Sustainable and Circular Gear Machining with Minimum Quantity Lubrication

Public report

Project within Circularity - FFI
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Fordonsstrategisk
Forskning och
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Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

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1. Summary

As sustainability requirements in the product life cycle continue to grow, there is a corresponding increase in the demand for sustainable alternatives in the manufacturing phase. MQL is already recognized as a substitute for traditional cutting fluids and flood lubrication in machining processes such as milling, turning, and drilling across a range of metallic materials. However, actors from KTH, along with industry partners, have identified significant potential for implementing MQL in gear manufacturing, specifically in hobbing and skiving processes, where minor or lacking research has been identified respectively. In contrast to previously performed research, the main objective of the project "Sustainable Gear Machining with Minimum Quantity Lubrication" is to investigate the possibilities for the practical implementation of the MQL technique specifically for the gear manufacturing processes of hobbing and skiving in automotive and heavy vehicle industry, and to afterwards formulate the scope of the future full study. Furthermore, this project aligns with two prior projects, both having been funded by Vinnova. One is the "SiTCoM" project, where a simplified testing process for gear machining was developed. The second is "Sustainable milling with Minimum Quantity Lubrication", in which a testbed for MQL cutting process has been developed and validated. The experience and knowledge gained from these projects will facilitate the execution of this pre-study and will enable the integration of previous work outcomes into the new project. The project will be carried out by KTH's Department of Production Engineering (KTH IIP) as the coordinator and main applicant and SWERIM as the research partner. The following companies will be involved in the project: Volvo, Leax, Sandvik, Ionbond, Erasteel, Ovako and Eco-Lubric AB (SME).

2. Sammanfattning på svenska

I takt med att hållbarhetskraven inom tillverkningsindustrin ökar, växer behovet av miljövänliga alternativ. Minimum Quantity Lubrication (MQL) erkänns som ett hållbart substitut för traditionella skärvätskor vid bearbetning. Trots omfattande forskning inom processer som fräsning och svarvning är dess tillämpning inom kuggbearbetning, särskilt kuggfräsning och skivning, fortfarande outredd. Denna förstudie, ledd av KTH och SWERIM i samarbete med industripartners såsom Volvo och Sandvik, undersöker möjligheten att använda MQL i kuggtillverkning för fordons- och tung fordonsindustrin.

Projektet bygger på tidigare Vinnova-finansierad forskning och syftar till att genomföra en litteraturstudie, definiera en experimentell uppställning och etablera ett konsortium för en fullskalig studie. Litteraturöversikten visar att MQL erbjuder fördelar som minskad miljöpåverkan, längre verktygslivslängd och förbättrad kugghjulskvalitet. Dock finns utmaningar såsom känslighet för parametrar, begränsade realtidsdata och bristande mätning av krafter och temperaturer. En förenklad testmetod med spårfräsning har utvecklats för att studera verktygsslitage, processeffektivitet och skärvätskans påverkan.

Studien bekräftar MQL:s potential inom kuggbearbetning men betonar behovet av vidare forskning. Nästa steg är ett fullskaligt projekt med titeln *Benchmarking of Sustainable and Circular Gear Machining with Minimum Quantity Lubrication*, med fokus på att optimera MQL-parametrar och industriell implementering.

3. Background

The Minimum Quantity Lubrication (MQL) method, also known as “Near-dry” manufacturing or “mist lubrication” method, has been proven to have positive impacts on environmental, social, and costs-related aspects throughout the production phase, aiming for a more resource-efficient manufacturing process across the product life cycle. The environmental and social aspects, among others, are tied directly to the FFI Circularity sub-program’s mission, more specifically: 1) The use of MQL method enhances the quality of machined workpiece, thereby prolonging its lifespan. Additionally, considering the lifespan of components within the same systems is important, as gear failures can trigger failures in other parts. 2) Tool lifespan is also prolonged, therefore leading to less material needs in production. 3) It enables more effective recycling of the waste material and eliminates or significantly reduces the need for waste management of the cutting fluid post-use. 4) In various studies, researchers concur that employing MQL leads to a safer working environment for machine operators when compared to the flood lubrication method.

Gears are a vital part of any vehicle, and with the goal of achieving a more sustainable production in the transportation segment it is crucial to explore new, environmentally friendly alternatives across all facets of the production process. Despite the widespread application of MQL and its associated benefits in numerous manufacturing processes, there remains a notable gap in knowledge regarding its application in gear manufacturing. This project will speed up the implementation of sustainable manufacturing in gear production for the automotive industry and decrease the existing knowledge gap in this area.

4. Purpose, research questions and method

MQL reduces costs with use of minimum amount of cutting fluid, improves conditions of work environment for operators, makes chip disposal more efficient, and with application of optimal parameters, increases quality of the manufactured workpiece and therefore improves the performance and lifespan of the manufactured component. However, the research on industrial implementation challenges of MQL in gear manufacturing is limited. Moreover, there is an increasing interest from industry partners, such as Scania CV AB and AB Volvo, to examine the suitability of this method for gear production in the automotive and heavy vehicle manufacturing industry. The intent of this project is to further investigate the previously performed research and to extend the knowledge-base on this topic through means of a thorough literature study, interviews with industry partners, and a limited experimental test to prove the validity of the compiled research as well as to create an experimental dataset for skiving with MQL. This will in turn be the base for the future application in the full scope experimental study. The research question is “What is the current state of the art and potential of MQL in gear manufacturing processes?” The main method is literature review.

5. Objective

This pre-study will perform a literature study and state-of-the-art in gear machining with MQL, as well as a proof-of-concept machining test on hobbing and skiving using MQL. Moreover, we will expand and strengthen the project consortium with additional providers. Thus, the objective of the project is to investigate the possibilities for practical implementation of the MQL in the gear manufacturing processes of hobbing and skiving in automotive and heavy vehicle industry and to afterwards formulate the scope of the future full study,

- Perform a literature study/ state-of-the-art specific to MQL in gear manufacturing processes.
- Define an experimental set-up and assessment criteria to evaluate MQL in gear manufacturing processes.
- To build a consortium and proposal for follow-up full study.

6. Results and deliverables

The expected result of the project is a concrete understanding of the current state and the prospects of MQL in gear manufacturing processes. And a well-defined experimental set-up and assessment criteria for its validation in follow-up study. Below are the outcomes of the literature study and the experimental set-up definition.

<u>Literature study method:</u>
The literature study was performed in accordance with an internal guideline for scientific paper research. To ensure comprehensive collection of relevant papers, the search process is conducted iteratively.
After the collected papers had been reviewed, a critical evaluation was performed. To ensure relevance, only papers published after the year 2000 were considered. Furthermore, to ensure credibility and reliability, only peer-reviewed articles from reputable journals or publications were included in the literature study.
<u>Significant Trends</u>
If a manufacturing process is to be considered sustainable, it needs to address environmental, economic, and safety concerns. A key aspect in addressing the sustainability of gear machining processes is reducing the adverse impact of the cutting fluids [1]. Minimum Quantity Lubrication (MQL) serves as an efficient method for reducing the use of environmentally harmful, mineral-based, cutting fluids in gear manufacturing processes. In contrast to processes that rely on flood lubrication (FL) or dry machining (DM), MQL machining offers reduced lubricant use without excessively compromising on tool wear or cutting speed. Notably, one study shows that the use of MQL as opposed to FL can result in both higher quality gears and longer hob life [2].
Several studies show that replacing traditional mineral-based lubricants with synthetic alternatives or vegetable oils can reduce both environmental impact and operator health risks, without significantly compromising gear quality [2,3]. These alternative lubricants offer comparable or even improved performance in certain conditions, indicating that they can be a sustainable and reliable choice for gear manufacturing. Further, recent studies explore integrating cryogenic

cooling with MQL to further improve process efficiency. This combination demonstrates promising results in mitigating tool wear and improving gear quality by reducing cutting temperature and enhancing chip evacuation [4-6]. By utilizing both MQL and cryogenic techniques, manufacturers can potentially achieve more sustainable processes with fewer drawbacks.

Another emerging trend in the literature is dry machining. While dry machining eliminates lubricants entirely, making it the best alternative option in terms of operator safety, it comes with inherent trade-offs that may limit its widespread adoption. It is reported in the literature that dry machining can come with a noticeable reduction in tool life, cutting speed and overall gear quality when compared with MQL [2]. The literature presents the situation where a cutting process does not meet requirements for gear quality. In such cases finishing processes can be utilized, where the literature outlines skiving as one example of a finishing process [11].

<u>Hob Wear</u>

Hob wear is a crucial aspect of sustainability in gear hobbing processes since it impacts both economic and environmental performance. Due to the lack of a standardized method, a wide range of criterion are used to measure hob wear in the literature. Several papers rely on some variation of hob flank wear width (VB) to measure hob wear [2, 3, 14], and two papers use composite models that integrate multiple roughness and wear measurements [4, 5].

The literature shows that MQL performs well in improving tool life for hobbing processes in the gear manufacturing industry. One research group shows that the use of MQL, as opposed to flood lubrication, can improve tool life by up to 91%, with the tool life extension being attributed to improved temperature regulation and increased chip evacuation [2]. The results are mixed though, another research group shows MQL performing slightly worse than flood lubrication in tool life. The mixed results can be attributed, to some extent, to MQL's high sensitivity to parameter selection. One paper specifically examines this by varying cutting speed and comparing the tool life between a process relying on MQL and a process using flood lubrication, concluding that an increased cutting speed can lead to a rapid degradation in tool life for hobbing with MQL [14].

The literature also highlights lubricant composition and application technique as two key factors that influence hob wear in gear manufacturing. In a study comparing lubricants and application techniques, dry machining was found to reduce tool life by 28% when compared to MQL under similar conditions. Furthermore, the research concluded that opting for a fatty-alcohol based lubricant like Hyspray 1536, instead of a synthetic ester-based alternative, can improve hob life by up to 14% in MQL conditions [5].

<u>Gear Quality</u>

The application of MQL shows promising results in improving gear quality while maintaining efficiency in gear hobbing. While results vary among studies, there is a consistent trend indicating that MQL can outperform both dry machining and flood lubrication in areas such as surface roughness and microhardness. One recent study explicitly reports that using MQL in gear manufacturing results in superior gear quality, while simultaneously providing increased material removal rate and extended hob life, thus making it a viable alternative for sustainable gear manufacturing [2]. However, an older study indicates that MQL may yield slightly higher surface roughness when compared to flood lubrication, highlighting the need for careful parameter selection to ensure maximized benefits [9].

A key insight from the literature is that while MQL demonstrates strong performance, its effectiveness is heavily dependent on optimizing process parameters. Factors such as axial feed, air pressure, and lubrication flow rate have a significant impact on surface roughness and overall gear quality. Furthermore, the results indicate that MQL's performance is highly sensitive to variations in these parameters, and that many parameters have local maximums where gear quality is the highest, reinforcing the importance of careful process optimization in industry applications [10]. It should also be noted that while the comparative studies do examine the effects varying one parameter at a time, the dependencies between parameters were not examined closely in the compiled literature.

Experimental Setup

In most of the covered papers, the experimental setup consists of a CNC-controlled hobbing machine, with HSS or carbide steel primarily serving as hob material, and an external MQL system that delivers a fine mist of lubricant on the cutting zone. Work pieces include case-hardening steel, cast carbon steel and chromium alloy steel. During the cutting process, data-acquisition is typically limited to measuring cutting temperature with thermal imaging.

In the case where a dedicated hobbing machine is unavailable, the process can be mimicked by using a flywheel with cutting teeth as the tool and synchronizing its rotation with that of a cylindrical workpiece mounted on a rotary axis. In this setup axial feed imitates the linear feed of a hob.

The authors of these papers use a wide range of measurement devices to collect experimental data. This includes, among other things, a wide range of microscopes, surface roughness devices, thermometers and thermal cameras. These devices are in turn used to evaluate the performance of MQL Systems in gear manufacturing. As it relates to experimental data, it can be noted that the research papers generally do not rely much on real time data. One example of where most studies fall quite short is in thermal readings. The papers that do use thermal readings for hobbing tend to rely on quite rudimentary techniques. One example of such a situation is a study where researchers used a handheld thermal camera manufactured intended for identifying leaks or electrical shorts to measure the cutting surface temperature [3].

Research Gaps

The literature review reveals that there are research gaps regarding real-time measurement of forces and temperature in gear hobbing with MQL. While MQL has been rigorously studied in other processes, its use in hobbing has not been studied in the same detail, especially when it comes to measuring tool and workpiece temperature in real time where only one paper measured temperature and used a rudimentary device to do so [3]. In contrast, taking temperature readings appears to be more common for hobbing and milling, highlighting the need for similar work in hobbing with MQL.

Another research gap in hobbing with MQL is benchmarking of parameters and rigorous comparisons between MQL. Several studies compare various application methods [2,13,14], and while most papers provide detailed accounts of the MQL parameters they used in their experiments, only two studies directly examined how choosing different MQL and hobbing parameters affect the performance of the process [6, 10]. Similarly, only paper examined the effects of varying cutting parameters for hobbing with MQL [8]. Together, these two research gaps potentially lead to weak guidance for future industrial applications, and thus limiting the use of the method [10].

There is a significant literature gap when it comes to skiving with MQL. Given that skiving is a relatively new machining process, it is not surprising that no studies have explored its application with MQL. However, as more companies rapidly adopt skiving due to its advantages over hobbing, understanding its compatibility with MQL becomes increasingly important. This presents a valuable research opportunity to explore and optimize MQL for skiving, potentially unlocking further efficiency and sustainability benefits in the process.

Summary

The literature on applying minimum quantity lubrication in gear machining shows that it holds potential as a sustainable alternative to other application techniques. MQL reduces the use of environmentally harmful cutting fluids while maintaining similar or improved tool wear and cutting speeds, when compared with other application methods. Compared to flood lubrication, MQL shows the potential to enhance gear quality and extend tool life, though its effectiveness is highly dependent on choosing optimal process parameters. The literature also indicates that replacing

traditional mineral-based lubricants with organic or synthetic alternatives can further reduce environmental and health risks without significant compromise in performance.
Despite these advantages, a number of challenges remain for encouraging implementation of MQL in gear machining. There does not exist a comprehensive benchmark of MQL parameters, and gathering real-time clearly remains a research gap. Addressing these gaps could simultaneously improve the understanding of MQL, and provide more reliable guidelines for industrial implementation, thus further encouraging the use of MQL in the gear manufacturing industry.

<u>Test method</u>
The aim of the test method is to enable process optimisation for gear manufacturing in a simple and effective setup with lower amount of work material, higher flexibility and shorter test times compared to testing in highly advanced production machines. Slot milling was chosen as the simple test process most close to actual gear manufacturing and can be performed in a normal 3 axis milling machine. A standard Coromill 162 tool is used and HSS test inserts are manufactured for tests of different tool materials. The work material test pieces are thick-walled tubes. Several different workpiece materials have been tested.
Axial grooves are made in the tubes and the cutting data is varied. After one completed groove (made up of up to 12 passes) the work piece is rotated 7.5 degrees giving 48 grooves in one test piece. In previous tests tool wear type, rate and life has been studied as a function of process data and workpiece material. The test method is easily instrumentalised and measurements of temperature, cutting forces and vibrations have been performed. The influence of cutting fluids and MQL on all these parameters can thus be tested.
The tool holder is shown in Figure 1. One test insert per run is used. The remaining 10 positions are protected using slightly smaller hard metal inserts. Wear on the tools are measured using an Infinite focus SL equipment from Alicona.

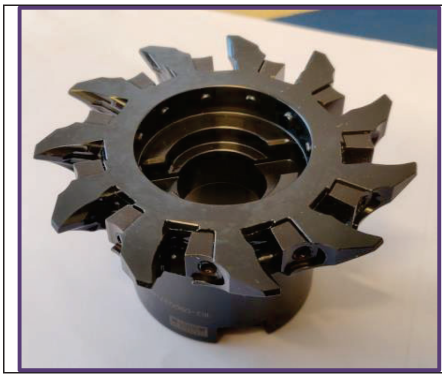
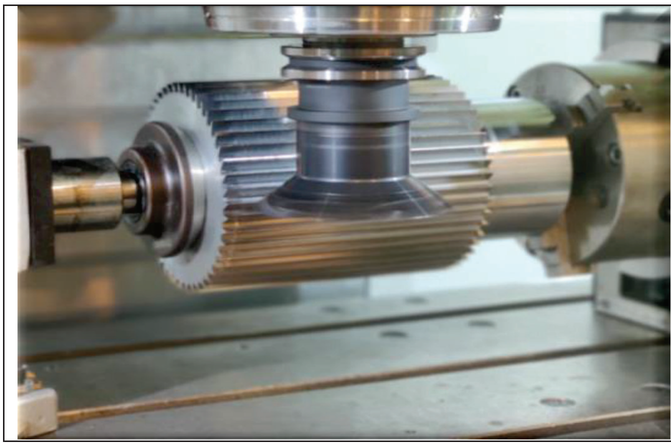
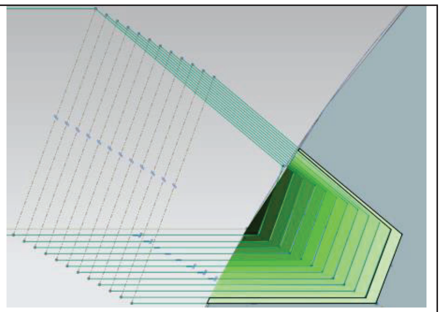


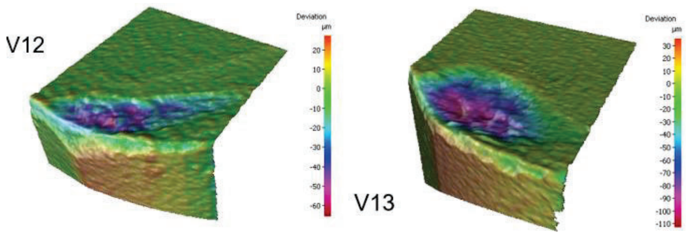
Figure 1 Tool for slot milling with test insert in HSS





Cutting pattern for the different sides of the insert during the 12 passes used to create the groove at 30º infeed angle.

Figure 2 Setup of test and cutting pattern of the tool



A proof-of-concept machining trials were run. During the trials, forces and temperature measurements were also taken. The set-up shall be used in follow-up full study project for machining trials.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	
Be passed on to other advanced technological development projects	X	Will be used as the basis for the follow-up full study project
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

The main dissemination of the results in the project is done through project meetings.

8. Conclusions and future research

The literature study has shown both potential and the research gaps in the topic. The test bed put together during the project provides a good prerequisite for follow up work in the topic. The project results clearly show good potential for MQL in gear cutting processes but this requires dedicated application specific studies and research. With this as the background, an outline for project continuation as a full study, Benchmarking of Sustainable and Circular Gear Machining with Minimum Quantity Lubrication has been presented to the project consortium. The research questions for the follow-up study have been formulated and presented to industry partners.

9. Participating parties and contact persons

	Participant organisation	Main contact
1	KTH Royal Institute of Technology	Project coordinator: Maran Tirougnanassambandamourty
2	Swerim	Jonas Jordberg
3	Ecolubric (Accu-Svenska)	Milan Martinovic
4	Erasteel Kloster AB	Stefan Sundin
5	Ionbond Sweden AB	Jörgen Hansen
6	Leax AB	Oskar Johansson
7	Ovako AB	Patrik Olund
8	Sandvik Coromant AB	Olof Larsson
9	Volvo AB	Jonas Svensson

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