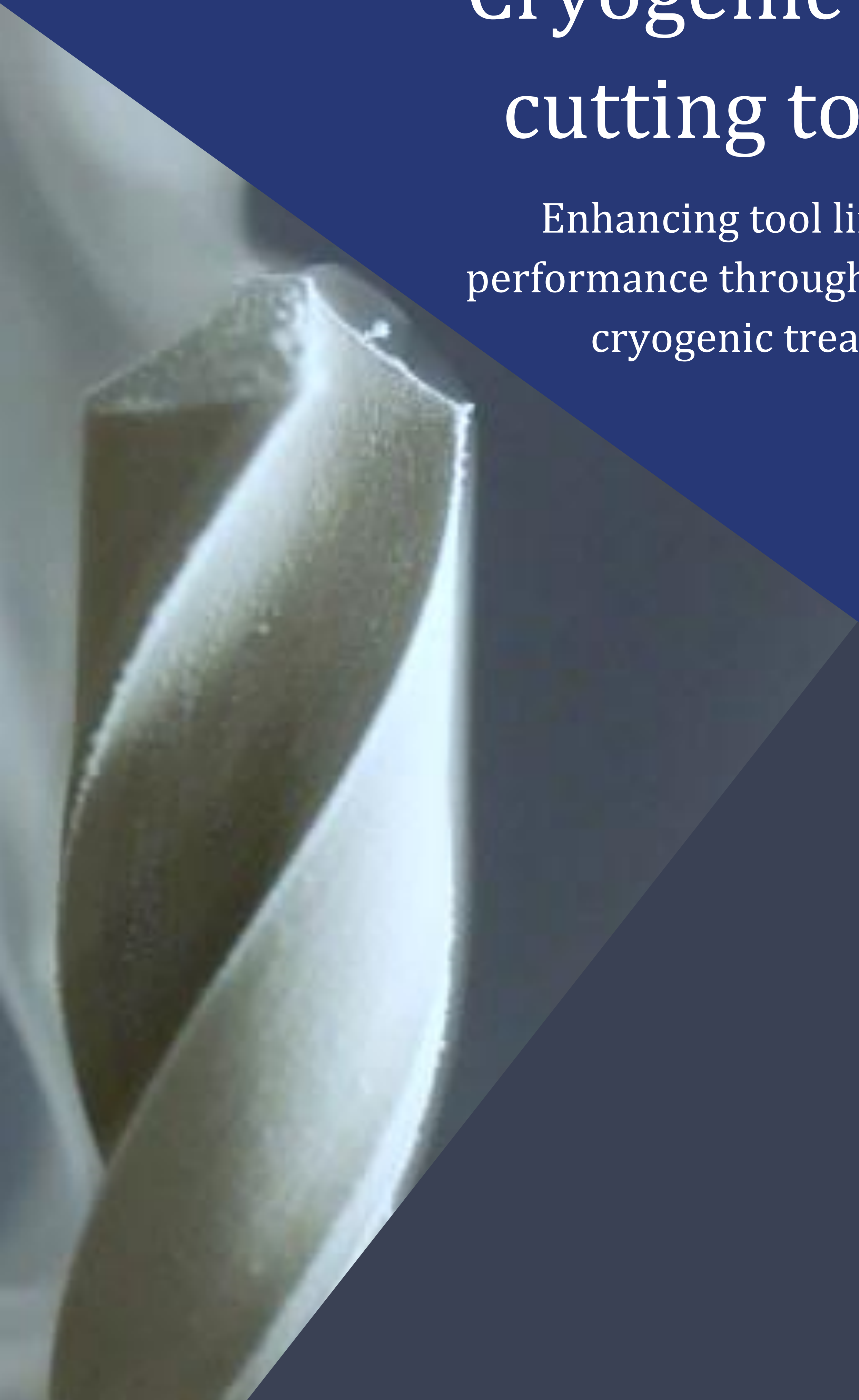


# Cryogenic for cutting tools

## Enhancing tool life and performance through deep cryogenic treatment

# Index

## This project is made in collaboration with

**Funding:**

INDUSTRIENS FOND

**Industry partners:**

STRANDMØLLEN

# 1 Executive Summary

This project applies deep cryogenic treatment (DCT) to cutting tools supplied by project partners and measures the resulting tool life under realistic industrial conditions. To verify the effect, a treated tool was tested against a non-treated tool under comparable machining parameters. Results indicate a later failure for the treated tool, achieving approximately a 17% increase in machining time before breakage. Despite operational challenges during treatment and testing, the study demonstrates the potential of DCT to extend tool life in demanding operations.

# 2 Introduction

The microstructure and mechanical properties of cutting tools significantly affect their tool wear. Several studies indicate that these two parameters can be adjusted by cooling the tools to cryogenic temperatures. One method to achieve this is by gradually soaking the tools in cryogenic liquid. Liquid nitrogen is a particularly effective choice since it has very low chemical reactivity with metal parts and stays liquid between -210 [°C] and -196 [°C]. Additionally, nitrogen represents 78% of the atmosphere, which means that the final disposal has a neutral effect on the environment.

The cryogenic process has been applied to several metals and ceramics, including ferrous, magnesium, and nickel-based alloys. In the case of HSS, the cryogenic process serves as an extension of the traditional quenching process. As shown in Figure 1, the quenching process normally consists of abruptly cooling down the temperature from 1050[°C] to 25[°C]; during this stage, the austenite (FCC) converts into martensite (BCT). While a huge amount of austenite transforms, a certain amount is always left over as austenite. It is worth noticing that commercial tools are normally provided with a tempering process after the quenching to homogenize the microstructure.

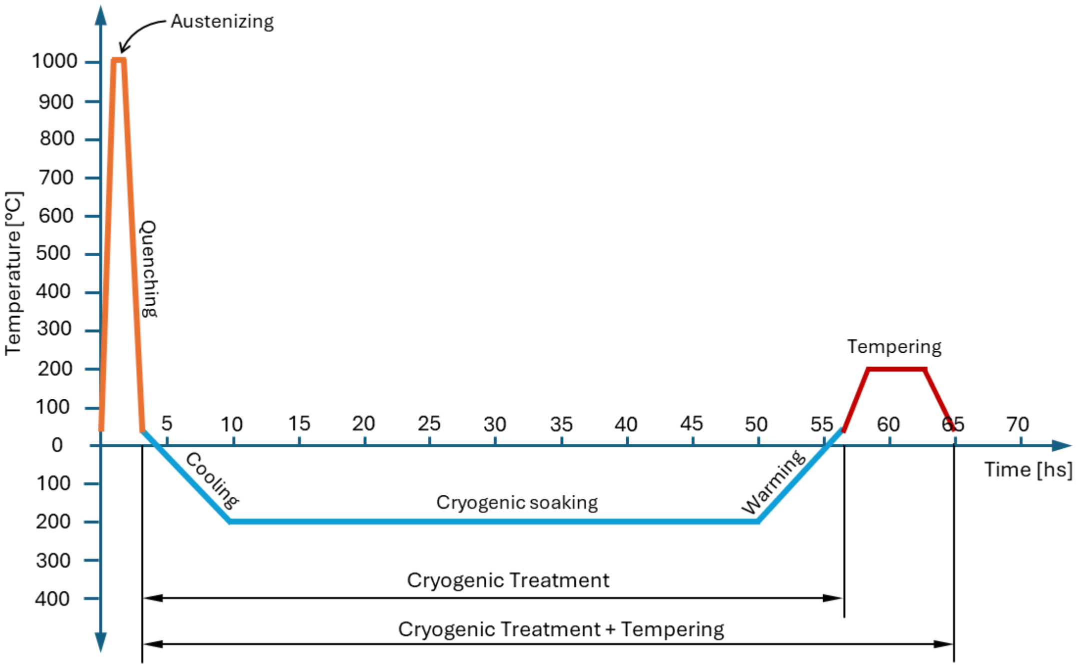


Figure 1 - Extended heat treatment

A modern solution to continue transforming the retained austenite is the cryogenic process. To avoid cracks on the metal structure, the process must take new parameters. The rapid cooling, which characterizes the quenching, transitions to mild cooling. After reaching the minimum cryogenic temperature, the process temperature shall be kept steady; this stage is called "cryogenic soaking". This stage heavily influences the final process results, in our case, the tool performance.

The following step consists of raising the temperature to room temperature. This must be done slowly to avoid thermal shocks. A tempering process, which can consist of more than one cycle, is performed to reduce brittleness and increase toughness.

# 3 Pre-analysis

Cutting tools are used in any machining process for metals. There are three costs when machining:

1. The machine
2. The labour
3. The tools

If you prolong the tools' service life, you cut down directly on the total costs. The potential benefit will be for the tool manufacturer to gain insight into the potential improvement of the tools by cryogenic treatment, thus, prolonging tool life.

## 4 Hypothesis

Cryogenic treatment of high-speed steel drills will enhance their performance when machining austenitic stainless steel (AISI 316L). It is hypothesised that the deep cryogenic process, applied after conventional heat treatment and followed by appropriate tempering, will transform retained austenite into martensite and promote the formation of ultrafine carbides within the HSS substrate. These microstructural changes are expected to improve wear resistance, reduce flank wear, and extend tool life without negatively affecting the coating of a drill. When tested under identical cutting conditions, cryogenically treated like e.g. drills are anticipated to exhibit lower cutting forces, improved dimensional stability, and better surface finish compared to untreated counterparts. Therefore, the cryogenic treatment is expected to provide measurable performance benefits in drilling operations involving difficult-to-machine materials like 316L stainless steel.

## 5 Success Criteria

Cryogenically treat the cutting tools by cooling them to a temperature between -145 [°C] and -200 [°C] and warming them back up, maintaining a temperature change rate not exceeding 3 [°C/min]. Success is achieved if the cryogenically treated tools demonstrate at least a 10% increase in service life compared to non-treated tools in standardized cutting tests.

## 6 Project Scope/Description

The project will attempt to cryogenically treat cutting tools to prolong the tool's service life. Cryogenic cooling has been found to both remove residual stress and increase the wear resistance of cutting tools and materials used for creating tools. S. Kumar et al. mention that in some cases, it can be up to 92% longer service life compared to no treatment.

# 7 Risk Analysis

The project must handle different challenges. It was decided to use the liquid nitrogen provision in several projects. Thus, making a resource “multipurpose” can have an impact, as for different projects, the liquid nitrogen will be used in different quantities, following different schedules and processes.

Another risk is that the infrastructure used was not intended for the particular purpose we aim for. The freezer controller, for example, cannot operate following a certain freezing curve. In an experiment, as part of a project previously carried out at DAMRC, an in-house controller was developed using an Arduino platform. There are some doubts about how this controller can handle long soaking times (around 40hs).

As many reports state, a successful cryogenic process consists not only of a freezing stage but an immediate tempering process. The acquisition of an oven capable of such a heat treatment becomes of paramount importance to the project.

# 8 Literature Study

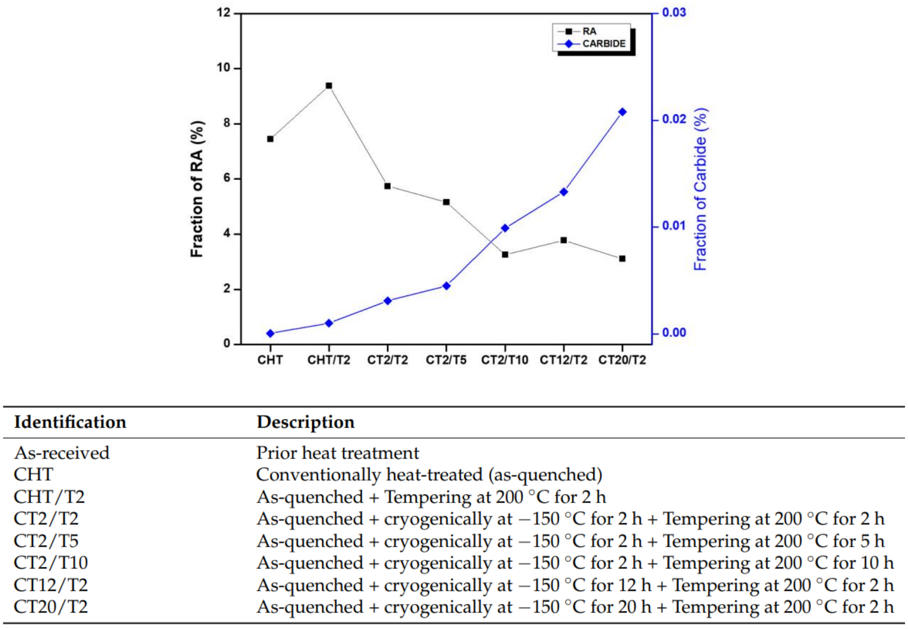
Since deep cryogenic treatment as a material processing technology was introduced, relatively few researchers have been performing comprehensive investigations on it. The first scientific article about cryogenic treatment on metals to improve wear resistance was from Barron [1]. It was found that the treatment applied to tool steels could improve tool wear characteristics significantly. The process was defined as a complementary process to conventional heat treatments, normally right after quenching and tempering.

Cryogenic treatment of High-Speed Steel (HSS) has evolved significantly since its early experimental applications in the mid-20th century. Initially, the process involved direct immersion in liquid nitrogen without temperature control, often leading to cracking and inconsistent results. With the development of programmable cooling systems in the 1980s and 1990s, researchers began to understand the metallurgical mechanisms at play. Most notably, the transformation of retained austenite into martensite and the precipitation of ultrafine carbides during post-treatment tempering. Therefore, modern studies have a strong focus on controlling all parameters in the cryogenic treatment (rate of cooling, soaking period and temperature, tempering process).

Having control over the process in detail led to numerous studies about how the temperature ramp affects the outcomes. Sıtkı Akincioğlu et al. [2] provided an interesting review on the progress of cryogenic treatments. They reported an investigation into the effect of cooling speed during cryogenic treatment on carbide cutting tools by applying different heating and cooling rates. The treatments were completed in eight hours with a cooling rate of 0.5 [°C/min] and in four hours with 1 [°C/min]. The study showed that tools cooled at 0.5 [°C/min] had better wear resistance. However, a faster cooling rate of 1 [°C/min] resulted in a more uniform distribution of carbides within the microstructure.

The soaking time is crucial for achieving optimal results. Kamran Amini et al. investigated how soaking time affects the microstructure of tool steel [3], finding a strong relationship between this parameter and the distribution of carbide precipitation. This led to improved particle uniformity and increased microhardness.

For HSS such as AISI M2, studies have shown that deep cryogenic treatment (DCT) can reduce retained austenite from approximately 25% to nearly 0%, while increasing wear resistance and hardness due to the formation of uniformly distributed η-carbides. Muhammad R. et al. researched the phenomenon, in Figure 2, it is possible to observe how the RA (retained austenite) values decrease while the carbide precipitation increases [4], for different heat and cryogenic treatments.



| Identification | Description |
|---|---|
| As-received | Prior heat treatment |
| CHT | Conventionally heat-treated (as-quenched) |
| CHT/T2 | As-quenched + Tempering at 200 °C for 2 h |
| CT2/T2 | As-quenched + cryogenically at −150 °C for 2 h + Tempering at 200 °C for 2 h |
| CT2/T5 | As-quenched + cryogenically at −150 °C for 2 h + Tempering at 200 °C for 5 h |
| CT2/T10 | As-quenched + cryogenically at −150 °C for 2 h + Tempering at 200 °C for 10 h |
| CT12/T2 | As-quenched + cryogenically at −150 °C for 12 h + Tempering at 200 °C for 2 h |
| CT20/T2 | As-quenched + cryogenically at −150 °C for 20 h + Tempering at 200 °C for 2 h |

Figure 2 - Fraction of RA (retained austenite)

Today, DCT is recognized not as a replacement but as an enhancement to conventional heat treatment, with standardized cycles that include controlled cooling rates, soaking at −196 [°C], and multiple tempering steps.

Our study will be centered on HSS-coated drill bits. One of the most concerning aspects of this specific case is how the cryogenic process affects the coating. Christian I. Chiadikobi et al. studied the effects of DCT on PVD-TiN coating [5]. They concluded the treatment is not detrimental to the system (PVD-TiN coatings on AISI M2 HSS).

# 9 Experiment Design

## 9.1 Introduction

The experimentation phase is the core of this project. In this section, a thorough plan was developed to maximise the chances of getting the expected results.

## 9.2 Test design/process

While the focus of this study is on the cryogenic process, several supplementary experiments were organized to capture and evaluate the results of this treatment. Thus, the complete test process consisted of 4 main blocks.

- **Cryogenic treatment**: Cutting tools were cooled to a target cryogenic temperature and warmed up to room temperature using a controlled cryogenic chamber.
- **Tempering heat treatment**: Following cryogenic processing, the tools underwent a post-treatment heating stage to stabilize the microstructure.
- **Drilling test**: Treated and non-treated tools were tested under identical machining conditions using a standardized drilling setup. Parameters such as cutting speed, feed rate, and total depth of cut were kept constant to ensure comparability.
- **Inspection**: After the drilling tests, tools were analysed for wear using optical microscopy. Tool life was quantified based on flank wear and predefined wear criteria.

## 9.3 Equipment for the test

The cryogenic experiment stages were already defined, and each cycle needs specific equipment.

- LN2 tank – Strandmøllen 1,5 bar – 176L
- Cryogenic container – Worthington 10K – CS100
- Temperature controller – N1050-PR
- Heat treatment oven - Tooltos

The complete cryogenic treatment system definition is shown in Figure 3. The main components are the freezer, the LN2 tank, and the extraction mesh basket. The hoses played a major role, which we will develop further in the report.

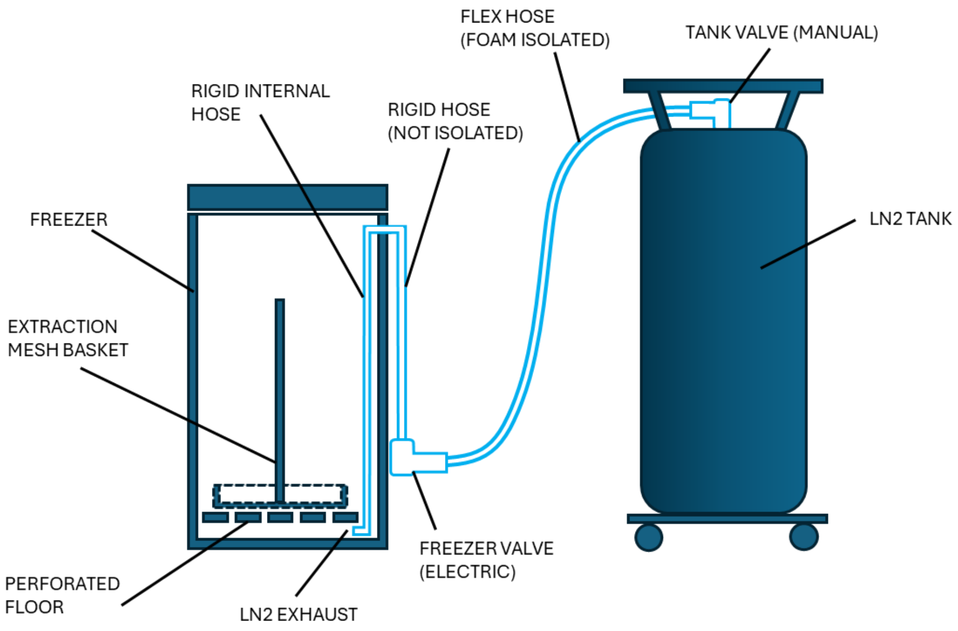


Figure 3 - Cryogenic equipment configuration

A CNC machine is needed to perform the machining tests. Once the tests are completed, we need to retrieve the output parameters. In our case, it will be roughness, tool wear, and tool breakage.

- CNC machine – DMU 80 T
- Rough material – Stainless Steel 316L
- Toolholder (Chuck)
- BRESSER USB digital Microscope DST-1028

## 9.4 Tool selection

Commercial HSS twist drills conforming to DIN 338 and coated with titanium nitride (TiN) were selected for this study due to their widespread commercial use in general-purpose drilling applications. Specifically, the selected tool was a DIN 338, HSS, TiN Coating, Ø10 [mm]. These tools typically feature a standardized geometry and are manufactured from high-speed steel grades such as M2, which are known for their good balance between toughness, hardness, and cost. The presence of a TiN coating provides additional surface hardness and wear resistance, as well as reduced friction during cutting, making these drills suitable for machining challenging materials like stainless steel. Importantly, using commercially available tools allows for the assessment of cryogenic treatment benefits under realistic operating conditions without the need for custom tooling. This choice ensures the relevance of the findings to practical applications while enabling direct comparisons between treated and untreated tools in terms of wear behavior, tool life, and drilling performance.

Figure 4 - Selected drill bit, Ø10[mm]

## 9.5 Material for the test

AISI 316L stainless steel was selected as the workpiece material due to its well-known machinability challenges, which make it a suitable candidate for evaluating improvements in cutting tool performance. As an austenitic stainless steel with high toughness and strong work-hardening characteristics, 316L tends to generate elevated cutting forces, significant heat, and rapid tool wear during drilling operations. These properties create a demanding test environment that allows for a more sensitive assessment of wear resistance, edge retention, and thermal stability in treated and untreated tools. By using 316L, it becomes possible to clearly observe the potential benefits of cryogenic treatment on HSS drills, particularly in terms of flank wear reduction, improved tool life, and better surface finish, thus providing meaningful insight into the practical advantages of the treatment under realistic industrial conditions.

Material previously used in a DAMRC project was reused for this experiment. This approach is advantageous since the stock had already been machined, providing a suitable surface to start drilling. A further benefit is the absence of lead time, which simplifies logistics and accelerates the experimental phase. Finally, reusing available stock contributes to a more sustainable project execution by reducing both cost and material waste.

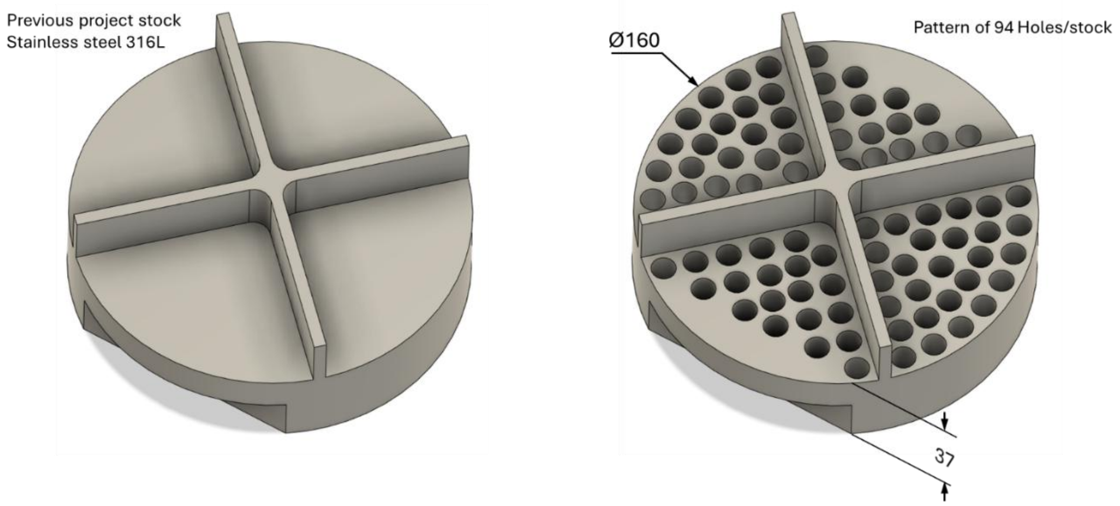


Figure 5 - Stock material geometry (left), stock material with planned drilling pattern (right).

## 9.6 Conduction of the test

The test was divided into two parts: one on the cryogenic process and analysis, and the other on the tool wear analysis and comparison.

### 9.6.1 Cryogenic and tempering process

For the experiment, a batch of untreated HSS tools was introduced into the freezer. After the cryogenic treatment, a tempering treatment is needed to homogenize the microstructure. The drilling tests are carried out using an untreated tool and a tool that comes from the tempering oven. The experiment flow diagram is shown in Figure 6.

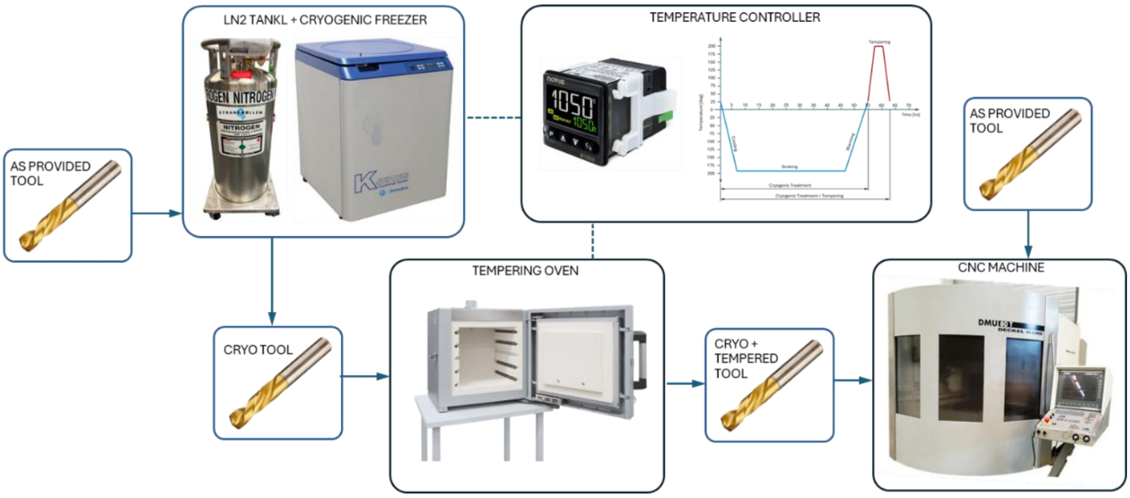


Figure 6 - Tool flow diagram - from cryogenic treatment to the CNC machine

***Cryogenic parameters***

The cryogenic cycle was defined using the parameters shown in Table 1. The mild temperature gradients (cooling and warming ramps) are specially set to avoid thermal shocks that could produce cracks in the tool coating, mainly between the carbide and cobalt binder.

| **Initial** | **Cooling ramp** | **Soaking** | **Warming ramp** |
|---|---|---|---|
| | $t_C$= 7,36 [hs] | $t_S$= 35 [hs] | $t_W$= 7,36 [hs] |
| $T_O$= 25 [°C] | $\Delta T_C$= -0,5 [°C /min] | $T_S$= -196 [°C] | $\Delta T_W$= 0,5 [°C /min] |

Table 1 - Cryogenic process parameters

***Tempering parameters***

The tempering parameters were defined in Table 2. In this step, the ramp had to be followed carefully as well to avoid cracks in the coating.

| **Initial** | **Warming ramp** | **Soaking** | **Cooling ramp** |
|---|---|---|---|
| | $t_C$= 1,1 [hs] | $t_S$= 2 [hs] | $t_W$= 1,1 [hs] |
| $T_O$= 25 [°C] | $\Delta T_C$= 2 [°C /min] | $T_S$= 200 [°C] | $\Delta T_W$= -2 [°C /min] |

Table 2 - Tempering parameters

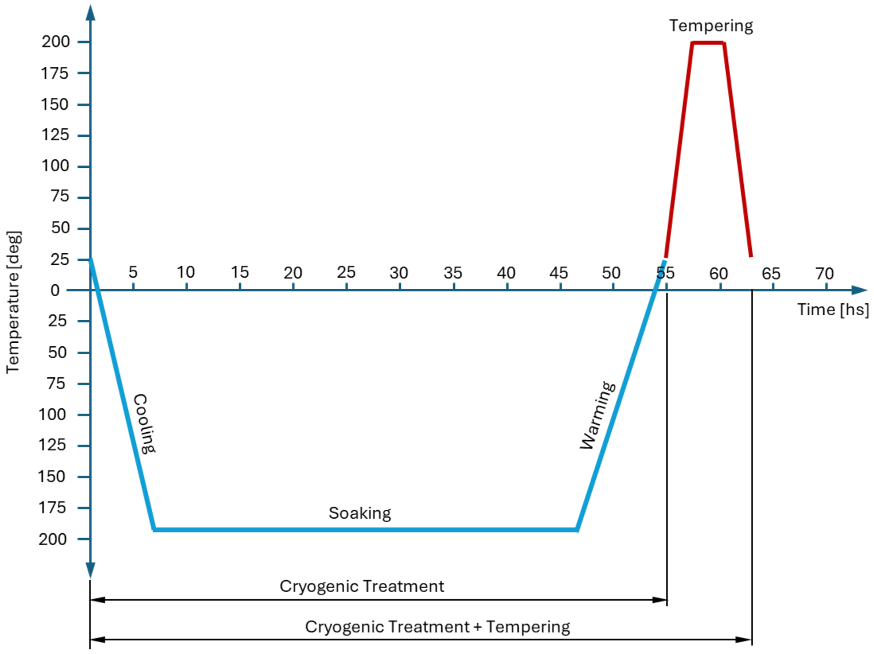


Figure 7 - Cryogenic and tempering process

The tools were identified marking the rear part with a simple code (see Figure 8), tracking the treatment they went through.

- One central mark: cryo-treated tool
- One side mark: tempered tool
- Two side marks: double tempered tool

Figure 8 – Tool treatments identification markings

### 9.6.2 Tool wear analysis and comparison

The goal of this stage was to determine how the tool wear progressed in both treated and untreated tools. After this, we established a comparison and extracted conclusions.

***Drilling and inspection process***

The test will consist of multiple drilling operations, measuring tool wear every six holes. The machining pecking depth of cut was defined as 5 [mm], while the total depth of cut was 35

[mm]. This value was selected to create demanding conditions to observe a substantive difference in tool wear on every step. The drilling process was further divided into quarters and carried out following a specific path shown in Figure 9 i → ii → iii → iv.

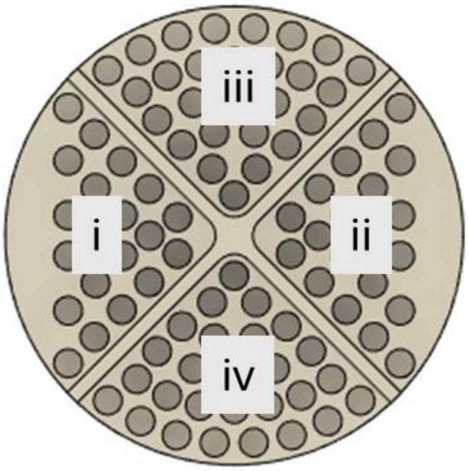


Figure 9 - Drilling process flow path

A tool condition monitoring (TCM) system was implemented inside the CNC machine to capture this deterioration. A proximity hatch opens every time the tool approaches a defined position and takes a picture of the tooltip condition. To enhance picture clarity, the microscope incorporates a built-in light and the CNC machine an air-line to clean the tooltip.

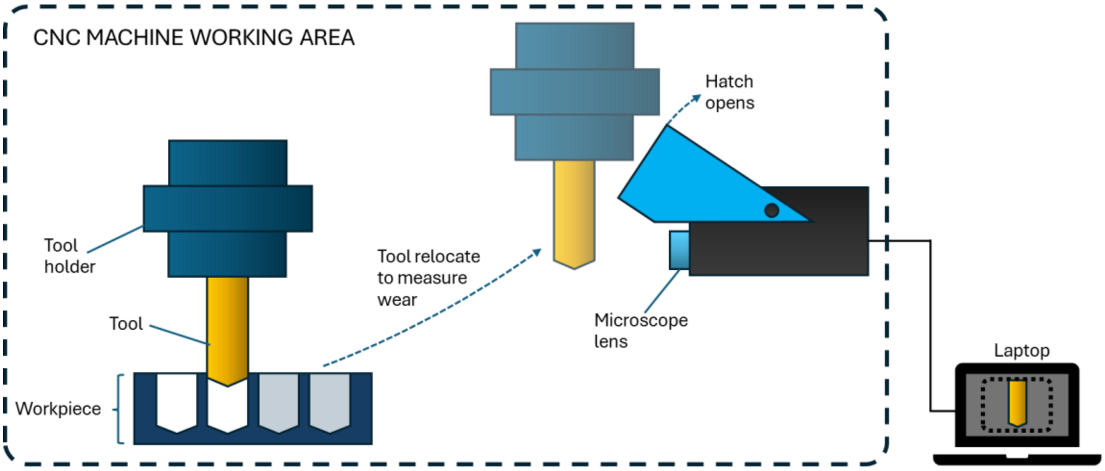


Figure 10 - Tool wear measurement procedure

Selected pictures were measured using the microscope software MGUSView. The wear plot (see Figure 11) was created using the VB (flank wear) values since it is the most suitable and practical parameter for monitoring tool wear in most machining applications.

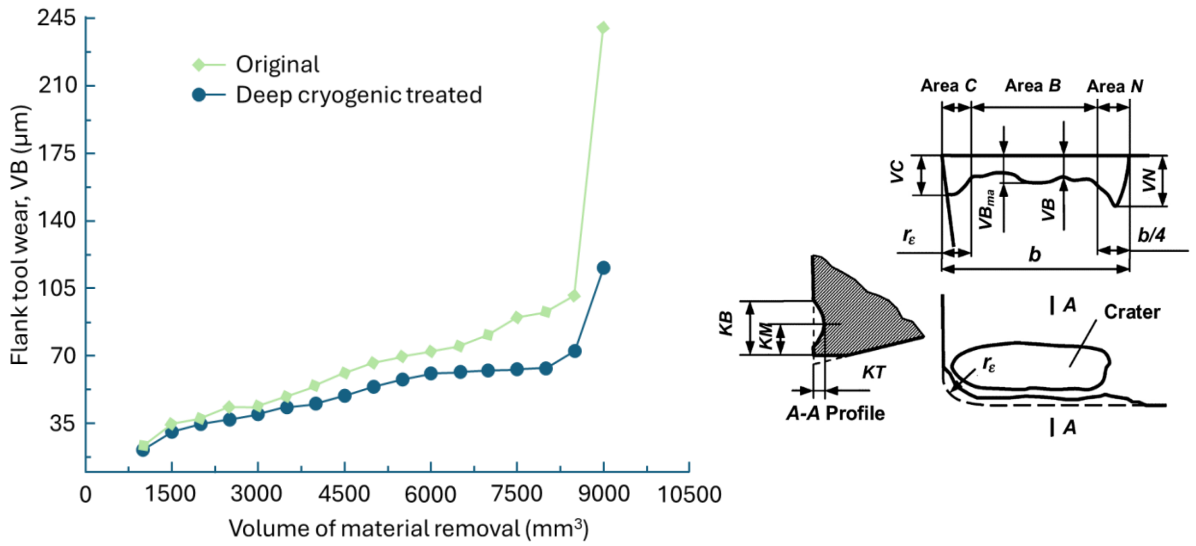


Figure 11 - Wear plot registration example

***Machining parameters***

The selected tool was acquired from a local hardware store. This implies that not much data was found regarding material properties and general performance.  A trial test was performed to tailor parameters. The idea was to achieve a tool breakage in a convenient number of holes, balancing step definition and experiment length.

The test parameters were set considering a generic drill performance. The cutting speed was established as Vc=10 [m/min], spindle speed SS=320[rpm], and feed per revolution fz=0,17 [mm]. As previously stated, parameters changed during the practical experiment stage.

# 10 Test Results

## 10.1 Cryogenic process results

For the test setup, an extraction mesh basket was assembled to carry the tools to the bottom of the freezer and to be able to extract them after the experiment. On the metal mesh, two temperature sensors were located at the same height, one of them (PT100) connected to the controller, and the other one (thermocouple type K), registering the same parameter over time (see Figure 12).

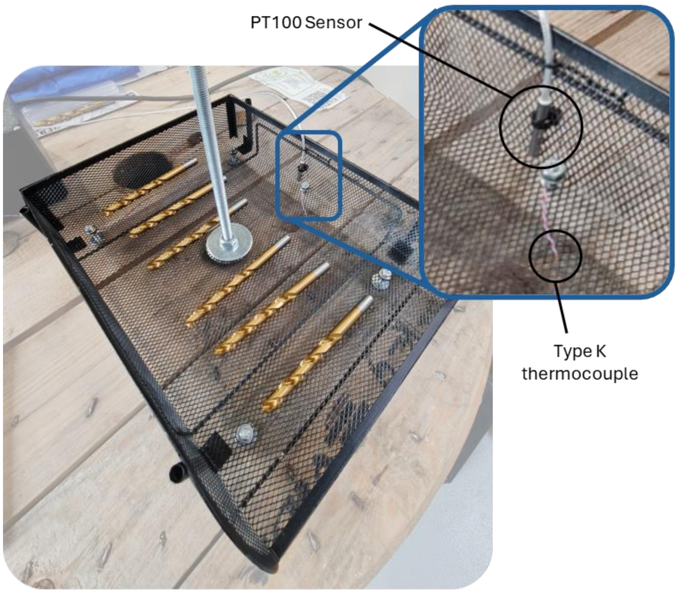


Figure 12 - Extraction mesh basket and temperature sensors

The cryogenic process was controlled by opening and closing the liquid nitrogen electric valve (on/off control). The process was followed within the controller's and system limitations. The original freezer is designed to keep a certain constant temperature for a period of time. By opening and closing the valve (ramp) at a certain frequency, the system's work dynamic is observed. We can summarize this local process in the following steps:

1. The valve opens: due to the initial pressure and temperature difference, the nitrogen comes out vaporized as a gas.
2. The nitrogen starts coming out as liquid, producing a consistent temperature drop.
3. The valve closes: due to the poor inlet isolation, the liquid retained in the hoses loses energy and vaporizes.
4. The valve opens: the vapour comes out, “warming” the inside freezer temperature.
5. The nitrogen starts coming out as liquid, producing a temperature drop.

The above description justifies the oscillating system response in the ramp section. Also, it gives us a perspective on the system limitation, concluding that the isolation in the inlet section is crucial to minimize nitrogen losses. As we can see in Figure 13, the controller follows the theoretical curve but fails to keep the temperature after 14,5 hours of soaking.

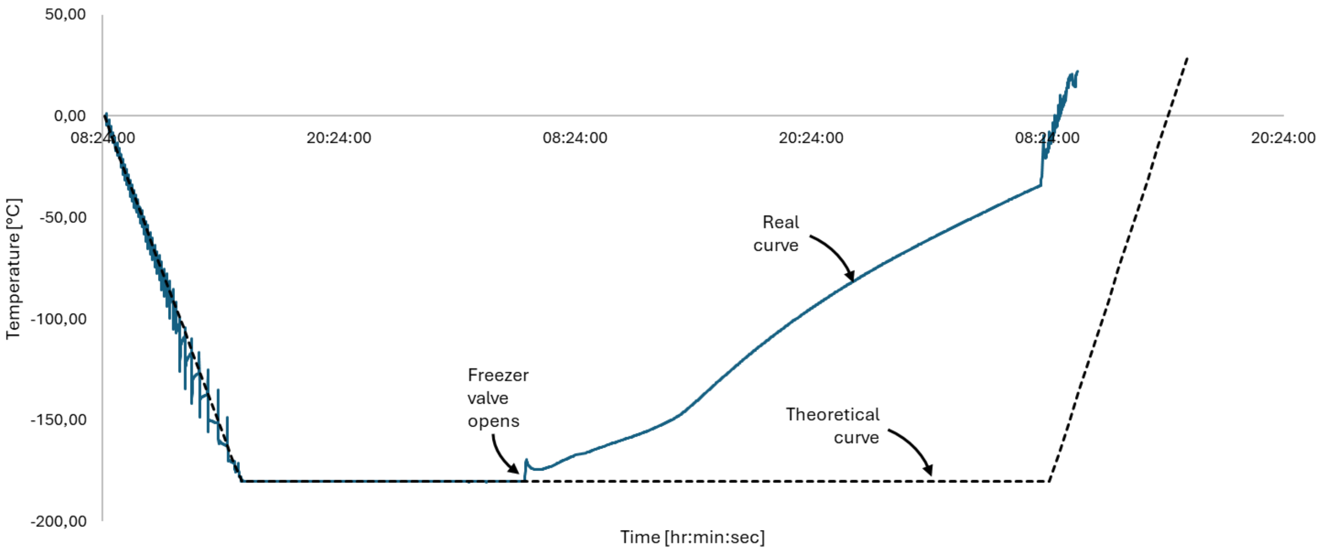


Figure 13 - Comparison between theoretical and real cryogenic process.

A considerable section between the tank and the freezer is not properly isolated (see figure 13). The graphic description of the phenomenon is shown in Figure 14. The rigid hose, located outside the freezer, and the flex hose connecting the tank are not properly isolated, leading to heat losses and vaporization.

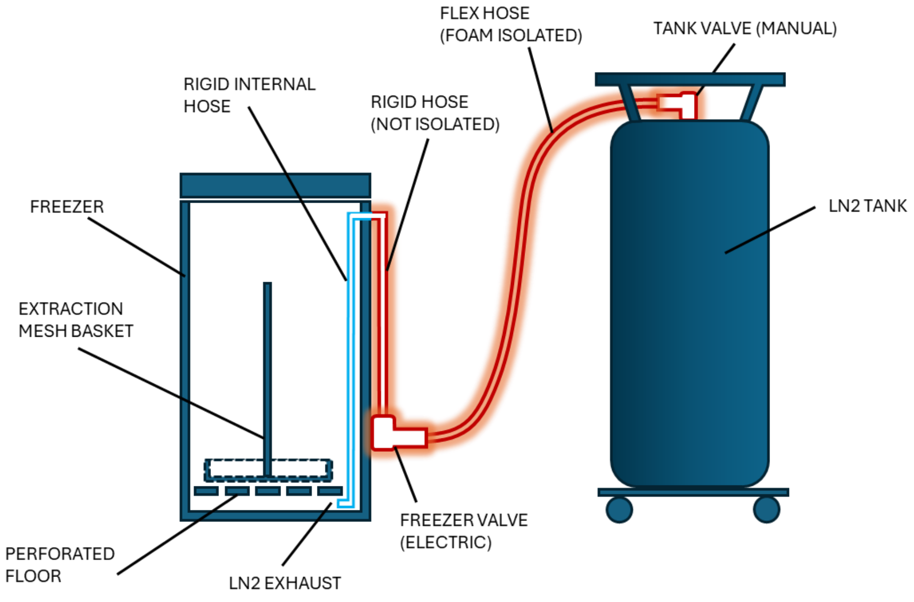


Figure 14 - System energy losses

The tempering process consists of increasing the part temperature progressively to 200 [°C]. This process could be repeated to achieve better results. In our case, two tempering treatments were performed.

Figure 15 - Heat treatment oven

During the first treatment, the oven was unable to follow a curve. The continued temperature overshooting required the user to intervene, turning the system “off” and “on” repeatedly. Finally, after an hour, it was decided to abort the process. The result is plotted in Figure 16.

Note: the difference between the maximum temperature (200[°C]) and the one expressed on these graphs (around 250 [°C]) is due to an error between the controller and the logger sensors.

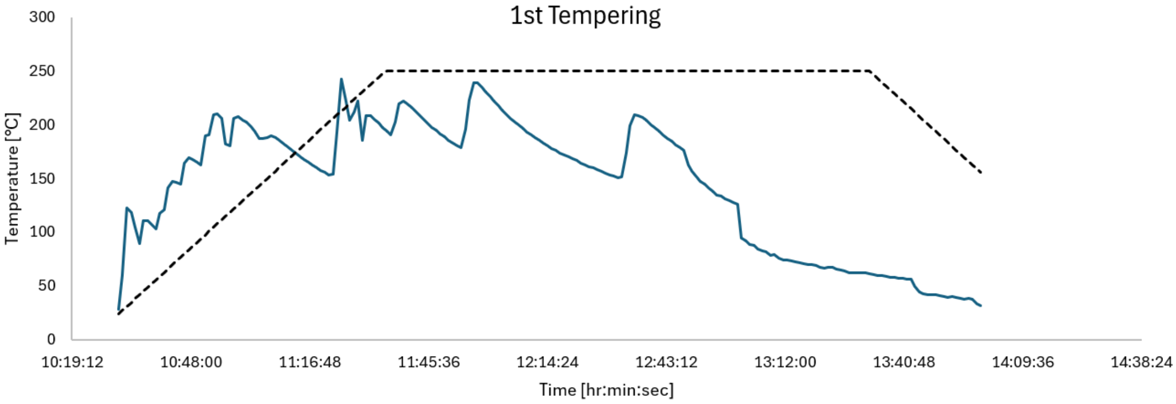


Figure 16 - First tempering control process

Before continuing with the second tempering, a troubleshooting was performed on the oven. It was decided to replace the controller and the thermocouple.

As we can see in Figure 1716, the new components considerably improved the oven's performance in the second tempering. No considerable temperature overshooting was observed.

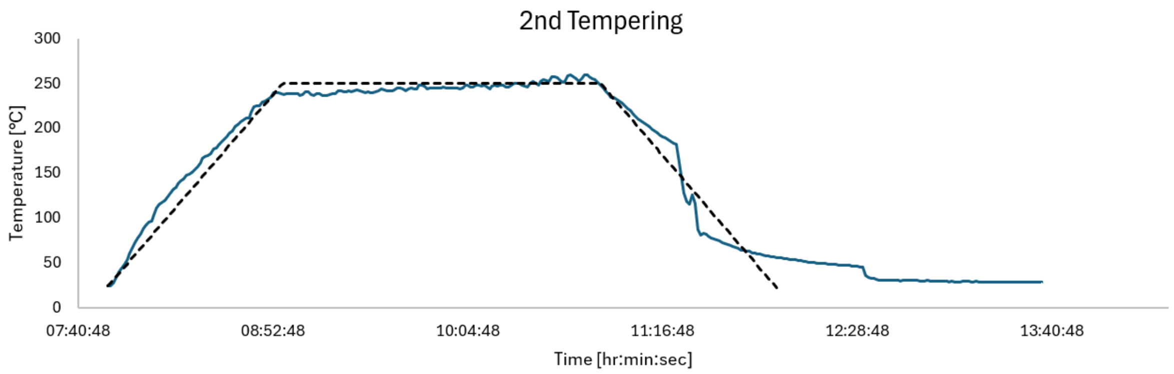
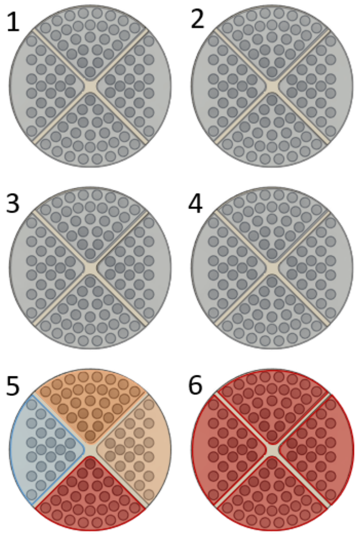


Figure 17 - Second tempering control process

### 10.2 Machining test results

As we developed in a previous section, the first two tools were used to estimate lower and higher limits regarding workpiece material. Starting with a non-treated tool (assumed to be the weaker one), we tried generic parameters and tested if a block of 94 holes was possible. After achieving this, we prepared an additional test with a new standard non-treated tool; this time, the goal was to break the tool. To do so, the parameters were changed, creating a profile we used for the next test. The feed per revolution was fixed at 0,17 [mm] for the whole experiment.



| Stock | Stock subdivision | SS [rpm] | Vc [m/min] |
|---|---|---|---|
| 1 | 1 | 320 | 10 |
| 2 | 1 | 320 | 10 |
| 3 | 1 | 320 | 10 |
| 4 | 1 | 320 | 10 |
| 5 | ¼ | 480 | 15 |
| | ¼ | 640 | 20 |
| | ¼ | 800 | 25 |
| | ¼ | 930 | 30 |
| 6 | 1 | 930 | 30 |

Table 3 - Drilling parameters profile during the test.

After drilling the workpiece material with both tools, we were able to perform 455 holes with the standard untreated tool and 532 holes with the cryogenically treated one (see Figure 18). This represents a 17% in machining time, giving a strong validation of the cryogenic treatment.

Figure 18 - Drilling comparison, on the right, the untreated tool, on the left, the cryo-treated tool results. In each case, a blue arrow is pointing to the hole where the tool broke.

### 10.3 Wear results

To speed up the imaging capture process, a TCM system was designed and implemented. Enclosing the microscope inside a plastic case prevented lubricant and chips from accumulating and obstructing the tool image. A hatch was designed to open when the spindle is close enough (see Figure 19).

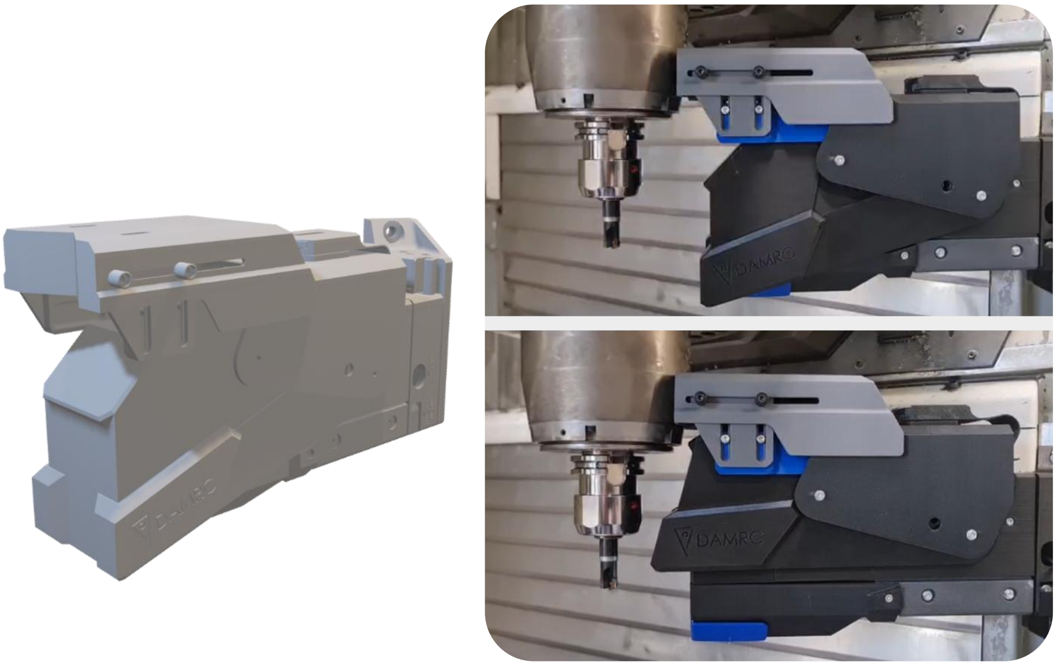


Figure 19 - 3D Microscope enclosure 3D model (left), spindle approaching the hatch lever (upper right), spindle acting on the microscope enclosure hatch (bottom right)

A total of 418 microscope images were captured during the machining process. Considering that not all of them present changes in tool wear, a few were selected to classify and measure (see Figure 20).

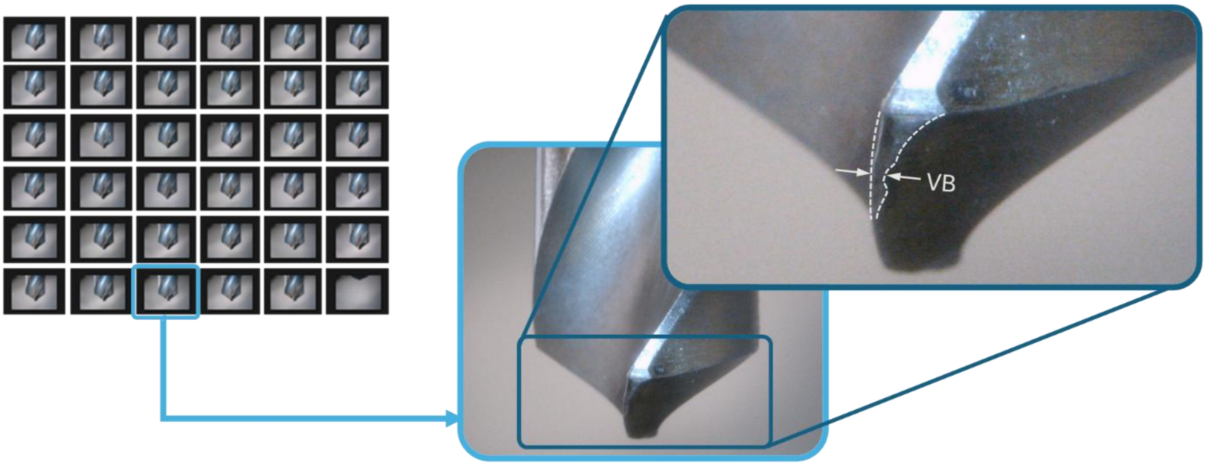


Figure 20 - Microscopy image analysis

To track the tool wear, 17 images were analysed and measured. The result is presented in Figure 21. In the plot, is possible to visualize the wear progress over the machining time. It worth noticing the timeline is considering machine stops and set ups.

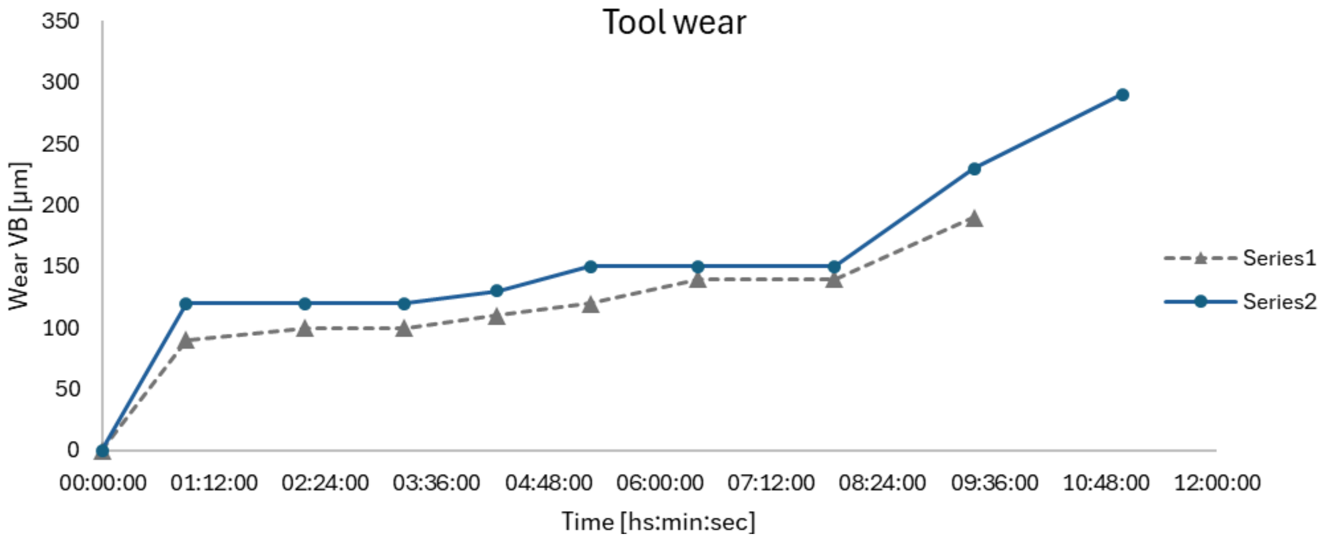


Figure 21 - Tool wear progression

While the cryogenically treated tool lasted more machining cycles, it is interesting to notice how the wear progresses faster. A possible explanation for this behaviour is the tempering treatment, where the tool, and especially the coating, was exposed to sudden heat shocks. This could cause cracks that favour the early deterioration.

## 11 Discussion

The application of cryogenic treatment in this project was aligned with the goal of enhancing tool performance, particularly in demanding machining conditions. While the experiment stayed largely within the original plan, certain adaptations were necessary due to equipment limitations and process control issues. For instance, oven component replacement and adjustments in the nitrogen supply system were made to ensure the correct execution of the treatment cycles.

The results, although based on a limited number of trials, show clear signs of performance improvement, with a 17% increase in machining time before failure. This has direct implications for the Danish manufacturing industry, especially for sectors that involve stainless steel processing, such as food processing equipment, pharmaceutical manufacturing, and energy technology. Companies operating with small to medium batch sizes and high material costs could benefit most from extended tool life and reduced downtime.

Cryogenic treatment presents several advantages over current solutions:

- It is relatively low-cost, requiring no special tooling.
- It can be applied to standard commercial tools, including coated ones.
- It fits well within sustainability goals, as it extends tool life and reduces waste. Additionally, liquid nitrogen can be easily disposed of in the environment without any negative impact.

However, the industrial uptake of cryogenic treatment remains limited, primarily due to a lack of standardization and robust data. If further developed, this technology could be introduced through partnerships with local tool suppliers or machine shops, where it could be tested under broader industrial conditions.

# 12 Conclusion

This study has demonstrated the potential of cryogenic treatment when applied to tool steel, supporting the initial assumptions presented in the literature review.

During the experimental phase, a comparison was made between a non-treated tool and a cryogenically treated one. Although the project faced several challenges — including a liquid nitrogen shortage during treatment, malfunctions in the oven controller, and an unexpected CNC machine shutdown — these obstacles were successfully overcome.

The results revealed different wear behaviours from the beginning of the test, with the cryogenically treated tool ultimately failing later than the untreated one, resulting in a 17% increase in machining time. While a more robust statistical analysis is required to strengthen these findings, the current results are promising.

Based on the experience gained, further exploration of cryogenic treatment is encouraged. Given the decreasing use of HSS tools in modern manufacturing, a logical next step would be to investigate the performance of carbide tools under similar treatment, which would represent a significant advance in this line of research.

# 13 Dissemination

The project’s potential and findings were shared through multiple communication channels. A LinkedIn post emphasized how using microscopy images inside the CNC machine allows for quicker monitoring of tool wear. During regular company visits, the project’s topic and progress were presented as practical examples of how tool life performance can be enhanced. Additionally, the project was showcased in-house at networking days with partners and visitors, highlighting its industrial relevance and applications. Finally, the report is published on the DAMRC webpage for public dissemination.

# References

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