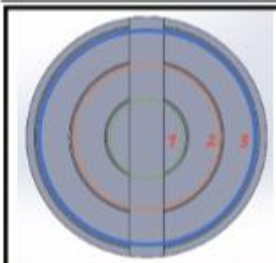
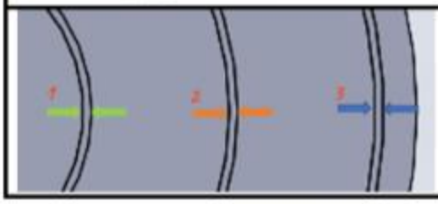
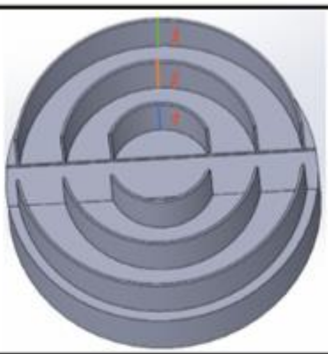
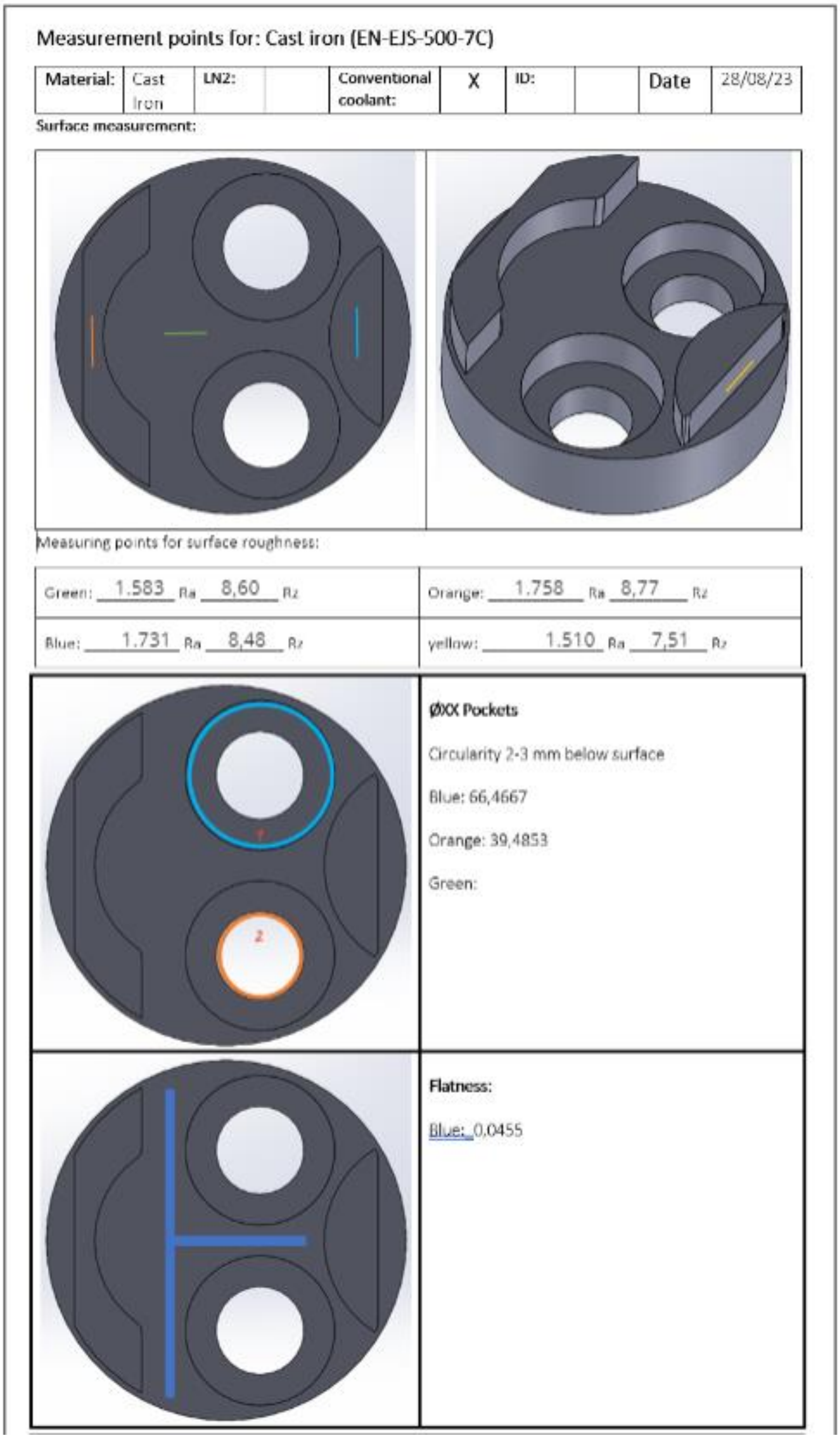
	**Circularity:** Circularity 2-3 mm below surface (inside the circle) Blue: 108,1404 Orange: 73,1828 Green: 38,0276
	**Wall thickness of Rib:** 3-5 mm under top surface Blue: 3,1156 Orange: 2,9898 Green: 3,0953
	**Straightness:** Straightness on wings, from bottom to top (one of each wing) Blue: 0,0106 Orange: 0,0201 Green: 0,0190

Figure 120 – Geometrical and Dimensional Tolerance measurement – Data sheet Aluminium-LN2.

7.1.2.3 Cast Iron – O/W



Measurement points for: Cast iron (EN-EJS-500-7C)

Material:	Cast Iron	LN2:		Conventional coolant:	X	ID:		Date	28/08/23

Surface measurement:

Measuring points for surface roughness:

Green: 1.583 Ra 8,60 Rz	Orange: 1.758 Ra 8,77 Rz
Blue: 1.731 Ra 8,48 Rz	yellow: 1.510 Ra 7,51 Rz

ØXX Pockets

Circularity 2-3 mm below surface

Blue: 66,4667

Orange: 39,4853

Green:

Flatness:

Blue: 0,0455

Figure 121 – Geometrical and Dimensional Tolerance measurement – Data sheet Cast Iron-A-O/W.

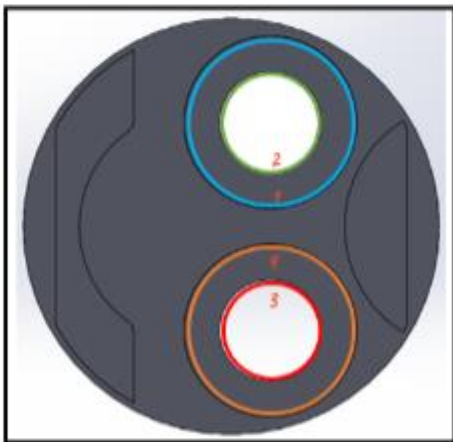
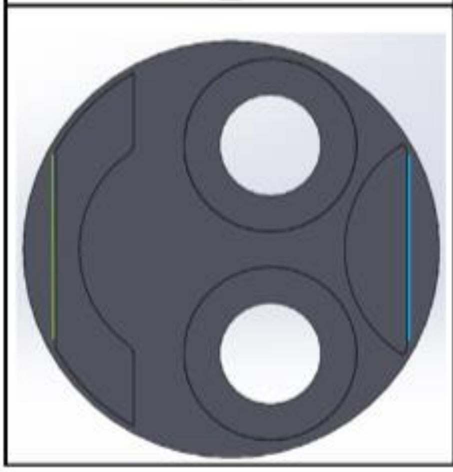
	**Concentricity:** 2-3mm under surface Blue/Green: 0,0907 Orange/Red: 0,1273
	**Parallelism:** Blue/Green: 0,0157 Perpendicular distance: 134,9725

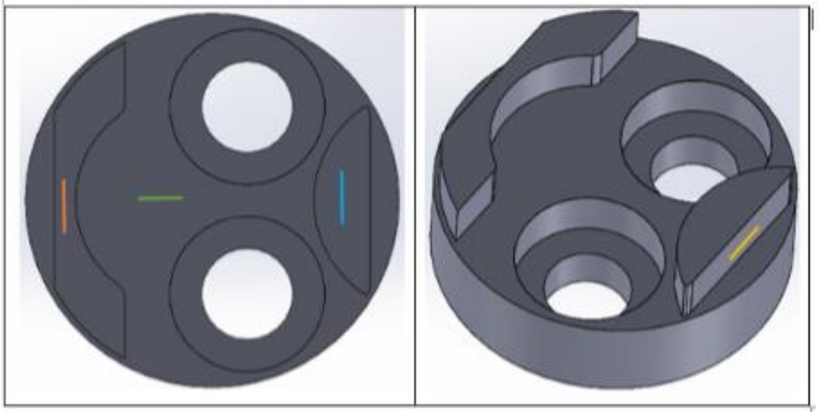
Figure 122 – Geometrical and Dimensional Tolerance measurement – Data sheet Cast Iron-B-O/W.

7.1.2.4 Cast Iron – LN2

Measurement points for: Cast iron (EN-EJS-500-7C)

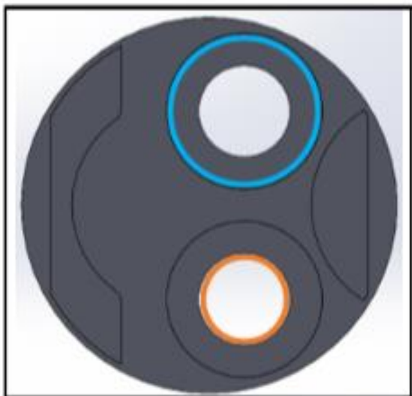
Material:	Cast Iron	LN2:	x	Conventional coolant:		ID:		Date	28/08/23

Surface measurement:



Measuring points for surface roughness:

Green: 1.583 Ra 8,60 Rz	Orange: 1.703 Ra 8,84 Rz
Blue: 1.01 Ra 6,63 Rz	yellow: XXXX Ra XXXX Rz



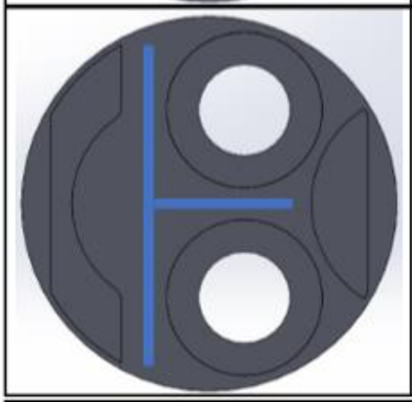
ØXX Pockets

Circularity 2-3 mm below surface

Blue:

Orange: 39,4938

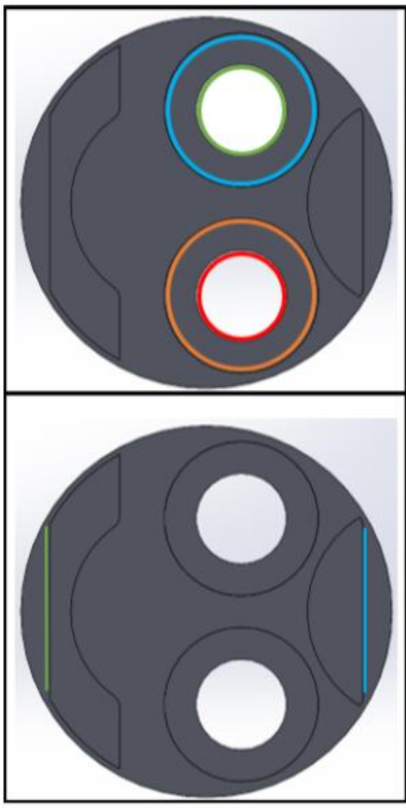
Green:



Flatness:

Blue: 0,0245

Figure 123 – Geometrical and Dimensional Tolerance measurement – Data sheet Cast Iron-A-LN2.



Concentricity:

2-3mm under surface

Blue/Green:

Orange/Red:

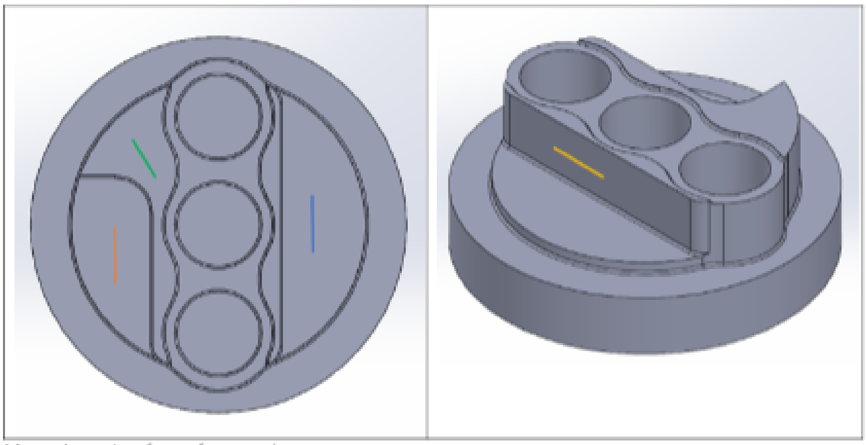
Parallelism:

Blue/Green: 0,0197

Perpendicular distance: 135,0897

Figure 124 – Geometrical and Dimensional Tolerance measurement – Data sheet Cast Iron-B-LN2.

7.1.2.5 Super Duplex – O/W



Measurement points for: Super duplex (EN 1.4301 / 1.4307 / AISI304)

Material:	Cast Iron	LN2:	x	Conventional coolant:		ID:		Date	28/08/23

Surface measurement:

Measuring points for surface roughness:

Green: 1,484 Ra 7,70 Rz	Orange: 0,301 Ra 1,75 Rz
Blue: 0,514 Ra 3,83 Rz	yellow: 0,373 Ra 1,69 Rz

Figure 125 – Geometrical and Dimensional Tolerance measurement – Data sheet Super Duplex-A-O/W.

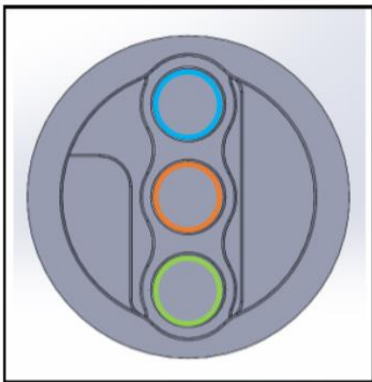
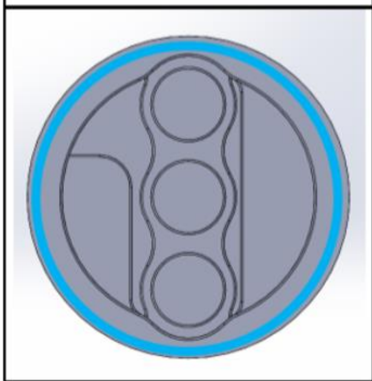
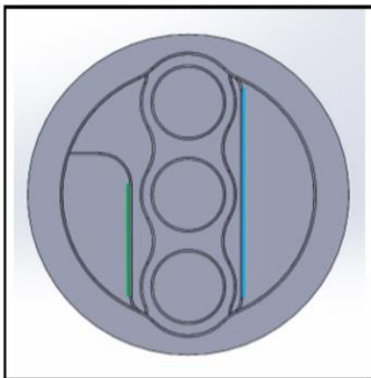
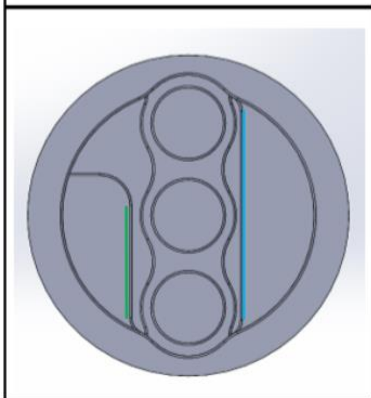
	**ØXX Pokket** Circularity 2-3 mm below surface Blue: 27,9180 Orange: 27,9323 Green: 27,9201 Center distance between blue and green: 68.9920
	**Flatness:** Blue: 0,0013
	**Straightness:** 3-5mm under surface Blue: 0,0005 Grenn: 0,0002
	**Parallelism:** 3-5mm under surface Blue/Green: 0,0046 Perpendicular distance: 40,5223

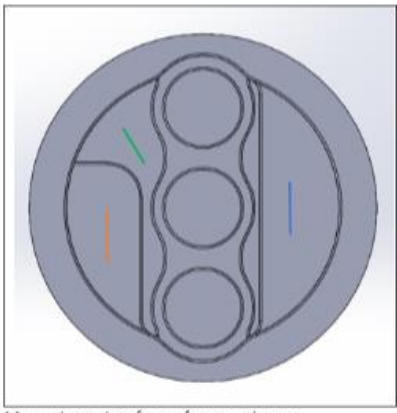
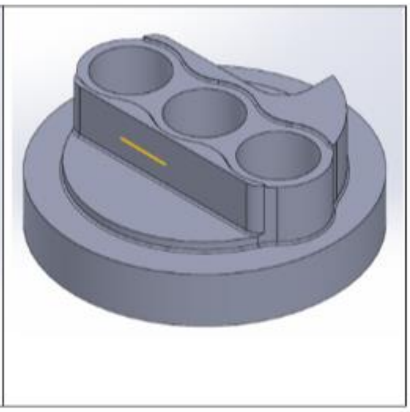
Figure 126 – Geometrical and Dimensional Tolerance measurement – Data sheet Super Duplex-B-O/W.

7.1.2.6 Super Duplex – LN2

Measurement points for: Super duplex (EN 1.4301 / 1.4307 / AISI304)

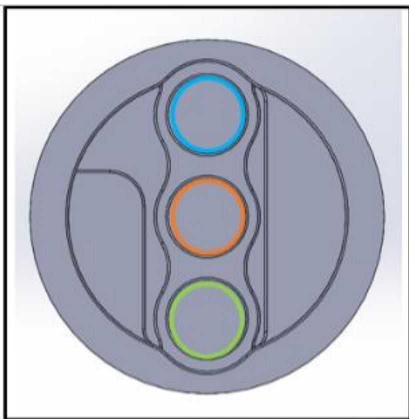
Material:	Super Duplex	LN2:		Conventional coolant:	X	ID:		Date	28/08/23

Surface measurement:

Measuring points for surface roughness:

Green: 1,646 Ra 6,82 Rz	Orange: 0,564 Ra 3,5 Rz
Blue: 0,327 Ra 1,72 Rz	yellow: 0,911 Ra 3,92 Rz



ØXX Pocket

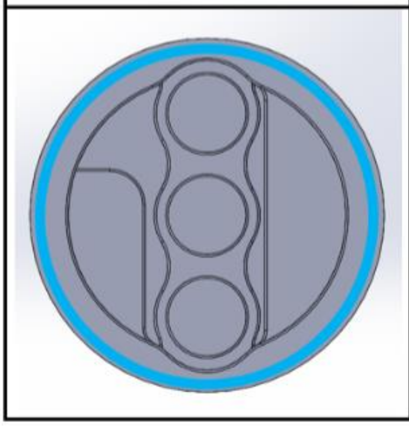
Circularity 2-3 mm below surface

Blue: 28,0171

Orange: 28,0094

Green: 27,9765

Center distance between blue and green pocket 69,1426



Flatness:

Blue: 0,0165

Figure 127 – Geometrical and Dimensional Tolerance measurement – Data sheet Super Duplex-A-LN2.

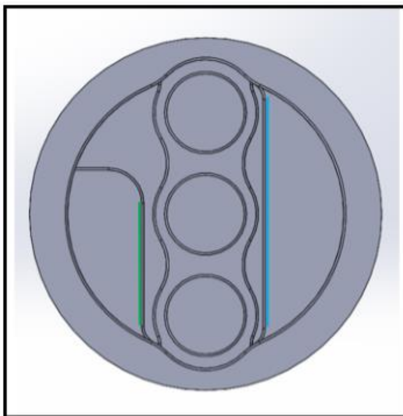
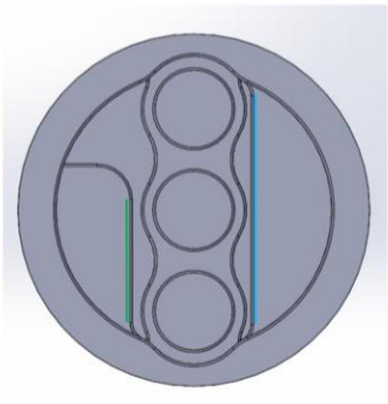
	**Straightness:** 3-5mm under surface Blue: 0,0048 Grenn: 0,0004
	**Parallelism:** 3-5mm under surface Blue/Green: 0,0112 Perpendicular distance: 40,6504

Figure 128 – Geometrical and Dimensional Tolerance measurement – Data sheet Super Duplex-B-LN2.

7.1.3 Power consumption analysis.

This section shows the result of the power consumption measurement taken during the milling of the different geometries with Liquid Nitrogen and conventional coolant. The device used to take this measurement is a Tiny Tag data logger from Gemini Data loggers (TinyTag TV-4804). Then average of the current consumption is calculated for each case to have a better overview of what is happening when the coolant is changed. Comparison are conclusion are taken in 8.Data analysis..

7.1.3.1 Aluminium – O/W

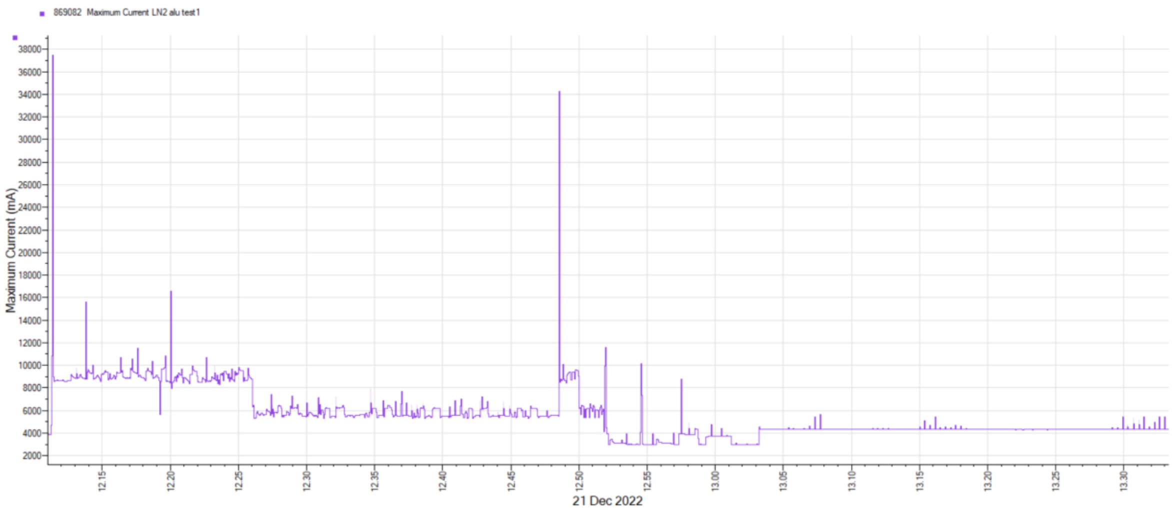


Figure 129 – Power consumption during Milling process in Aluminium using conventional coolant.

Average value:	5.62 A

7.1.3.2 Aluminium – LN2

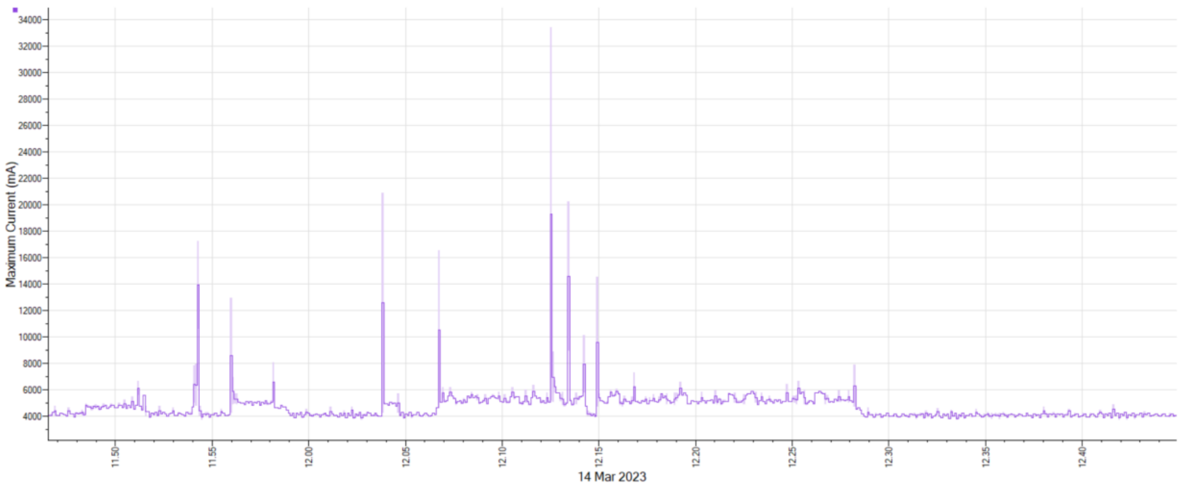


Figure 130– Power consumption during Milling process in Aluminium using LN2.

Average value:	4.72 A

7.1.3.3 Super Duplex – O/W

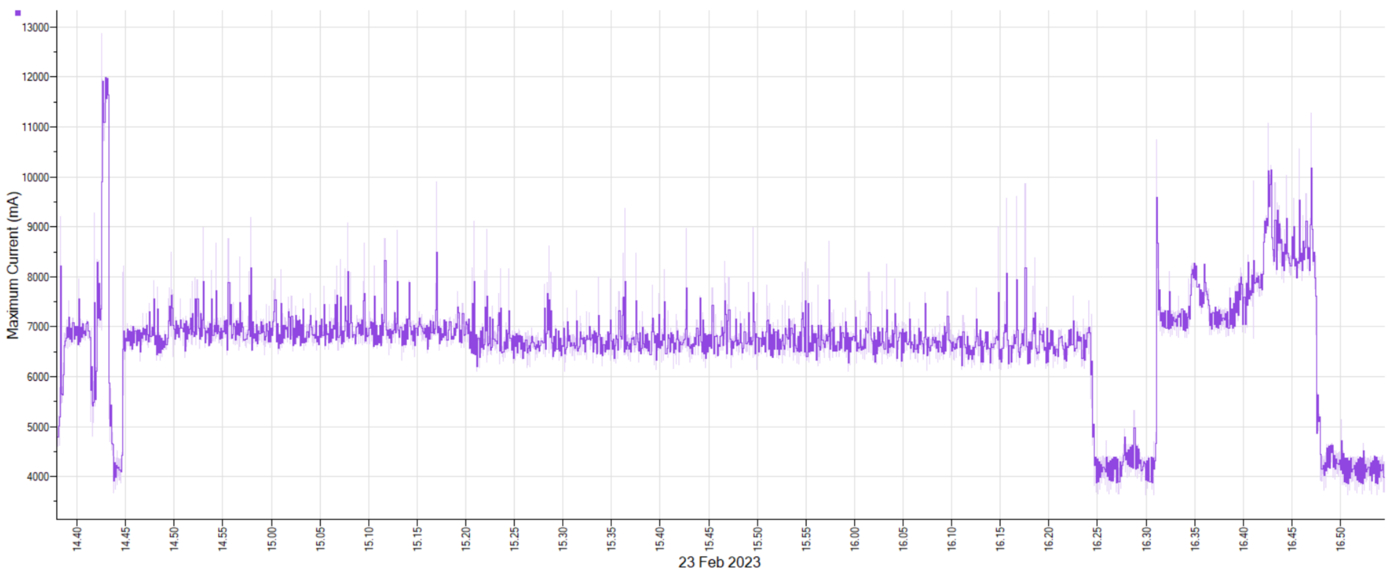


Figure 131– Power consumption during Milling process in Super Duplex using conventional coolant.

Average value:	6.68A

7.1.3.4 Super Duplex – LN2

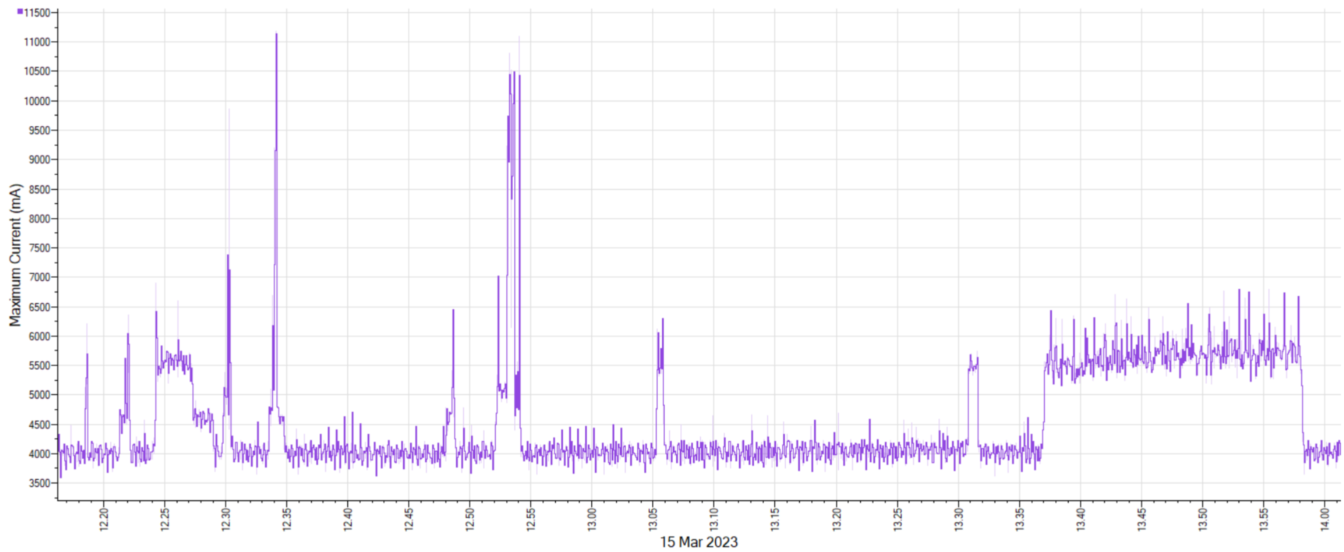


Figure 132– Power consumption during Milling process in Super Duplex using LN2.

Average value:	4.53 A

7.1.4 Noise analysis.

This section shows the result of environmental noise measurement taken during the milling of the different geometries with Liquid Nitrogen and conventional coolant. The device used to take this measurement is a digital sound level meter GM1357 from Shenzhen Jumaoyuan. For study and presentation goals, the maximum levels of noise for each operation in each combination material/coolant, are presented in the Table 3.

Material	Coolant	Operation	Maximum per operation (dB)
Aluminium	Oil / Water	Slotted	65
	LN2	Slotted	82
Cast Iron	Oil / Water	Drilling	85
		Milling	99
	LN2	Drilling	88
		Milling	101
Super Duplex	Oil / Water	Drilling	91,2
		Roughing	90,5
		Finishing	63
	LN2	Drilling	85
		Roughing	87
		Finishing	69

Table 3- Noise measurements.

7.2 Second battery of test – Internal delivery system of LN2.

In this new section, we shift our focus to the evaluation of an internal delivery system for coolant during milling processes. As previously discussed, the decision to transition to this system was prompted by the challenges encountered with the external delivery method. The internal system, facilitated by a newly acquired commercial tool holder, is specifically designed to deliver coolant through the internal passages of the tools. This transition aims to enhance the precise application of liquid nitrogen (LN2) coolant to the work area for all machining operations and to allow for controlled and reduced LN2 delivery. Our objective in this section is to provide an in-depth analysis of the results obtained from our experiments with the internal delivery system. We will assess its effectiveness in overcoming the limitations experienced with the external delivery system, such as challenges in controlling coolant presence, achieving optimal cooling, and ensuring part stability, especially when working with materials prone to high dimensional changes under temperature changes. The shift to an internal delivery system represents a significant step in our ongoing efforts to refine the milling process, and the results from these experiments will provide valuable insights into its potential benefits and limitations for future steps of our research.

For the experiments, a Sk40Xer32x100-ad tool holder with the capability to transport coolant internally was utilized to test two different tools (The tool holder was modified by adding two 3D printed seals to prevent LN2 leak between the collets slots and tool, and along the clamping side of the tool holder). On other hand, a solid end mill (SGS 44641) was employed, while on the other side, a tool (R390-016A16-11L with insert R390-11 T3 10M-MH 1040) was used to mill. The workpiece consisted of a block of Aluminium AW6026-LF-T6, and various passes with different RPM and depth of cut settings were conducted.

Concerning LN2, a vessel of 5Bar and 190L was employed to provide LN2 across a system created by a metallic house isolated by foam, as can be observed in the provided pictures Figure 133. To control the pressure of the system, two ball valves and a manometer were used between the tool holder and the LN2 recipient. On the other hand, as a safety condition, a plastic hose was used as a fusible before reaching the tool holder to act as a safety measure in the case that the tool holder got stuck, avoiding damage to the devices up current.

Figure 133 – Internal delivery system with R390-11 T3 10M-MH 1040.

The tests conducted for the two different tools involved running the tool holder without any coolant for 2 minutes to warm up the grease of the bearings and prevent freezing. After that, LN2 was delivered into the tool, and the temperature was measured 5 millimeters behind the tip of the tool to check when Liquid Nitrogen was being released from the tool. Then, once the temperature reached that of the liquid nitrogen, a different pass had to be carried out, starting with 500RPM and 1mm, then 500RPM and 5mm, followed by 1000RPM and 5mm, and finally, 3000RPM and 5mm.

An aspect that had an importance relevance during the test was the diameter of the conduct of each tool tested to perform the test, As we can see in Figure 134-139, the end mill SGS 44641 have to separated input holes of 1 mm each one than derive in two outlet holes of the same diameter, while the R390-016A16-11L have only one entry of 4 mm than then derivate in two outlet holes of 2mm each one, it´s mean, the doble of area to conduct LN2.

Figure 134 – Internal delivery system with R390-016A16-11L.

Figure 135 – End mill SGS 44641.

Figure 136 – Coolant inlet hole R390-016A16-11L.

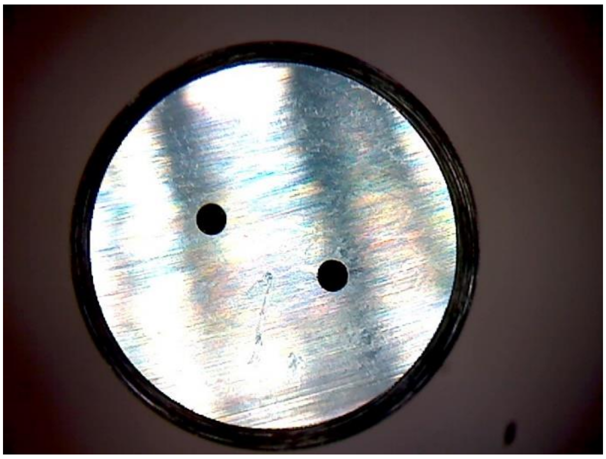


Figure 137 – Coolant inlet hole End mill SGS 44641.

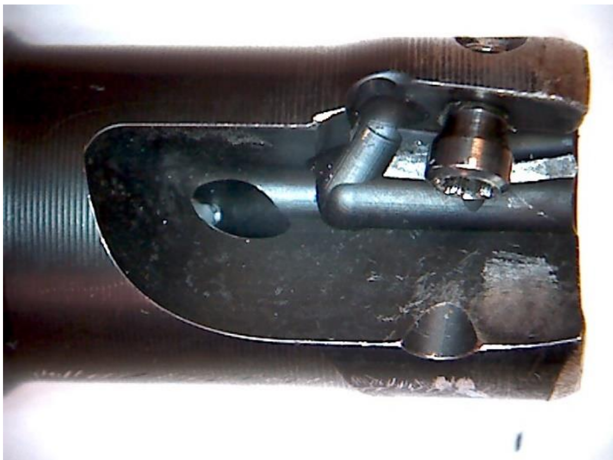


Figure 138 – Coolant outlet hole R390-016A16-11L.

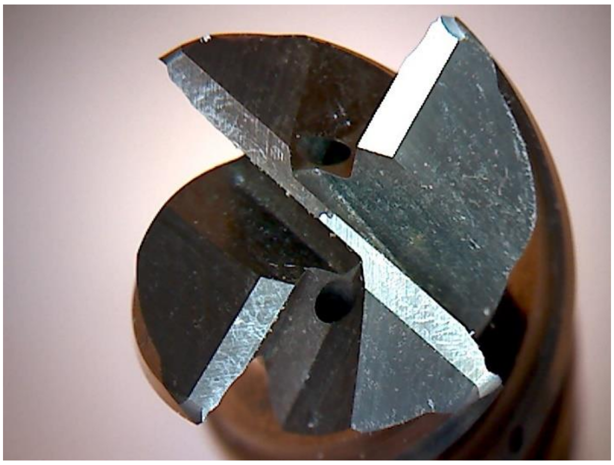


Figure 139 – Coolant outlet hole End mill SGS 44641.

During the test carried out with the end mill SGS 44641, regardless of the time spent trying to obtain LN2, it was impossible to cool the temperature below 0°C, in fact after a certain time the temperature began to rise, and the torque necessary to rotate the spindle was higher, probably because a large part of the delivered

LN2 could not be evacuated through the tool outlet, contracting the parts of the tool holder and increasing the friction between parts, so no milling tests were carried out with this tool. In Figure 140 you can see the temperature graph resulting from the test mentioned.

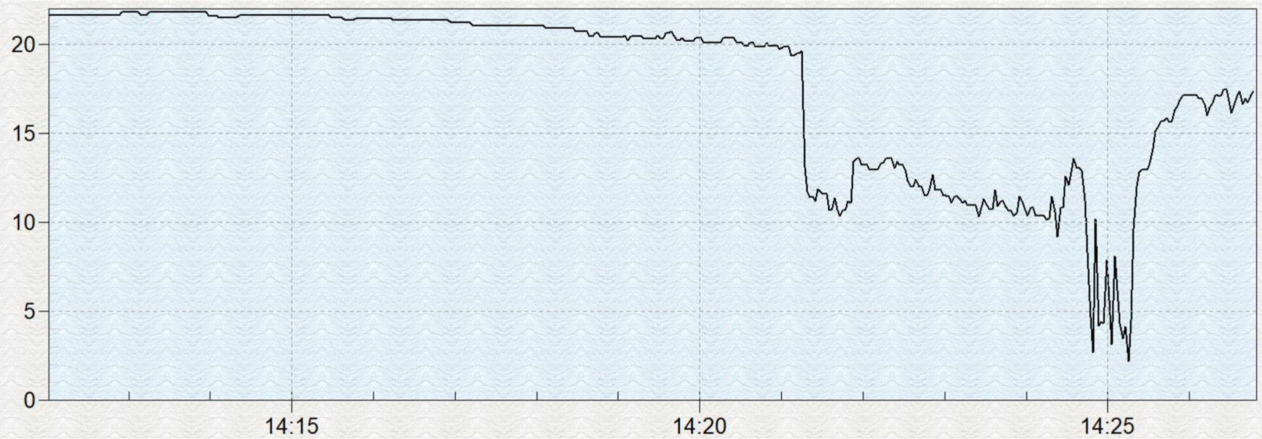


Figure 140 – Temperature chart resulting of test with End mill SGS 44641 – No milling – 800RPM – 5 Bars of LN2.

In the other hand, for the R390-016A16-11L tool with larger exit holes, LN2 was obtained in approximately 10 minutes, which can be seen in Figure 141.

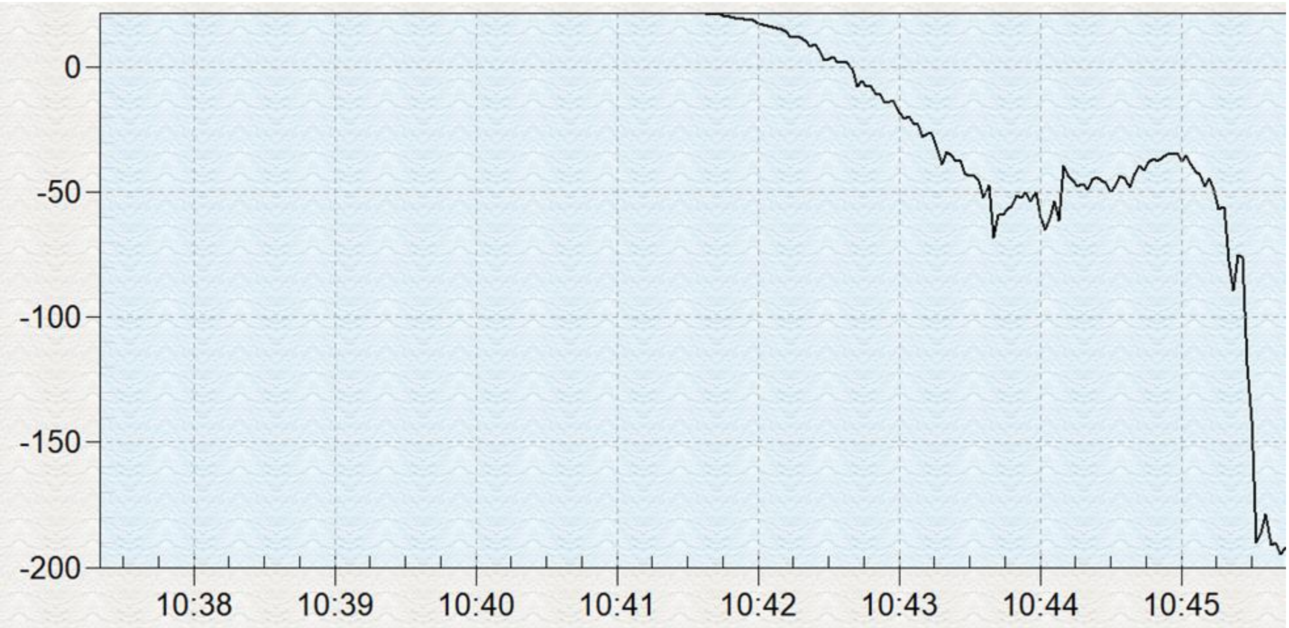


Figure 141 – Temperature chart resulting of test with R390-016A16-11L 800 RPM– 5 Bars of LN2.

This difference in behaviour between the tools, for the same pressure, could be associated with the geometry of the tool channels, considering that this defines the mass flow necessary to cool the entire circuit and achieve LN2 at the tool outlet.

After reaching the liquid Nitrogen that comes out of the tool R390-016A16-11L, the mentioned test was carried out, images of the tool used, chips and workpiece are shown in Figure 142-145.

Figure 142 – Insert R390-11 T3 10M-MH 1040 After milling.

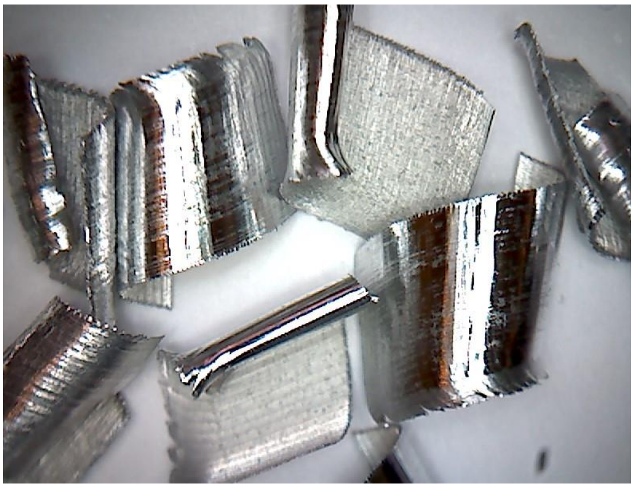


Figure 143 – Aluminium chips – 5mm Milling at 3000RPM using LN2 as coolant.

Figure 144 – Workpiece Aluminium AW6026-LF-T6 after test.

Figure 145 – Workpiece Aluminium AW6026-LF-T6 after test.

Where for the milled surfaces of the workpiece, the Surface roughness measurements are showed in Table 4.

Deep of cut (mm)	RPM	Surface Roughness Ra (µm)
1	500	2.123
5	500	0.571
5	1000	0.378
5	3000	0.609

Table 4 – Surface Roughness – Internal delivery system.

8. Data analysis.

Along with this technical report, the result of different tests and the literature in which these were based have been showed. The test conducted were classified in two main sections depending on what kind of delivery system for LN2 was used, and then, different sections were presented for each material/coolant combination used during the milling process. In this section all this data is analyzed to reach different conclusions that allow clarify the capabilities of the Liquid Nitrogen as a replacement for the conventional coolant used in industry for milling process.

8.1 First battery of test – External delivery system of LN2.

As we have mentioned before in previous sections, we are looking for validate the effect of the liquid nitrogen in the part stability (Dimensional and geometrical Tolerances, Surface Roughness) and in the productivity (Tool wear and chip shape inspection, noise, and power consumption). With this goal, first the effect on productivity is analyzed getting conclusions about the chip shapes and tool wear.

For the Aluminium test using LN2 as a coolant, the machining process could not be finished, unlike the machining carried out with Oil and Water, because the amount of LN2 delivered by the external system and the way it was carried out was such that part of the refrigerant , not only used to extract the heat generated during the cutting process, but also to cool the piece, where considering that the coefficient of expansion of Aluminium is greater than that of steel (Material of the jaws of the CNC machine), the piece suffered a greater contraction and went out the place during the milling process. This is strong evidence that for some materials, a better way to regulate and supply the LN2 must be implemented. The result can be seen in Figure 52.

After a comparation of the **chip shapes** resulting of the process for Aluminum where the LN2 and O/W were used, is possible to appreciate that the chips obtained of the O/W have a less warp curvature ratio in their structure not only for the finishing process but also to the scrub. At the same time the chips coming from the LN2 process have torn axes that in general result in less surface quality.

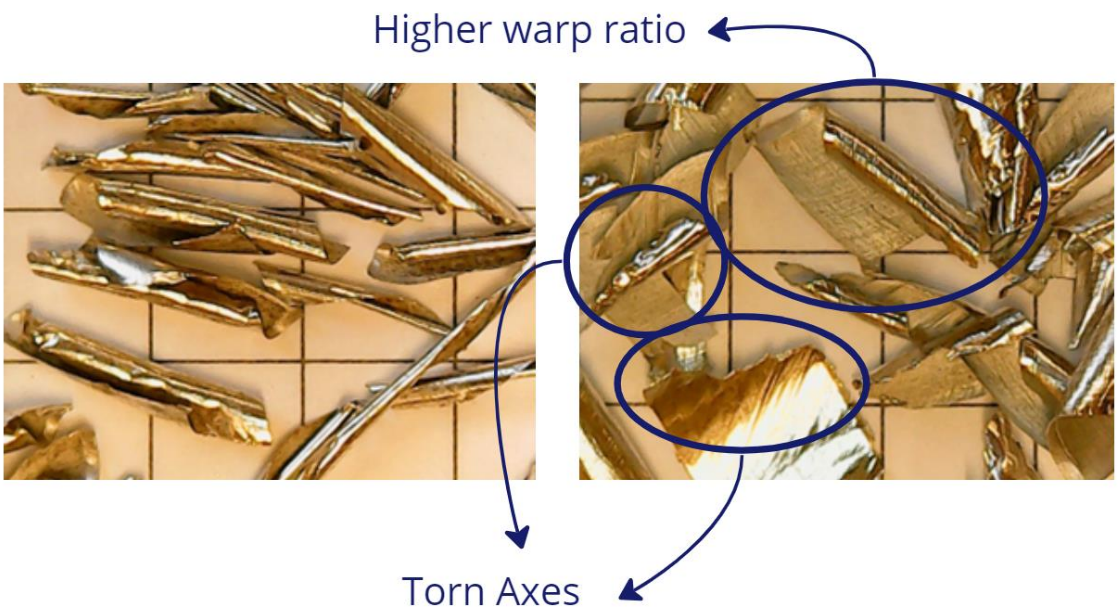


Figure 135: Aluminium chips comparation.

The **tool wear** was higher in the part milled with LN2, while in the O/W process the tool looks without appreciable damage, in the LN2 process is possible to identify wear represented by irregular cracks in the face of the tool.

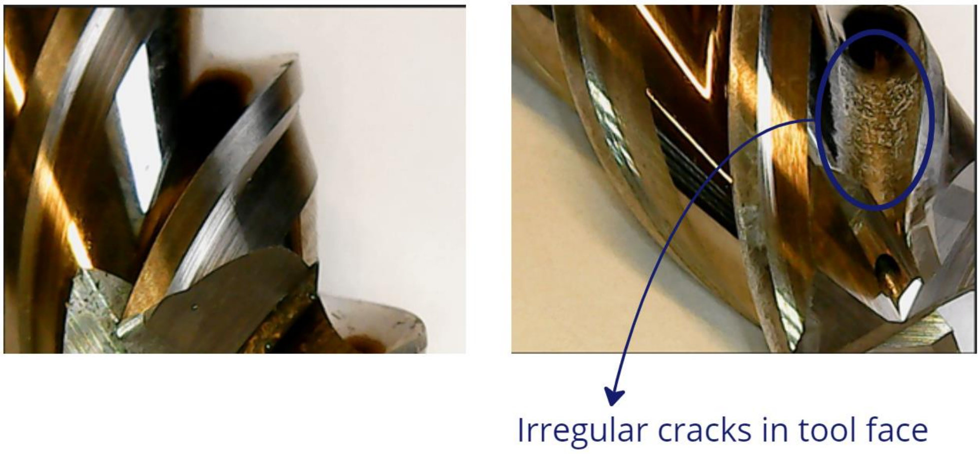


Figure 136: Aluminium chips comparation.

The analyses of the cast iron chip show that in the process where LN2 was used for drilling, smaller chips with smaller radius of curvature are obtained, presenting a neater and more regular cut than in drilling with O/W.

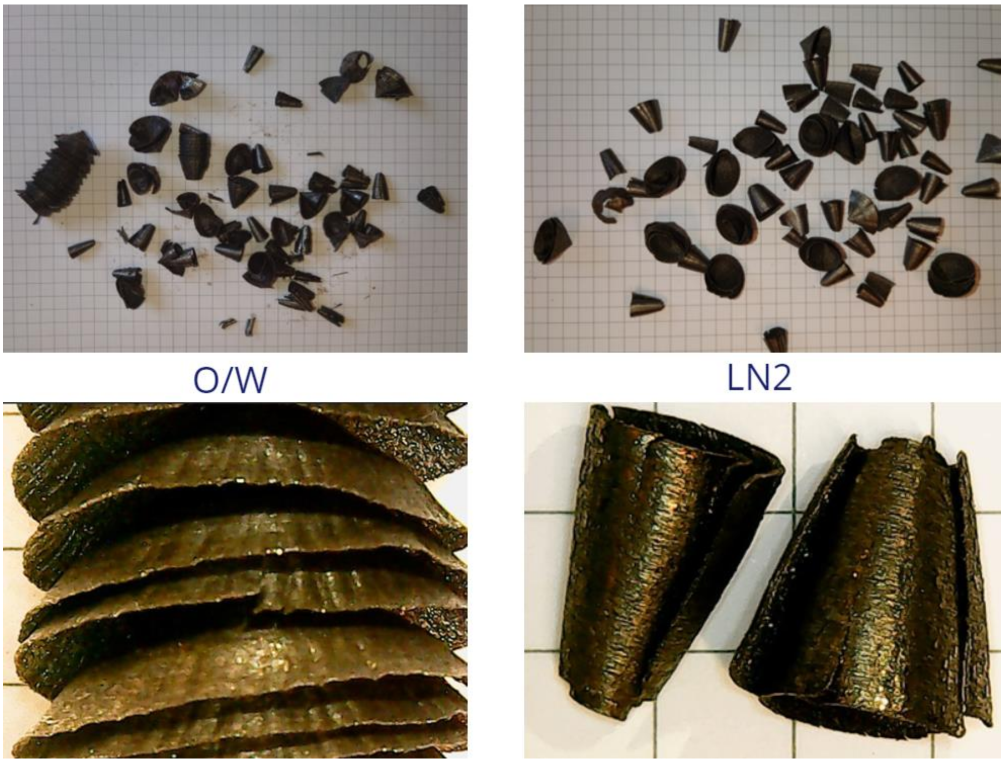


Figure 137: Cast Iron chips comparation.

With visual inspection it is possible to detect a slightly higher flank wear in the tool where O/W was used for scrub in the cast Iron part.

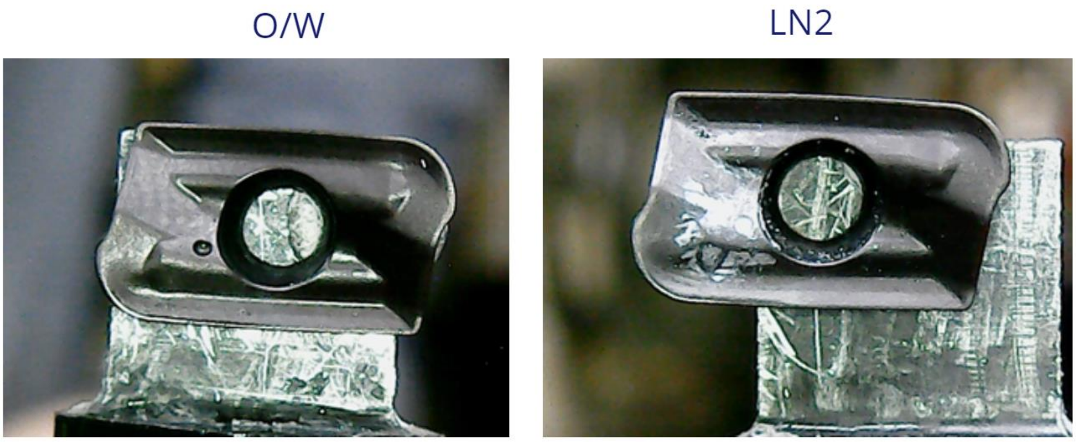


Figure 138: Cast Iron tool comparation.

Regarding the Super duplex chips, there is not a big difference noticeable to the naked eye, but in both the scrub and finishing processes, a lower warpage curvature ratio can be observed on the chip axes in the O/W process. For drilling, the difference is notable, the radius of curvature is still smaller in the O/W process, but the length of the chips is similar at a general level.

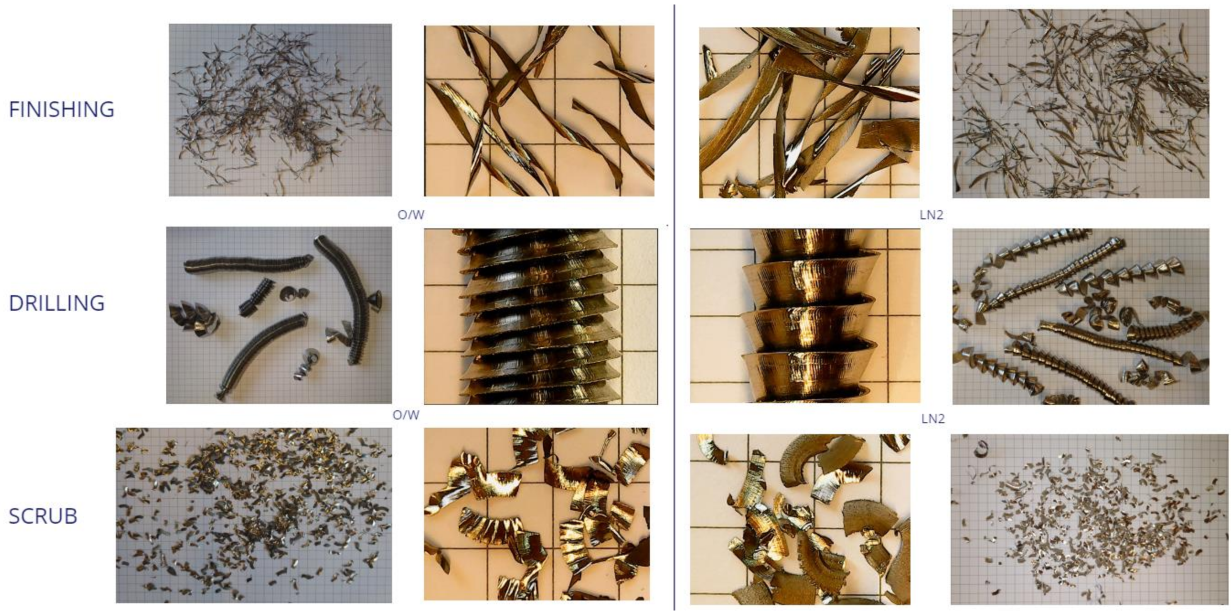


Figure 139: Super Duplex chips comparation.

The wear was higher in the tools used to machine Super Duplex with LN2, where it is possible to observe flank wear, cracks and facture of the inserts as can be observed in the flanks of the tools used for drilling.

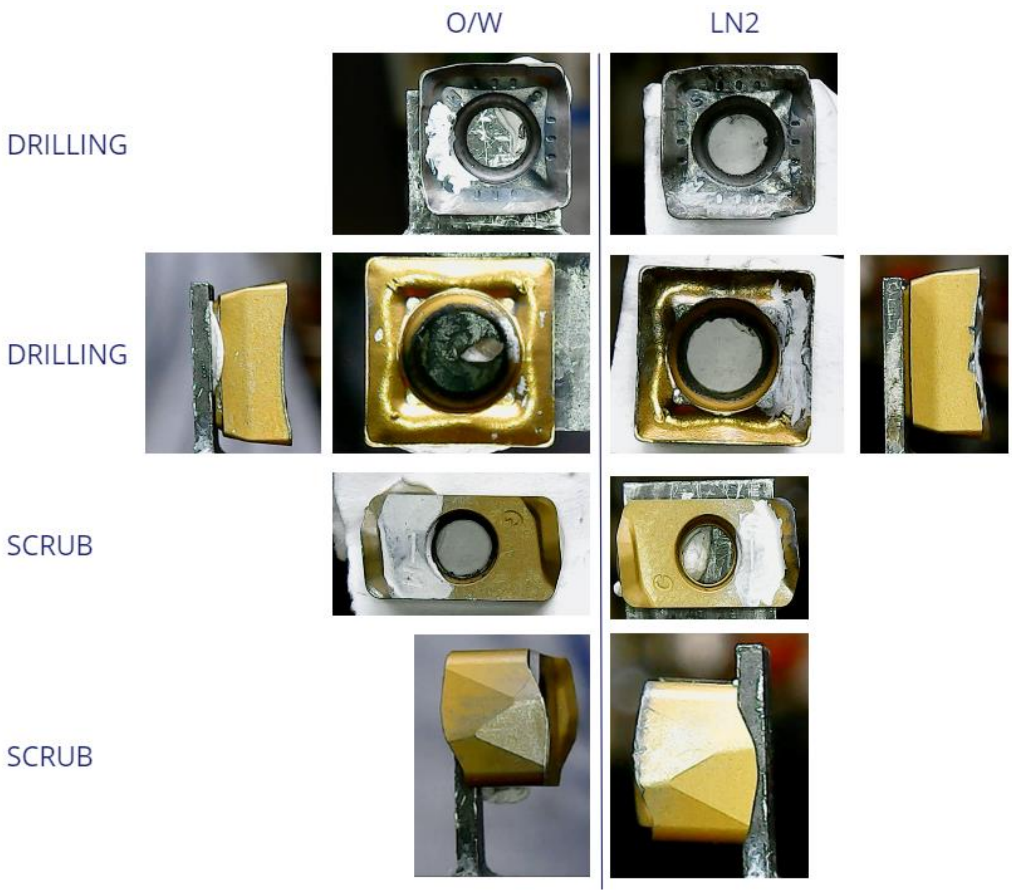
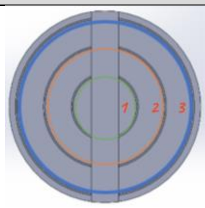
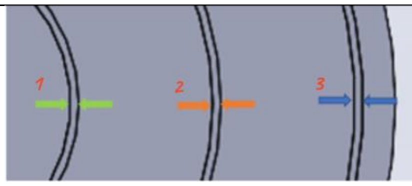
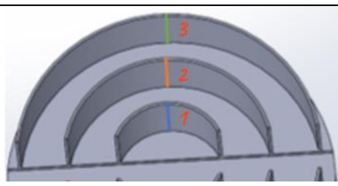


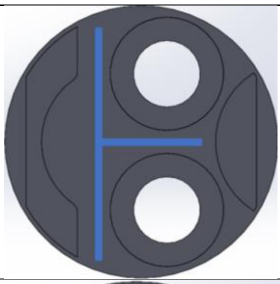
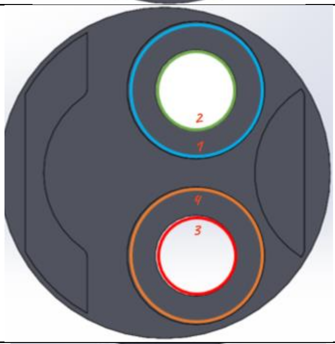
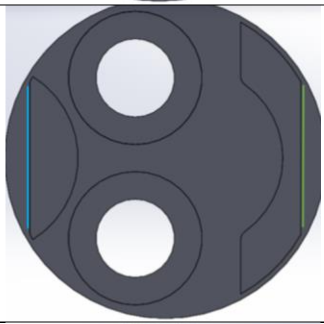
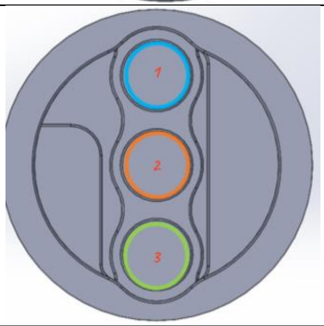
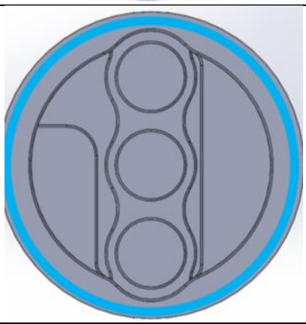
Figure 140: Super Duplex tools comparation

In our analysis of **power consumption**, a noticeable reduction of 15% to 30% is evident when employing LN2 as a coolant. This decrease aligns with expectations, especially when considering that during our experiments with the external LN2 delivery system, the hydraulic coolant system of the machine, which usually pumps conventional coolant, was deactivated. This resulted in a significant reduction in energy usage during the process. To better quantify the proportion of energy savings attributable to the hydraulic system deactivation and the more efficient chip breaking facilitated by the lower temperature, a dedicated test was conducted. This test involved toggling the hydraulic system on and off during a standard milling process, with precise measurements taken to discern the differences in energy consumption.

During the evaluation of **noise levels**, a consistent observation emerges, indicating higher noise levels during all tests where LN2 was employed as the primary coolant. This effect has been previously documented in the existing literature. It can be attributed to the absence of a lubricating component in the cutting zone when LN2 is used, as opposed to the presence of lubrication when an Oil/Water mixture serves as the coolant. The absence of a lubricant in the LN2 coolant leads to increased friction, resulting in the generation of heat and consequently, higher levels of noise. This phenomenon aligns with findings from prior research and underscores the importance of considering the role of lubrication in the machining process, not only in terms of friction reduction but also in mitigating noise emissions.

In another substage, the analysis of the **geometrical and dimensional tolerances**, and **Roughness surface** is analyzed from the Table 4.

Material	**G&D tolerances**			**Obs.**
	Parameter	**LN2**	**O/W**	
Aluminium	**Diameter 1**	108,1404 (xxxx)	109,8553	
	Diameter 2	73,182 (xxxx)	74,8616	
	Diameter 3	38,0276 (xxxx)	39,8705	
	Wall Thickness 1	3,11 (xxxx)	1,1184	
	Wall Thickness 2	2,9898 (xxxx)	1,1061	
	Wall Thickness 3	3,0953 (xxxx)	1,1443	
	Straightness 1	0,0106 (xxxx)	0,0192	
	Straightness 2	0,0201 (xxxx)	0,0082	
	Straightness 3	0,0190 (xxxx)	0,0088	
Cast Iron	**Pocket Diameter 1**	(XXXX)	66,4667	
	Pocket Diameter 2	39,4938	3 9,4853	

	Flatness	0,0245 (xxxx)	0,0455	
	Concentricity 1/2	(xxxx)	0,0907	
	Concentricity 3/4	(xxxx)	0,1273	
	Parallelism	0,0197	0,0157	
	Perpendicular distance	135,0897 (xxxx)	134,9725	
Super Duplex	**Pocket Diameter 1**	28,0171	27,9180	
	Pocket Diameter 2	28,0094	27,9323	
	Pocket Diameter 3	27,9765	27,9201	
	Flatness	0,0165	0,0013	
	Straightness 1	0,0048	0,0005	
	Straightness 2	0,0004	0,0002	
	Parallelism	0,0112	0,0046	

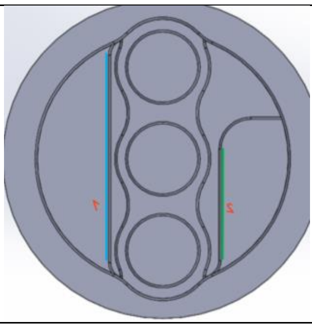
	Perpendicular distance	40,6504	50,5223	

Table 4 - G&D Tolerances measured – (xxxx) indicates process not finished.

The measurements for the Aluminium parts are not 100% comparable because, as we mentioned before, the aluminium workpiece milled with LN2 as a coolant went out of the clamp due to the thermal contraction (The values in the table where (xxxx) are indicated means that the process couldn´t be finished). However, the results are showed in the table to have an idea of the values reached in a roughing operation using LN2. To compare the values, the part milled with LN2 should have the finished operation in walls as the part milled with Oil and water.

For Cast Iron, the external holes that are observed in the figures of the Table 4 and the 100% of the roughing operation of the bottom couldn´t be finished. For the Drill operation, related with the dimension Pocket Diameter 2, we can see that the diameter in the LN2 milled part is bigger by only eight thousandths of a millimeters, which different could be easily adjudicated to the thermal contraction during the milling due to the different of temperatures. Regarding the Flatness in the bottom, if well we can not compare the values because the part milled with LN2 wasn´t finished during the milling, is possible to appreciate than the part milled with LN2 have higher flatness by two hundredths of a millimeters.

In the machining process of Super Duplex, the diameter of the pockets is higher in one tenth of millimeters, different that again is associated with the thermal contraction. Regarding Flatness Straightness and parallelism, the results show to be more accurate in the part milled with Oil and Water.

In summary, we examined the impact of utilizing an external LN2 delivery system as a coolant in milling processes on productivity and part stability. While we did obtain interesting results related to productivity factors such as noise, power consumption, chip analysis, and tool wear, we also encountered problems stemming from the delivery system's geometry and configuration. For instance, the design of the delivery system required positioning the LN2 nozzle at a considerable distance from the cutting zone during certain operations, causing the liquid nitrogen to turn into gas before reaching the workpiece. This hindered our ability to control the area where LN2 affected the part, along with difficulties in managing the LN2 flow. Consequently, for materials like aluminium with a high coefficient of contraction, significant dimensional changes occurred during the process, leading to parts coming loose from the clamps and disrupting the milling process. Considering these challenges, we are now considering a next stage with an internal delivery system to address these issues and potentially improve the overall milling process.

8.2 Second battery of test – Internal delivery system of LN2.

In this new section, we shift our focus to the evaluation of an internal delivery system for coolant during milling processes. As previously discussed, the decision to transition to this system was prompted by the challenges encountered with the external delivery method. The internal system, facilitated by a newly acquired commercial tool holder, is specifically designed to deliver coolant through the internal passages of the tools. This transition aims to enhance the precise application of liquid nitrogen (LN2) coolant to the work area for all machining operations and to allow for controlled and reduced LN2 delivery. Our objective in this section is to provide an in-depth analysis of the results obtained from our experiments with the internal delivery system. We will assess its effectiveness in overcoming the limitations experienced with the external delivery system, such as challenges in controlling coolant presence, achieving optimal cooling, and ensuring part stability, especially when working with materials prone to dimensional changes. The shift to an internal delivery system represents a significant step in our ongoing efforts to refine the milling process, and the results from these experiments will provide valuable insights into its potential benefits and limitations for future steps of our research.

In conclusion, our project involved testing two delivery systems, external and internal delivery system for liquid nitrogen (LN2) in machining processes. The internal delivery system yielded superior results in terms of both LN2 delivery volume and accuracy in reaching the cutting area. This system demonstrated a more controlled exchange of temperature, allowing for efficient cooling without affecting the entire workpiece. Additionally, the internal delivery system exhibited a faster cooling rate and LN2 acquisition compared to the external delivery system.

In the internal delivery system, two different tools were evaluated, with the R390-016A16-11L tool proving successful, while the SGS 44641 did not. We attribute this difference in performance to the design of the coolant channels. The R390-016A16-11L tool has larger and singular channels, facilitating a higher flow mass of nitrogen. In contrast, the SGS 44641 has half the cross-section divided into two channels, resulting in lower flow mass, and hindering the evacuation of all LN2, thus impacting in the capability to cool down the whole system.

The success of the R390-016A16-11L tool can be attributed to its higher nitrogen flow, allowing for efficient cooling at low temperatures and refreshing continuously until it reaches LN2. In contrast, the SGS 44641 faced challenges due to its divided channels, preventing effective evacuation of LN2 and resulting in warming within the system. These findings reach the importance of channel design in optimizing LN2 delivery for machining applications.

8.3 Particle concentration test:

We were not able to make a particle concentration test as described in the application, as the first delivery system of the LN2 was not stable enough and did not work as expected and therefore we were not able to mill with a steady level, and it was only in the end of project with the internal delivery system, that we was able to mill very shortly what a good result, and as such this part was left out of the test.

9. Conclusion

Throughout this study, the existing literature has been studied in detail and different experiments have been carried out to evaluate the potential of nitrogen in its liquid phase to act as a potential candidate to replace conventional emulsion-based coolant/lubricant. in different operations during machining processes. During this research, different challenges associated with LN2 supply systems have arisen, which has led to the study of an internal liquid nitrogen supply system, through the tool, and an external system in which the refrigerant flow is supplies to the work surface without entering in the end mill.

Internal delivery system

The internal delivery system demonstrated superior performance in terms of LN2 delivery volume and accuracy, overcoming limitations associated with the external system. The R390-016A16-11L tool, which has bigger channels to conduct the coolant, outperformed the SGS 44641 tool. This emphasizes the critical role of channel design in optimizing LN2 delivery for machining applications.

Power consumption

In our productivity analysis, LN2 exhibited reduced power consumption (15-30%) due to the deactivation of the hydraulic coolant system and more efficient chip breaking at lower temperatures for Cast Iron. However, higher noise levels were consistently observed during LN2 tests, attributed to increased friction in the absence of lubrication compared to conventional coolants.

Process and part stability

The impact on part stability was evident in the Aluminum test with the external delivery system, where inadequate LN2 regulation led to dimensional changes causing part displacement from the clamp due to the high thermal contraction coefficient of this material. Chip analysis revealed differences in chip curvature and tool wear, with LN2 processes showing higher wear and less favorable chip shapes.

For super Duplex, it was possible to see greater wear on the tools, probably due to the absence of lubricant, but with the conservation of the chip size regardless of its radius.

In general, this essay has allowed us to determine not only the potential of LN2 to be used as a coolant in different applications but also the importance of a meticulous design when selecting the LN2 supply system in the work zone. This is a fundamental aspect to consider for its applicability in the industry.

For the case of the external supply system, where the mass flow of LN2, as well as the phase in which it is found during contact with the work surface, cannot be strictly controlled, a slight loss of dimensional stability can be appreciated. This is due to the contraction of materials produced by the supply of liquid nitrogen higher than necessary, which results in the contraction of materials during the machining process. When stabilizing and returning to room temperature, the obtained dimensions are slightly different from the desired ones, increasing the deviations of the resulting pieces.

Although the geometric and dimensional analysis was performed only for the external liquid nitrogen supply system, a much more stable process can be appreciated during the internal supply of liquid nitrogen through the tool. In this case, the temperature of the workpiece is maintained in a range closer to room temperature, and, on the other hand, the cooling of the system during the start of the process occurs much more efficiently.

Future work

Hence, for future work, it is crucial to emphasize the development of a suitable LN2 supply system that allows supplying of the LN2 directly in the cutting zone, which is essential to get an optimized chip braking and optimal surface roughness .A flow of LN2 close to the theoretical flow to get the correct temperature in the chip braking area is necessary to remove only the amount of heat generated by the machining process and through that get optimal process stability and longer tool life, and a better working environment.

10. Dissemination

- Spånligaen at DAMRC 2022
- VTM (Værktøjs- og Maskinmessen) 2023
- SOME Post on Linkin
- Roll up at DAMRC
- Presentations to visitors and seminars at DAMRC

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