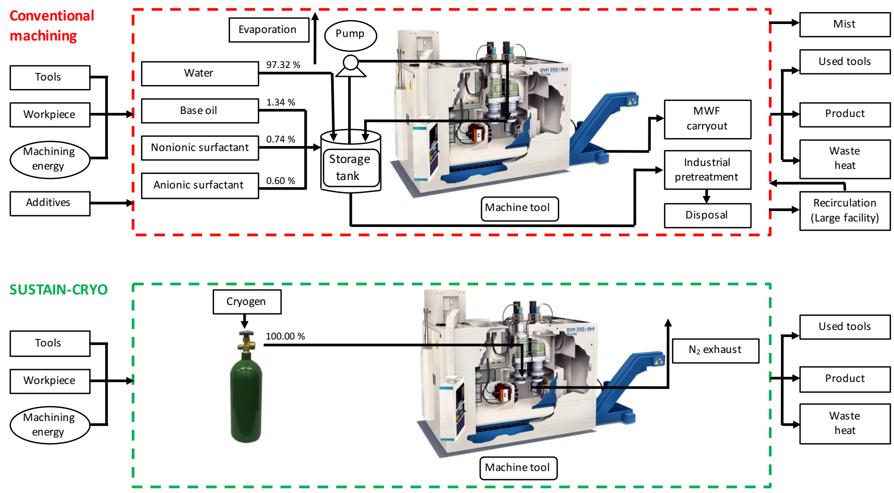
SUSTAIN-CRYO

Publik rapport



Författare: Peter Krajnik, Dinesh Mallipeddi
Datum: 2021-06-26
Projekt inom Hållbar produktion - FFI - 2017-06-13

FFI Fordonsstrategisk Forskning och Innovation
VINNOVA Energimyndigheten TRAFIKVERKET FKG VOLVO SCANIA VOLVO

Innehållsförteckning

1 Sammanfattning

Inom majoriteten av all bearbetning är den höga konsumtionen av skärvätskor starkt kopplat till både höga kostnader och negativ inverkan på vår miljö och har därmed en stor betydelse ur hållbarhetssynpunkt. En transformation från den rådande konsumtionen av skärvätskor till en hållbar produktion kräver speciella och riktade hållbarhetsangreppssätt och kräver också förbättrade och nya verktyg inom simulerings och modellering av processerna som ska verka för att påvisa vinsterna.

För att kunna minska miljöpåverkan inom skärande bearbetning har den senaste tiden skett en intensifiering av forskning av nya tekniker för att minimera behovet av skärvätskor, vilket innebär bearbetning i torrt stillestånd, använda av minimala skärvätskor och även användning av kryogenkylning. Trots den utveckling som har skett den senaste tiden, har kunskapen och kompetensen inte kommit till nytta för fordonsindustrin. I ett led att stärka konkurrenskraft inom fordonsindustrin samt att bidra till en mer hållbarproduktion, vi demonstrerade prestanda för hybrid kryogenkylning kombinerad med minimal användning av skärvätskor inom skärande bearbetning. Projektets metod för teknikbedömning inkluderar hållbarhetsbedömning, simulering/modellering och experimentellt arbete (till exempel bearbetningsprov). I ett led att även undersöka potentialen att få en större effekt av att fler kan använda resultaten undersökte vi också utmaningarna kopplas med eftermodifiering av befintliga maskiner till att använda kryogenbearbetning.

Det patenterade cryo-MQL-systemet från Accu-Svenska utvecklades vidare i projektet och validerades på TRL-6-nivå – i två testanläggningar (hos Chalmers & Sandvik Coromant). Demonstrationsaktiviteterna fokuserade på industriella fallstudier, till exempel bearbetning av gjutjärn och CGI (AB Volvo); såväl härdat verktygsstål (Uddeholms). Fördelarna med förbättrad kvalitet och produktivitet klargjordes – vilket ska leda till framtida teknikutveckling vid högre TRL.

2 Executive summary in English

Sustainability is recognized as the driver for resource-productivity and improved competitiveness of the automotive industry. The abundant use of metalworking fluids in manufacturing processes and the associated costs and environmental impacts have been a major sustainability concern. Transitioning to sustainable production requires tailored sustainability assessment methods, as well as improved predictive models and simulation tools – to aid industrial end-use validation and demonstration – vital for decision-making and implementation of advanced manufacturing processes in production lines.

In the case of machining, increased awareness of the need for sustainability has led to significant research in new and more sustainable manufacturing processes such as near dry and cryogenic machining, especially in the aerospace sector. These achievements, however, have so far gained limited impact in the automotive and steel-making industry. To overcome this, the project addressed sustainability assessment, modelling and simulation to gain a better understanding of the “cryogenic” process mechanics and material performance, as well as the implementation challenges in terms of cutting tools and process-machine integration. SUSTAIN-CRYO developed and validated (TRL5) advances in cooling-lubrication to improve sustainability across different machining operations thus enabling environmentally friendlier manufacturing.

The SUSTAIN-CRYO proposal was initiated by the Volvo Group, Sandvik Coromant and Uddeholms within the Chalmers Centre for Metal Cutting Research (MCR) that coordinated this work. The project was supported by the “Component Manufacturing” cluster of the Swedish Manufacturing R&D clusters which also attracted the participation of Scania, KTH Royal Institute of Technology and RISE. The total project budget was SEK 9.660.000 of which 50% was funded by Vinnova.

All objectives and impacts of the project were achieved. The sustainability assessment followed a bottom-up approach and was limited to a “machining system”, encompassing a unit machine tool and auxiliary systems for cooling-lubrication. The framework for assessment was established and published in a thesis; the real data from the trials however are not published here due to proprietary concerns of the end users. The pilots were limited to automotive and steel-making industry; in the future these activities need to be extended to other sectors, e.g. aerospace and medical. Machine-tool spindles need to be redesigned and retrofitted for the optimal use of this technology.

3 Bakgrund

Automotive industry is under increasing pressure to make a transition towards environmentally neutral production. One way of achieving this in production is via reduced resources for purchasing-, maintenance- and disposal- of metalworking fluids (MWFs). Additionally, in a sustainable machining process, a higher competitiveness can be realized by reducing costs through higher productivity and improved machining quality. Adopting such sustainable-production practices would offer the end users in the automotive industry several cost-effective routes to improve their economic, environmental, and social performance.

MWFs have undergone intense regulatory scrutiny and continually changing environmental and occupational health and safety (OHS) demands in recent years. The permissible exposure limit for MWF has been reduced by the factor of 10; nowadays a mandatory requirement in the automotive industry. Other environmental and social sustainability requirements include compliance with the EU's REACH regulations on chemicals and recommendations that OHS, exposure monitoring, system management and employee training are necessary to improve the sustainability impact of the production. These types of issues have been systematically addressed by the Chalmers MCR's competence network Process Fluids Centre (PVC) since 2007. Through this, the PVC operates as a Swedish national "nod" to exchange various best practices regarding the MWF. This competence network, furthermore, facilitated the considerations to eliminate the use of MWF in machining operations to achieve higher sustainability. The experience, however, indicates that the application of "dry machining" is not economically feasible in the industrial end-use, because dry machining cannot be run at the material-removal rates needed to achieve the productivity gained with using MWF.

The industrial demands for higher productivity require machining with higher cutting speeds, which lead to excessive cutting temperatures – that can result in increased tool wear. The most effective (yet untapped) solution to drastically avoid the onset of thermal damage while employing high cutting speeds is to significantly lower the temperatures by using cryogenic cooling. At the same time, improved lubrication is needed in cryogenic machining to reduce tool wear and costs associated with the cutting tools. Therefore, it is crucial to simultaneously advance both cooling and lubrication methods, and to clearly quantify the impacts for the industry (via sustainability assessment), better understand cryogenic machining, and identify the implementation challenges.

Cryogenic machining is a rather new sustainable cooling method using different systems to deliver either liquid nitrogen (LN_2) or carbon-dioxide (CO_2) to the cutting zone, enabling higher cutting speeds and increasing tool life compared to conventional cooling-lubrication. The two cryogens are distinguished regarding the mechanisms for generating low temperatures that imply different requirements for their use. LN_2 is an inert, non-hazardous, non-toxic, non-flammable media, which disperses into the air after application – thus reducing the requirements for maintenance, post- machining cleaning and disposal. Lower temperatures in machining result in increased hardness and toughness in the cutting tool material, which in turn allows higher material removal rates, and therefore higher productivity. Recent studies report that cryogenic cooling has significantly improved the functional performance of machined components in terms of wear and corrosion resistance, and fatigue life. In the US, the cryogenic cooling proved feasible in the automotive industry for machining of cylinder blocks/heads, crankshafts, rods, and turbo components – being implemented by the companies such as GM, Ford and Cummins. The European automotive industry is lagging behind in this development, therefore SUSTAIN-CRYO gave an opportunity to the Swedish industry, especially in view of the technology-push from the tooling sector (Sandvik Coromant).

Other method in focus was minimum-quantity lubrication (MQL), which was developed a while ago as an alternative to flood (conventional) cooling-lubrication to reduce MWF consumption. In MQL, the lubricant is supplied as a mixture of air and oil in the form of aerosol. In the automotive industry, for example, MQL works well for aluminium machining (e.g. transmission case) and drilling of crankshaft oil holes and is used to a large extent in the German automotive industry (e.g. within the Volkswagen Group). Since it is an established (high-TRL) method, it will be considered in this project only to (a) add lubrication of cryogenic cooling and (b) to ease the implementation. The novel cooling-lubrication method pursued in this project is using small quantities of cryogenically cooled vegetable-oil particles in MQL that has been patented by Accu-Svenska in December 2016. The patent idea was upgraded to a prototype in SUSTAIN-CRYO and was made available for initial testing and validation (TRL5).

The focus of SUSTAIN-CRYO proposal was to benchmark the cooling lubrication method against a shopfloor baseline, i.e. processes run in real shop floors. These piloting activities, although lab based, set ground for demonstrating advanced cooling-lubrication that has two main roles:

- Cooling to reduce machining temperatures, which improves machining quality and allows for utilization of higher cutting speeds (=increased productivity).
- Lubrication to reduce friction and wear, thereby allowing for more sustainable machining with less consumption of tools (=resource conservation & lower tool costs).

By fulfilling these two main roles, the development and pilot implementation of the SUSTAIN-CRYO cooling-lubrication made (an initial) contribution towards environmentally neutral production, especially by opening up the alternatives to reduce the use of mineral-based oils. This strategy sounds straightforward and is aligned with the future requirements of the fossil-free production, but industrial end-use applications of advanced cooling-lubrication are not yet readily available. In view of this background, the SUSTAIN-CRYO work revolved around the carefully identified industrial needs and was carried-out to provide solutions to the challenges listed below:

- The end-use benefits of using advanced cooling-lubrication methods need to be clarified for the industry (especially in terms of productivity and quality).
- The industry lacks clear indicators and metrics to evaluate sustainability of manufacturing processes.
- The implementation issues need to be addressed, e.g. in view of low-temperature effects on precision/quality resulting from delivery of a cryogen fluid.

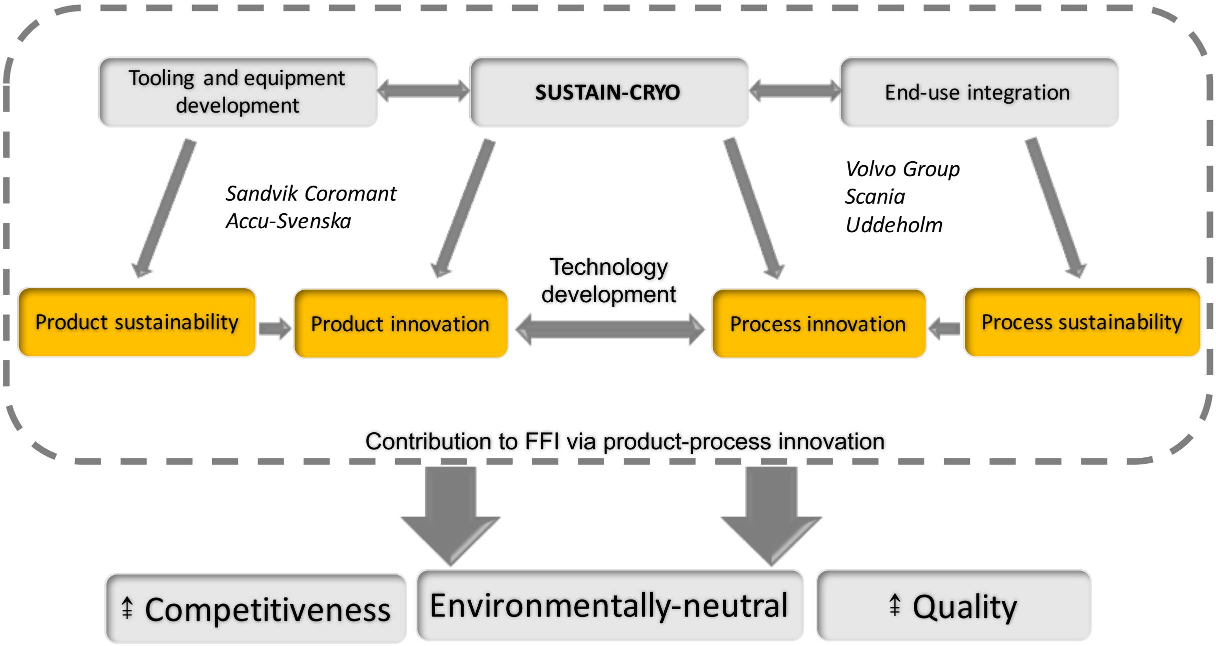
4 Syfte, forskningsfrågor och metod

Swedish manufacturing industry requires improvements towards **higher production efficiency and to reduce the environmental impact of manufacturing processes**. Just as the Sustainable Production strategic roadmap describes, research and innovation are needed to solve the economic, social and environmental challenges that are facing production. Driven by the demands of higher **competitiveness** and **quality**, this project initiated the transition of the manufacturing industry towards higher **resource efficiency** and **minimization of emissions**. **Cryogenically-assisted manufacturing processes are emerging as environmentally-neutral, toxic-free operations, producing high quality products.**

A series of industry-driven cryogenic machining pilots were validated to support early industry demonstration. Here, the focus was on LN_2-cooled MQL developed by Accu-Svenska, which was assessed in the identified industrial use-cases. Pilot applications targeted three demonstrators: two in the (1) automotive industry (Volvo Group), and one in the (2) steel-manufacturing sector (Uddeholms).

The overall aim of SUSTAIN-CRYO project was to further develop **cooling-lubrication methods** to contribute to **environmentally neutral production** in Sweden. The impacts refer to achieving comparable **machining quality** (zero thermal-damage, 100% compressive residual stresses on surfaces), **productivity gains** (20-30%) along **increased sustainability** (positive impacts). For this, a combination of (a) better understanding of the underlying process mechanics and material performance via **modeling/simulation**, (b) clear **technology-integration** path, and (c) **cooling-lubrication** validation pilots were realized to support the assessment of the KPIs, enabling the needed **transition towards sustainable production**.

The research approach followed the canvas, illustrated below. Here the SUSTAIN-CRYO technology development was pursued from two distinct angles; (i) product (tooling and equipment development); and (ii) process (demonstration in real-case pilots).



5 Mål

The above aim can be divided into specific objectives:

- **Productivity increase** of about 20-30% in the automotive (Volvo Group) and steel (Uddeholms) use-cases due to utilizing higher cutting speeds (while 100% avoiding work-material thermal damage) and improving tool life.
- Accu-Svenska brings its cryogenic-machining system **closer to the market** thanks to the SUSTAIN-CRYO demonstration activities required for the end-use technology-pull.
- **Reduced time-to-market** for Sandvik Coromant's cryogenic-tooling solutions by at least 50% thanks to acquired knowledge in the industrial use-cases.
- **Reduction of scrap** by producing high-quality components (no thermal damage, compressive residual stresses) through advanced cooling-lubrication and optimized process parameters.
- **Zero use of mineral-based oils** by making use of toxic-free, hazardless cryogenic cooling-lubrication – contributing to fossil-free production.

How achieved: The benefits of advanced cooling-lubrication is demonstrated in a series of machining **use-case pilots,** and their performance was validated in terms of **productivity**, achieved improved **quality** and **sustainability**. The project put significant effort on assessing the impacts of cryogenic machining via demonstration activities, solving real industrial challenges. The reason for this is that the barrier to wider implementation of cryogenic machining refers to unclear benefits to the end users.

6 Resultat och måluppfyllelse

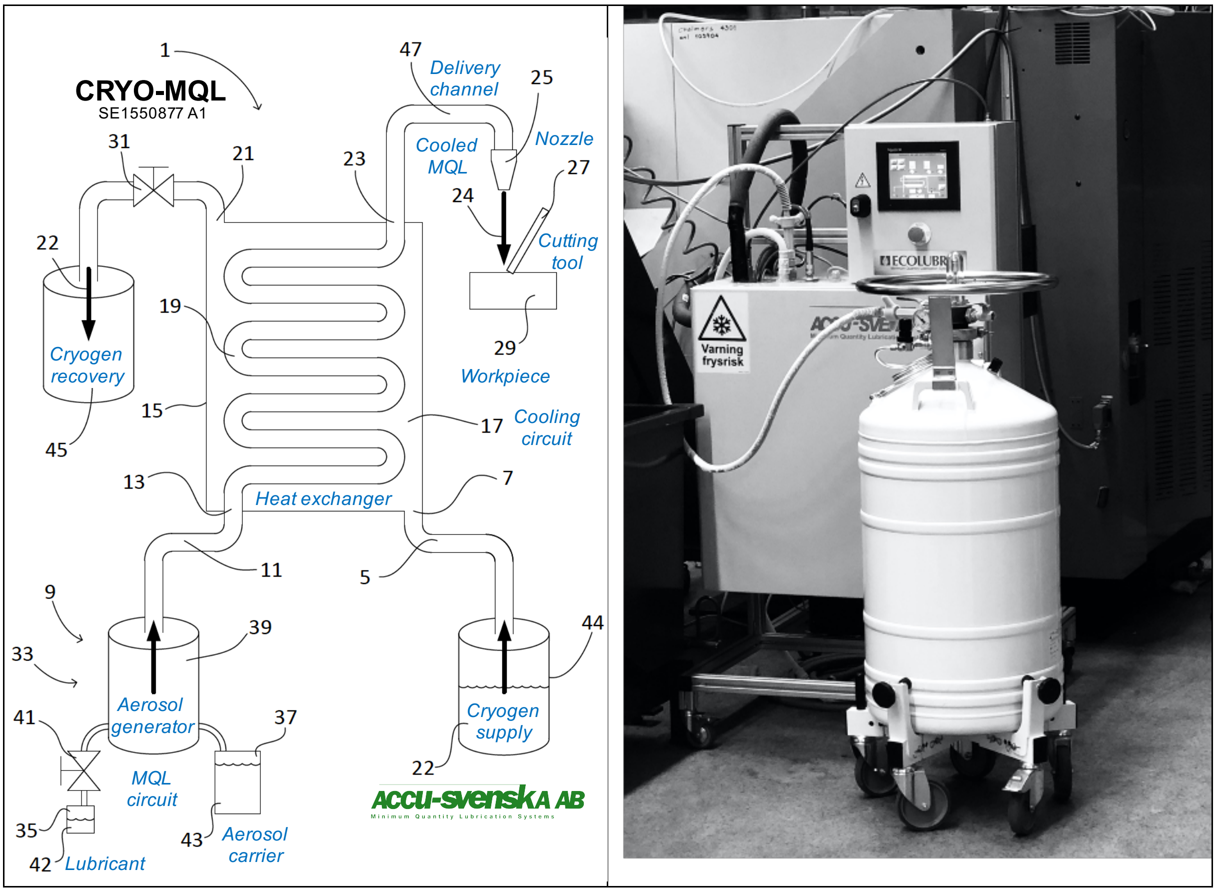
The underlying FFI call, based on the Sustainable Production's strategic roadmap, clearly advocated the need to obtain concrete and positive industrial results. Through several research approaches, our main objective was to contribute to a (more) competitive Swedish industry, creating "business" for the whole value chain. The project aimed at "Environmentally-neutral production", which involved reducing the amount of MWFs, waste elimination, better final quality, process improvements and higher cost-effectiveness.

Expected impacts were: (1) new cooling-lubrication method and technologies developed in the relevant sectors; (2) contribution to the reduction of MWFs; (3) contribution to the reduction of waste; (4)

contribution to the reduction in the use of material resources; (5) participation and benefits for SMEs (in our case Accu-Svenska – owner of the patented subcooled MQL (see figure below); (6) skilled industrial engineering profiles and contribution to education/professional training; (7) contributions to IPR. SUSTAIN-CRYO touched upon all impacts – contributing to environmentally-neutral production. Hence, the project's main impacts were environmental, industrial/technological, and (indirectly) social and economic. All of them contributed to Sweden's increased competitiveness – when environmental aspects are addressed in production, and when skills-development and resource utilization are of big concerns.

The consortium reviewed all (initially) intended results to judge the overall success of work carried out. All results were achieved. Specific details are as follows:

- **R1 – New products** (Sandvik Coromant's customized tooling; Accu-Svenska's LN_2-MQL system) and **process innovation** via technology development for industrial use cases: cylinder heads (GCI, CGI), and hardened tool steel.
- **R2 – Cooling-lubrication methods**: subcooled MQL system upgraded & method validated. Accu-Svenska's system was brought from prototype to product – tested in manufacturing-relevant environment using production machinery (TRL5). Cooling-lubrication control fully developed and integrated; GUI compliant with end-use requirements.
- **R3 – Optimized technologies**, achieved via modelling & simulation, that yield optimal process operating windows, maximizing tool life and productivity. Hardened tool steel case fundamentally researched – covering the aspects of modelling/simulation.
- **R4 – Quality improvements** in the defined use cases, obtaining better surface integrity. Dedicated surface integrity studies performed and available.



Industrial impacts:

The SUSAIN-CRYO cooling-lubrication methods proved increased productivity and improved tool life – providing the end-users with higher added-value, i.e. components of higher quality and (more) environmentally-neutral production. The industrial impacts were addressed/achieved thanks to/via:

- *Environment*

A favourable environmental impact was attained via the following two main aspects: (a) Minimization of processing-fluids use and residual products (e.g. no cleaning of components); (b) Waste minimization, including toxic wastes avoidance by replacing conventional MWFs with cryogenic media and MQL-delivered vegetable oil (non-fossil and renewable resource).

- *Gained know-how*

The developed models and simulation tools enable testing of cooling-lubrication methods in a virtual environment - reducing costs of (experimental) trial and error and technology-development costs – and supporting aid to optimize machining operation(s), e.g. via the established process operating window(s) customized for each use-case. Depending on the application, productivity was improved up to 30%. This definitely strengthens the competitiveness for the end-users. Post-project development will be needed for industrializing the solution at high TRL levels – namely the machine-tool integration.

- *Increased components quality*

End-users have the possibility to introduce components of higher quality, with a higher added value and a better commercial benefit. The process optimization increases quality and offers a technically customized product with a longer life cycle with practically the same price. In some specific use-cases involving difficult-to-machine materials, the project demonstrated to achieve a comparable workpiece quality, but while using a more environmentally friendly technology. The latter is an important impact in itself as superior quality is not always necessary.

- *End-users*

Specific benefits are: merged concept of prototype and industrial first demo – opening a new paradigm for use-case experimentation – reducing the production lead time; Generated know-how will improve the manufacturing processes, improving quality; The elimination of mineral-based oils used today will yield significant environmental and social benefits, including operational health and safety; Assessment of sustainability will improve the overall perception of production at the end-user; Currently uncertain implementation challenges will be addressed from the system perspective.

The below table illustrates the alignment between the overarching FFI objectives and the project:

FFI objectives	Proposed action
Increasing the Swedish capacity for research and innovation, thereby ensuring competitiveness and jobs in the field of vehicle industry	The SUSTAIN-CRYO project will advance cryogenic processes that will give response to the current issues in manufacturing, e.g. fossil-free production.
Developing internationally interconnected and competitive research and innovation environments in Sweden	Utilization of Chalmers MCR and KTH DMMS wide international networks and background in advanced machining and precision engineering research
Promoting the participation of small and medium-sized companies	Participation of Accu-Svenska – a SME producing environmentally-friendly lubricants; and bringing newly patented CRYO-MQL system to the pilots
Promoting cross-industrial cooperation	The cooperation between the end-users in the (a) automotive and (b) steel-manufacturing sector
Promoting cooperation between industry, universities and higher education institutions	The project partners cover the whole value chain for manufacturing improvement, involving: 3 end users, 1 tool & technology suppliers, 1 CRYO-MQL equipment manufacturer, 2 universities, 1 research institute
Promoting cooperation between OEMs	Volvo Group and Scania join forces towards more efficient manufacture of engines; one contributing significantly to the pilots (Volvo Group); while Scania supports overcoming the implementation issues and sustainability assessment

Alignment between the sub-programme objectives and the expected impacts in the proposal:

FFI sub-programme objectives	**Expected impacts**
Environment: significantly reduced environmental impact of process fluids and residues, 2025	100% elimination of mineral-based oils in the pilots; MQL system integration using environmentally friendly vegetable oils; clean environment with zero residuals - components and chips are clean allowing for easier production, clean up, and recycling
Environment: integration of economic, ecological and social sustainability perspective in manufacturing and process development	Environmental aspects were addressed via sustainability assessment. The framework is developed and publicly available, whereas the LCA data is confidential. If implemented at large, the operational health and safety benefits are expected, e.g. operators no longer suffering from dermatitis and lung-related problems that come from the mist in the air, and these are alleviated by using cryogenic coolants – combined with MQL with vegetable oils.

7 Spridning och publicering

7.1 Kunskaps- och resultatspridning

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	SUSTAIN-CRYO is the first project dedicated to cryogenic machining in Sweden – covering a wide value chain from system producer, tooling-solutions provider, industrial end users and researchers. It will serve as the baseline and first project that contributed to capability building in the field – both at Chalmers and the industry
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	The initial development of SUSTAIN-CRYO was transferred to higher TRL innovation action under the EIT Manufacturing umbrella; with a clear goal of further upgrading the TRL of the technology and to extend the pilots to other applications and testing on real production shop floors (not research labs). EIT Manufacturing also internationalized this research in a wider EU context and brought in additional SMEs to specifically support the machine-tool integration issues.
Föras vidare till produktutvecklingsprojekt	X	Accu-Svenska underwent a series of product upgrades during the project. Sandvik Coromant customized its tooling solutions and equipment for (easier) machine integration
Introduceras på marknaden	X	Thanks to the project, Accu-Svenska is now able to commercially offer the technology at around 700.000 SEK/system which is a tangible impact for an SME. One system was already sold to France during the project duration.
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		Not applicable

7.2 Publikationer

- Lisa Gustafsson, Evelina Karlsson, *Sustainability assessment of manufacturing techniques: a case study on machining,* B.Sc. Thesis (Chalmers), 2020.
- Sampsa Laakso et al., *Evaluation of subcooled MQL in cBN hard turning of powder-based Cr-Mo-V tool steel using simulations and experiments*, The International Journal of Advanced Manufacturing Technology (submitted manuscript).
- Agathe Lassalas*, Effect of cooling media (dry, flood and* LN_2*-cooled MQL) on wear behavior of cBN tools in finishing turning of Dievar tool steel, Study Internship Report (ENISE), June 2021.*
- Bharath Reddy Mandara*, Effect of cryogenic (*LN_2*-cooled MQL) media on surface integrity characteristics of machined Vanadis8 tool steel,* M.Sc. Thesis (Chalmers), Aug. 2021.
- Dinesh Mallipeddi et al., *Effect of cooling media on the wear behavior of cBN tools in turning hardened tool steel*, Draft manuscript.

7.3 Industrial Use-case Pilots

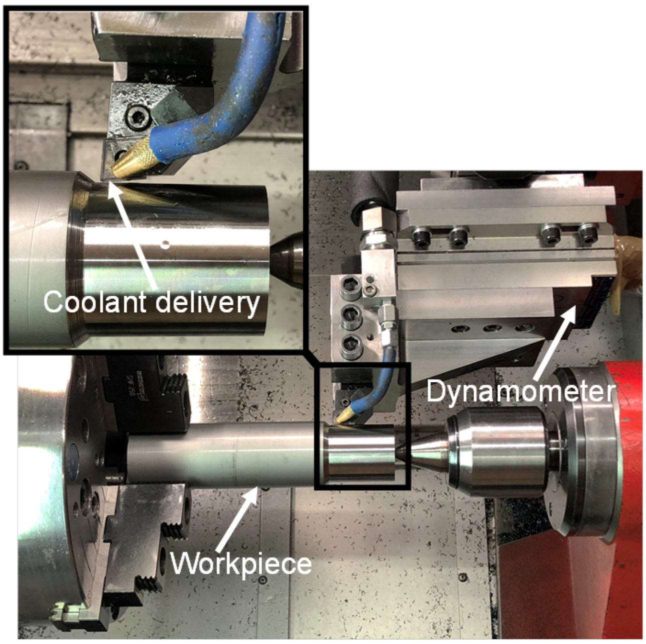
As mentioned earlier, a series of use-case pilots were tested for early industry demonstration using the novel LN_2-cooled MQL developed by Accu-Svenska system. In addition, single channel LCO_2+MQL system was also utilised for validating one use-case.

Use-case pilot in steel-manufacturing sector: Here both the tool wear and surface integrity tests were performed. Two different tool steels; i.e. Dievar and Vanadis 8 were selected as per the interest of Uddeholms. A short summary of these studies is presented below.

Tool wear tests

Study 1: Effect of cooling media (Flood, MQL and LN_2-cooled MQL) on the wear behaviour of cBN tools while turning Vanadis 8 tool steel. In this study, Uddeholm produced Vanadis 8 powder metallurgical cold work tool steel was used as a work piece material. This is a vanadium-chromium-molybdenum rich alloyed steel. The workpieces were delivered in a hardened and tempered condition and received as cylindrical specimens with dimensions; 200 mm in length and 50 mm in diameter. Microstructure analysis of the workpiece revealed high fraction of V-rich carbides in the matrix. The average macro hardness of the workpiece material was 822 HV 10.

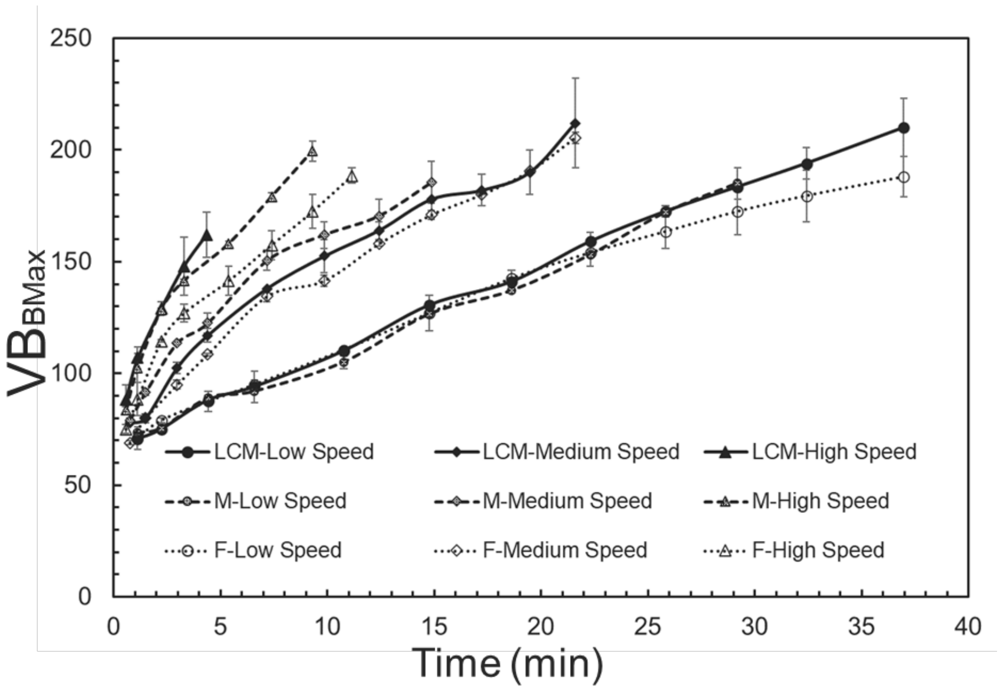
For tool wear studies, longitudinal turning tests were performed at Chalmers MCR using EMCO 365 CNC lathe equipped with three component Kistler 9275A dynamometer. Regarding cutting tools, commercially available AlTiCrN coated cBN inserts were used (Sandvik Coromant, CNGM120408F-HGR 7125). Flank wear (V_B) of 0.2 mm was set as a main criterion to assess the tool life. To follow the progression of tool wear, the tests were interrupted at defined intervals and the respective width of the flank wear land (V_B) was measured using a stereo microscope. For experiments, both the cutting feed (f) and depth of cut (a_p) were chosen to be constant. Since, turning is performed on hardened workpiece, the chosen value was selected is in the range of semi finishing/finishing operation. Two cutting conditions; cutting speed and cooling modes are evaluated



Experimental set-up

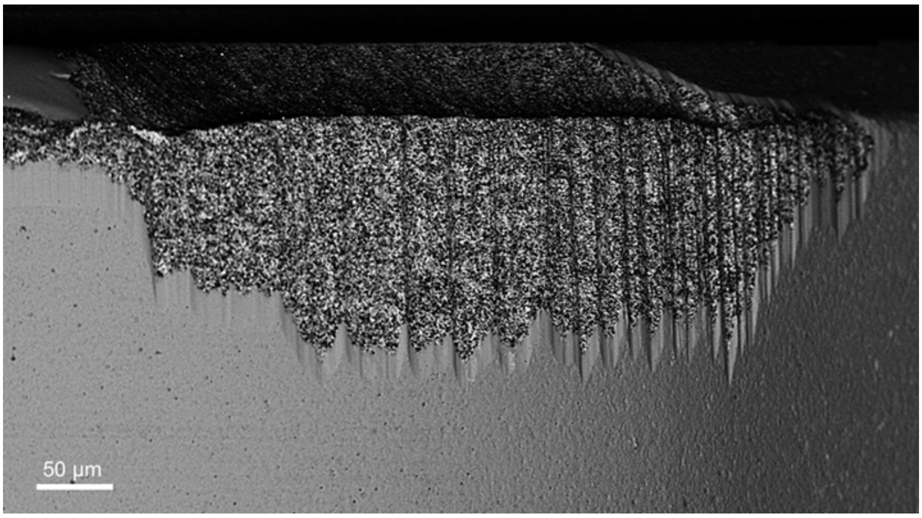
in the present study. Three levels of cutting speed (Vc) and three cooling strategies (Flood cooling-represented as F, MQL-represented as M and LN_2-cooled MQL-represented as LCM) which led to a total of 9 tests were performed. The range of cutting speeds were selected based on the preliminary trail tests. Noteworthy that the coolant was delivered externally over the rake face. The nozzle was positioned near the cutting edge of the tool as shown in Fig.1b. When LCM was used as coolant, the exit temperature of the aerosol at nozzle was maintained as -10°C, and this temperature was selected based on the preliminary tests.

Figure below shows the gradual growth of flank wear (VB) as a function of machining time for three different cutting speeds and cooling conditions. It is clearly seen from the graph that the wear progression increased with the increase in cutting speed irrespective of the cooling media used. This indicates that the cutting speed has a great effect on the tool wear behaviour. Based on the observations, it is reasonable to assume that higher cutting speeds elevates the temperatures at the cutting edge and hence the higher tool wear rate. Furthermore, for the given cutting condition, the wear trends show that the targeted flank wear (VB) of 200 µm reached slower when flood cooling (F) was employed followed by LN_2-cooled MQL (LCM) and MQL (M). The slightest better performance achieved by LN_2-cooled MQL in comparison to MQL could be attributed to the initial lower temperatures of the aerosol which might enhance the extraction of the heat from the cutting zone and at the tool-chip interface.



Flank wear progression as a function of machining time for various speeds and cooling conditions.

The detailed analysis of the inserts revealed abrasive wear as the dominant wear mechanism when machining Vanadis 8 tool steel, for reference see figure below. Abrasive marks on the cBN grains were clearly visible when inserts were characterised at high magnification (images not shown here).



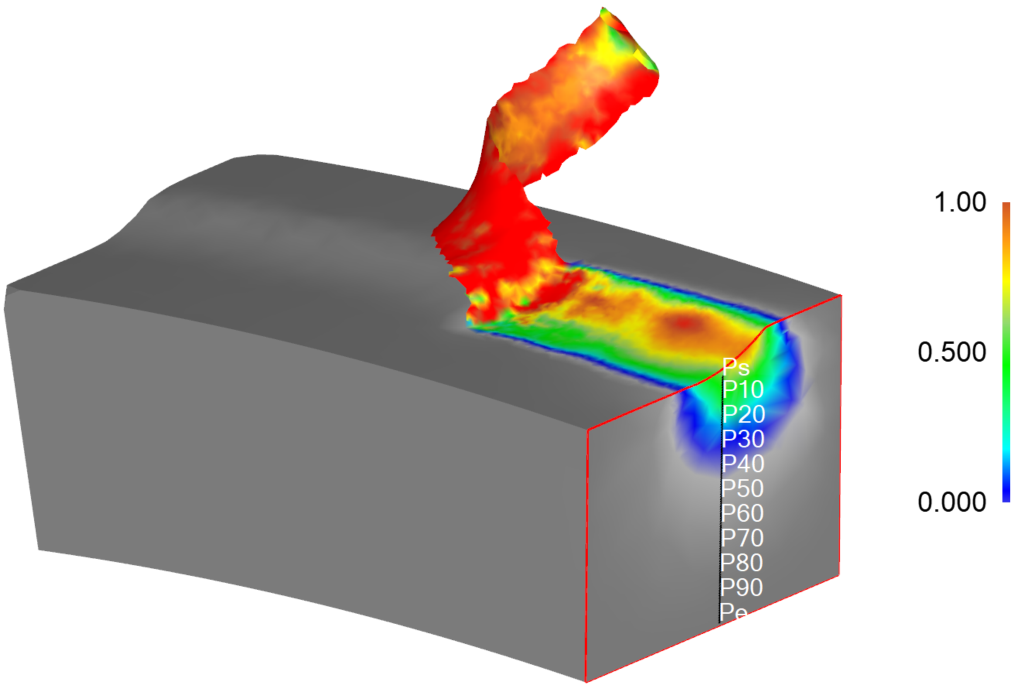
SEM image of the insert after removal of adhered layer using hydrochloric acid. This insert belongs to low cutting speed (Vc) condition with LN_2-cooled MQL as a coolant.

Overall, both cooling conditions LN_2-cooled MQL and MQL are lagging behind the flood cooling in terms of tool life. However, flood cooling is not used in real production due to sustainability and cost concerns. On the other hand, one should remember that the coolant delivery is not optimal as the stream of aerosol is hitting the insert only on the rake side. Therefore, greater efforts must be placed in designing tailored made tool holders for optimizing the delivery of the LN_2-cooled MQL. For example, stream of aerosol hitting the cutting edge from both the rake and flank side should improve the injection of coolant at the contact conditions. This in turn reduces the friction further and improves the tool life.

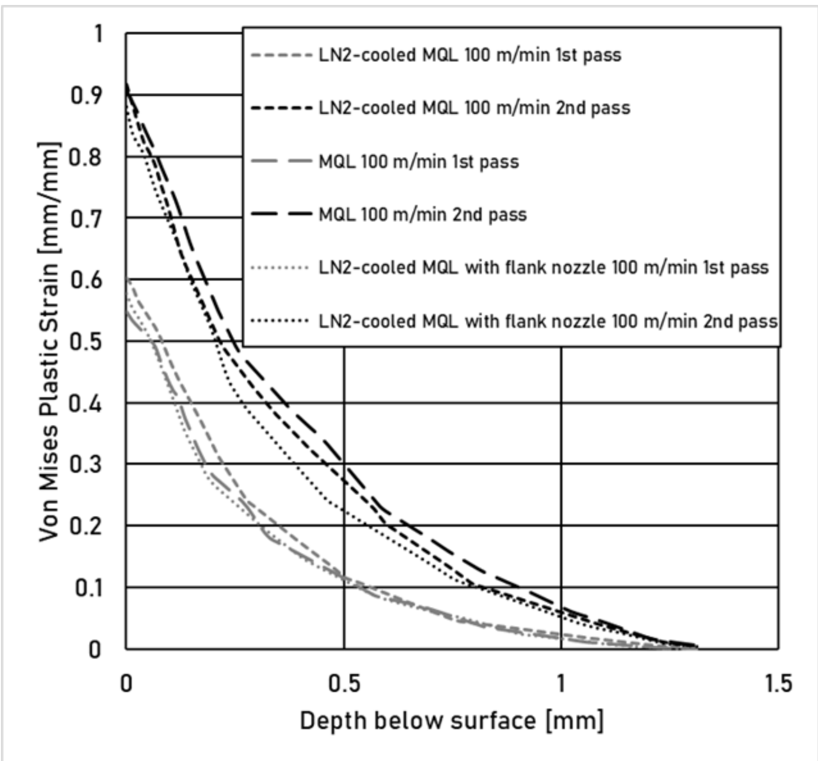
Finite element simulations of the LN_2-cooled MQL were also performed to investigate the effect of the cooling on chip formation and residual stresses. The cutting forces and tool wear were measured from the experiments, that are used as the calibration factor for the simulations. After calibration, the simulations are used to evaluate the thermal effects of the subcooled MQL, and the surface residual strains on the workpiece. The simulations are in good agreement with the experiments in terms of chip morphology and cutting forces. The cutting experiments and simulations show that there is a small difference between the LN_2-cooled MQL and MQL regarding the wear behaviour, cutting forces or process temperatures. The simulations predict substantial residual plastic strain on the workpiece surface after machining, but the LN_2-cooled MQL had 70% lower stresses than regular MQL. The surface deformations are shown to have significant effect on the simulated cutting forces after the initial tool pass, an outcome that has major implications for inverse material modelling.

The following conclusions were made:

- The simulations accuracy is good (<5.1% error) when the material model is calibrated correctly at the second tool pass, especially the feed force errors that have been omnipresent in cut-ting simulations were diminished.
- The LN_2-cooled MQL had slightly better performance over the MQL. The small difference is due to highly abrasive work material, which causes high wear rate regardless of temperature.
- Optimizing the nozzle placement for MQL is critical and it has a significant effect on the surface residual strains.
- Simulations suggest that friction coefficient increases with increasing cutting speed with vegetable oil MQL.
- Modelling of the heat transfer of coolants in metal cutting is not sufficiently developed in existing research.



Residual plastic strains on workpiece surface.

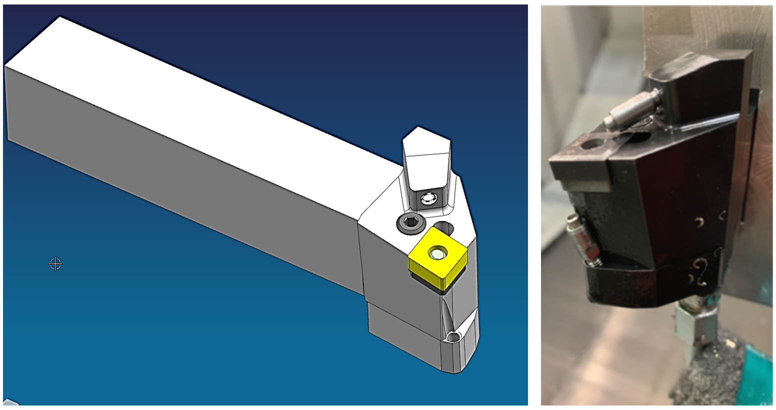


Comparison of residual plastic strain after 1st and 2nd tool pass at 100 m/min.

Study 2: Effect of cooling media (Flood, and LN_2-cooled MQL) on the wear behaviour of cBN tools while finish turning of Dievar tool steel.

In this study, Uddeholm produced Dievar powder metallurgical hot working tool steel was used as a work piece material. It is a chromium-molybdenum-vanadium rich alloyed steel. The workpieces were delivered in a hardened and tempered condition and received as cylindrical specimens with dimensions; 200 mm in length and 50 mm in diameter. Microstructure analysis of the workpiece revealed the presence of both Mo and V-rich carbides in the matrix. The average macro hardness of the workpiece material was 550 HV 10.

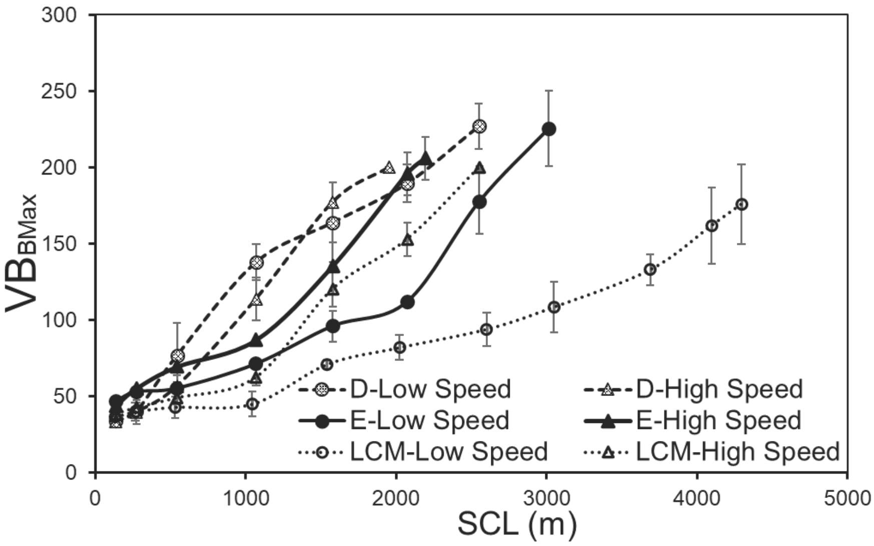
For tool wear studies, longitudinal turning tests were performed at Chalmers using EMCO 365 CNC lathe equipped with three component Kistler 9275A dynamometer. Regarding cutting tools, commercially available coated cBN inserts were used (Sandvik Coromant, CNGM120408F-HGR 7125). Realising the importance of optimal delivery of the cryogenic cooling media, a tailored made tool holder was designed and produced by Sandvik Coromant. The coolant was supplied internally through the tool holder and the aerosol stream is delivered directly to the cutting edge both on to the rake and flank side of the insert via specially designed nozzles. The nozzles were also optimized both in terms of length and diameter for enhanced supply of cryogenic media. Flank wear (V_B) of 0.2 mm was set as a main criterion to assess the tool life. To follow the progression of tool wear, the tests were interrupted at defined intervals and the respective width of the flank wear land (V_B) was measured using a stereo microscope. Also, in this study both the cutting feed (f) and depth of cut (a_p) were chosen to be constant. Two cutting conditions; cutting speed and cooling modes are evaluated. Two levels of cutting speed (Vc) and three cooling strategies Dry (as reference)-represented as D, Emulsion cooling-represented as E, and LN_2-cooled MQL- represented as LCM which led to a total of 6 tests were performed. The range of cutting speeds were selected based on the preliminary trail tests. When LCM was used as coolant, the exit temperature of the aerosol at nozzle was maintained as -20°C, and this temperature was selected based on the preliminary tests.



Tailored tool holder holder

Figure below shows the gradual growth of flank wear (VB) as a function of spiral cutting length (SCL) for two different cutting speeds and three cooling conditions. The results indicate that the wear progression is higher for the higher speed. For the given cutting condition, the wear trends show that the targeted flank wear (VB) of 200 µm reached slower when LN_2-cooled MQL (LCM) was employed followed by emulsion (E) and dry (D) conditions. Importantly, at low-speed condition, the application of LCM has improved the tool life to about 60% in terms of SCL compared to reference dry condition. At higher speed, the improved tool life is around 30%. A detailed investigation of the inserts using high magnification SEM revealed adhesive wear as a dominant wear mechanism. Regarding cutting forces, passive forces were recorded higher than cutting and feed forces for every cutting condition which is typical of hard turning process. Irrespective of the cutting speed, lower passive forces were recorded when LCM was applied as coolant in comparison to the other cooling strategies.

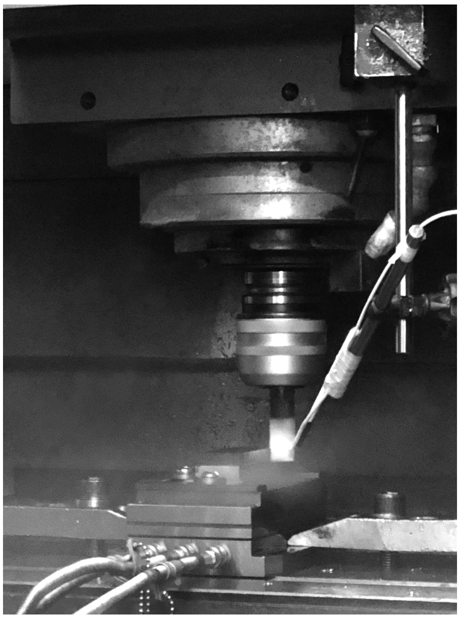
Overall, the tailored tool holder used for delivering the cryogenic coolant provides an effective means for cooling the cutting edge during the machining operation. As a result, increased tool life was achieved when LCM was delivered using tailored tool holder. The obtained results prove the aims of the project which is to contribute to an "Environmentally-neutral production" which includes reducing the amount of MWFs, process improvements and higher cost-effectiveness.



Flank wear progression as a function of spiral cutting length for various speeds and cooling conditions.

Study 3: The effect of cooling strategies (Flood, LCO_2+MQL) and dry machining on the surface integrity characteristics of Vanadis 8 tool steel. It is well known that the functional performance of a component highly relies on the surface integrity characteristics generated by the final machining operation. Recently, special focus has been shifted to cryogenic machining as satisfying results are reported for different alloys. In this study, dedicated tests were performed to investigate the effects of cryogenic coolant-single channel LCO_2+MQL on surface integrity characteristics; roughness, residual stresses, and white layer thickness etc. in hard machining of Vanadis 8. The results were compared with dry and flood machining at varying process parameters.

For surface integrity studies, side milling tests were performed. Commercially available PVD coated-Sandvik Coromant, 2S342-2000-100-CMA 1740 – solid end mills were used. Five cutting conditions with combination of three different cutting speeds (V_c) and feed (f_z) values were tested. For each combination of cutting speed and feed, depth of cut (ap) and radial engagement (a_e) were maintained constant. Two reptations were carried out for each cooling strategy. The workpieces were delivered in a hardened and tempered condition and received as rectangular specimens with dimensions; 75 mm in length and 40 mm in width.



External delivery of cryogen

After machining experiments each surface for every test condition was analysed. The obtained roughness values for both the parameters R_a and R_z were found to be consistently superior when LCO_2+MQL was used as coolant compared to dry and flood cooling strategies. This is true irrespective of the cutting condition used.

Regarding residual stresses, highest surface tensile residual stresses and clear hood-shape profile was observed under dry machining. While both for flood and LCO_2+MQL strategies less surface tensile stresses, and with a less pronounced hook-shape profile was observed. This indicates the lower temperature development during machining.

The microstructure analysis revealed the presence of white layer irrespective of the cooling strategy employed. The white layer thickness is in the range of 0.5 up to 1.5 µm. Overall, considering all the integrity characteristics, one can conclude that the hard machining of Vanadis 8 tool steel under cryogenic cooling- LCO_2+MQL has the potential for enhancement of surface integrity which in turn improves the quality of component (and product life).

Use-case pilot in automotive sector;

In this piloting activities, tool wear tests were performed to validate and demonstrate the potential benefits of the cooling-lubrication system developed by Accu-Svenska. Two different cylinder-head materials; Compacted Graphite Iron (CGI) and Grey Cast Iron (GCI) were selected as per the interest of the Volvo Group. A short summary of these studies is presented below. Note this use case is less detailed compared to the tooling case, due to confidentiality concerns. Sandvik Coromant was responsible for the testing and validation, in close collaboration with Volvo Group.

For these pre-industrial (lab based) trials, a specimen which is representative of an engine block was specially manufactured. The workpiece material was casted for both the materials, GCI, and CGI. Face milling tests were performed with three cooling strategies i.e. Emulsion, MQL and LN_2-cooled MQL. The obtained results were compared with reference condition of dry machining. Specially designed CoroMill 490 equipped with 6 inserts-490R-8T308M 3330 on a Ø63mm tool was used. All the experiments were performed on a Hermle C40U CNC machine. The technical challenge here lies in the supply of chilled MQL. The easiest way to deliver LN_2-cooled MQL is via external nozzles around the tool. Such systems allow for low-cost implementation of cooling solutions by eliminating the necessity to retrofit the spindle. However, for milling operation, the disadvantages are that there is a need of manually adjusting the nozzles with respect to tool. Secondly, such way of aerosol dispersion could result in mass and thermal loss, and hence reduced cooling-lubrication efficiency. To overcome this issue, a special spindle nozzle adaptor (rotary unit) was designed and manufactured by Sandvik,. Flank wear (V_B) of 0.3 mm was set as a main criterion to assess the tool life.

Rotary Unit

In case of CGI, the tool life has improved by 10% for MQL and 20% when LN_2-cooled MQL was used as a cooling media in comparison to the reference dry condition. For GCI, the improved tool life was about 50% for both the cooling conditions, i.e. MQL and LN_2-cooled MQL. Tool-life has profound effect on productivity, even if the cycle time is not changed. Due to proprietary concerns, the obtained cycle times are not revealed. No vibrational issues have occurred with respect to the usage of the rotary unit. Further improvements are attainable if single-channel integration is enabled, i.e. delivery of the cryogenically-cooled MQL through the spindle & tool directly to the cutting zone.

8 Slutsatser och fortsatt forskning

Sustainable Production is an industrial paradigm aiming at establishing a new sustainable development path by decoupling economic growth and resource consumption. Sustainable Production shows potentials to significantly increase resource efficiency in manufacturing. The industry is under increasing pressure to make a transition towards waste-free production. The SUSTAIN-CRYO project explored the pathways to minimize/eliminate waste, e.g. resources for acquiring-, maintenance- and disposal- of metalworking fluids (MWFs) by implementing minimum-quantity lubrication (MQL) with crucial integration of cryogenic cooling for superior performance in terms of productivity and quality.

Building upon our research in cryogenics and minimum-quantity lubrication, the project brought the patented method of cooling and lubrication aided by liquid nitrogen to applications from the automotive and steel-manufacturing sectors. Stemming from this research, solutions for cryogenic machining came closer to the market. More specifically, within this project the Accu-Svenska’s cooling-lubrication system was developed from TRL3 to TRL6 – achieved through demonstration activities in industrial pilots. This innovation proved successful in replacing conventional metalworking fluids and offers realistic solution for manufacturing problems where improved sustainability could greatly impact the current industrial baseline. SUSTAIN-CRYO clearly showed (at TRL6) that we can increase product quality, process efficiency & productivity (min. 20%), and tool life by 2-5x – while improving the sustainability impact.

SUSTAIN-CRYO project is being followed-up by the innovation action funded by EIT Manufacturing. This innovation action is extending the work of this project by another two years (2021-2022). EIT Manufacturing is not funding research, therefore the aim is to bring the Accu-Svenska's technology developed in SUSTAIN-CRYO to TRL8 and closer to end-use exploitation. In this regard Uddeholms plans to test the concerned cryogenic machining in real production line. Moreover, a wider market conditions, drivers and barriers are addressed. Some of the technology integration issues identified by SUSTAIN-CRYO are tackled via new spindle development for the Accu-Svenska system, next to spindle retrofitting options for existing machines. Dedicated tooling solutions for through-spindle cases and 3D printed external nozzles for multi-channel integration (external delivery) are addressed as well. Pilots done here in SUSTAIN-CRYO will be further extended for additional use-cases in 2022: e.g. Aerospace pilot incl.: (i) Drilling of structural (stacked /e.g., Ti-CFRP) aerospace parts; (ii) Milling/drilling of Inconel 718; and medical use-case pilot. Through CRYO-MQL Chalmers will further and fully consolidate research capability in cryogenic machining and finalize its investment into this research infrastructure. This will secure further development of this technology in Sweden and support future research in the field. There is no other university/research institute which has this capability available.

9 Deltagande parter och kontaktpersoner

SUSTAIN-CRYO partnership combined research excellence, critical industrial backing, as well as capability to demonstrate the outputs of this project. The industrial partners from the automotive and steel-making manufacturing sectors, brought the needed competence, complementarity and critical mass in terms of expertise and resources to ensure the KPI-achievement of the demonstration activities and the impact of the pilots. The key IPR owner, Accu-Svenska was part of the partnership as well, proving the potential of SMEs to engage in R&D projects with OEMs and research providers. Overcoming of the first (obvious) technology-implementation barrier was entrusted to Sandvik Coromant – one of the world’s largest providers of comprehensive metal cutting solutions; Sandvik Coromant’s role was key in the implementation of the automotive pilot. The partnership proved successful in understanding the end-users’ needs and bringing new technological solutions closer to the market.

The table below shows participating researchers and industry representatives:

Participant	**Value chain**	**Key staff**	**Role in the project**	**Key expertise/contribution**
Volvo Group	End-user (automotive)	N. Nordstrand; S. Palmqvist; D. Chen; S. Siren	Use-case definition WP1; sustainability assessment WP2, key support in WP4 & WP5	Industrial support to WP2 – sustainability; facilitate its use-case, components and expertise
Scania	End-user (automotive)	L. Daghini	Use-case definition WP1; technology-integration aid WP4	Industrial support to WP4 – integration; assist WP5 use-case
Uddeholms	End-user (steel)	L.-G. Nordh	Use-case definition WP1; key support in WP4 & WP5	Industrial support to WP5 – validation; facilitate use-case
Sandvik Coromant	Tools manufacturer & tooling solutions	A. Morandeau, O. Larsson, H. Strandlund	WP5 leader; background support to WP3; facilitator of WP4-5	Most recognised machining-solutions provider; validation tests

Accu-Svenska	Equipment manufacturer	M. Martinovic, I. Martinovic	IPR holder; equipment supplies to WP4-5; enhancing the equipment TRL	Expertise in MQL; definition of controllable parameters; facilitate equipment (CRYO-MQL) for tests
Chalmers	University	D. Mallipeddi, S. Laakso, P. Krajnik	Project coordinator. Leader of WPs 1, 3 and 6. Support of WP2. Overall project responsibility	Background in sustainable cryogenic machining & modelling and simulation
KTH	University	T. Laspas	WP4 lead; manufacturing-system technology-integrator	Expertise in the field of precision engineering; assessing accuracy
RISE	Research institute	J. Hildenbrand, S. Hosseini	WP2 lead; sustainability assessment expert; support of WP3 (surface integrity)	Expertise in sustainability assessment and background in machined surface integrity