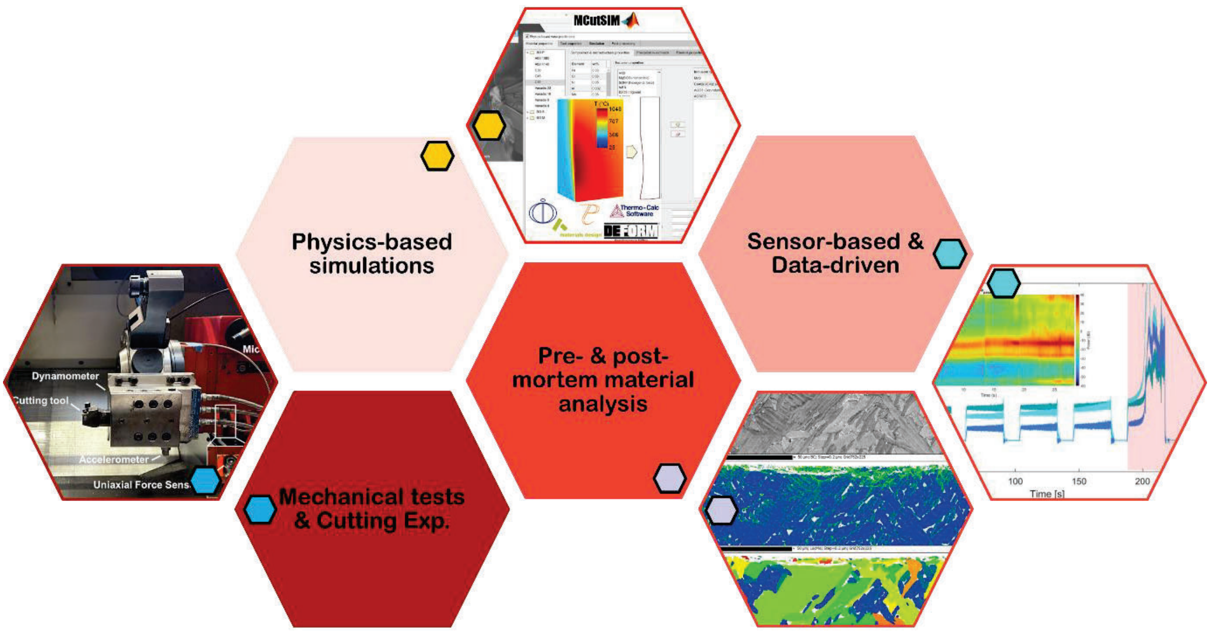
A framework for the physics-based estimation of tool wear in machining process

(WEAR-FRAME)



Project within FFI sustainable production

Authors Amir Malakizadi, Charlie Salame

Date 2025-05-16

Fordonsstrategisk
Forskning och
Innovation

Contents

1. Summary

The project focuses on the development of machinability guides and roadmap realised through a digital twin framework, integrating virtual simulations with empirical machining trials. A central motivation for this work stems from the persistent challenges in securing consistency in production lead time and tool life – primarily due to the batch-to-batch variations in microstructural properties of input materials. To deal with the uncertainties stemming from the batch-to-batch variations, the component manufacturers typically use conservative cutting conditions resulting in economic loss, competitiveness in global market, and often greater energy consumptions and carbon footprints.

To address these challenges, the proposed integrated experimental and simulation-based machinability platform serves as a generalised tool for translating simulated data into actionable insights for production environments. The development of this machinability platform is underpinned by interdisciplinary research encompassing metal cutting fundamentals, advanced material characterisation, and computational materials science. By leveraging this tool, industrial stakeholders are expected to cope with the challenges associated with the batch-to-batch material variation induced along the value-chain. When implemented effectively, this platform significantly minimises the reliance on extensive experimental trial-and-error procedures on the shopfloor. The successful integration of reliable and robust physics-based models and methods with the experimental approaches is thus critical, enabling more efficient process planning while concurrently reducing associated costs and environmental impacts. Furthermore, the ability to predict and optimise machining operations with high fidelity is expected to enhance the quality of critical powertrain and engine components. However, the complex (and in some cases the stochastic) nature of tool wear in machining (e.g. edge chipping and tool breakage) necessitates a parallel development of reliable tool wear monitoring platforms to complement the proposed physics-based framework. To this end, we have developed and implemented two distinct, yet complementary, solutions:

- A state-of-the-art physics-based platform for modelling and simulation of tool wear in machining adaptive to the major changes in microstructural properties of carbon steels and cast irons.
- Reliable and robust tool wear monitoring solutions which are based on various sensors (e.g., accelerometer, force, acoustic emission and microphone) and signal processing approaches adaptable for metal cutting and grinding processes.

Collectively, these implementations demonstrate the potential of the integrated WEAR-FRAME platform to facilitate robust, data-driven decision-making in advanced manufacturing settings. The project has been carried out by a consortium of four industrial partners, AB Volvo, Scania CV AB and Seco Tools AB, Gnosjö Automatsvarvning AB, a national association representing about 90 SMEs in cutting technology: Skärteknikcentrum Sverige (SKTC) and two departments at Chalmers University of Technology: a) Industrial and Materials Science (IMS) as the coordinator and b) Microtechnology and Nanoscience (MC2) as the academic and research partners. The main applicant is Dr. Amir Malakizadi, Dep. of Industrial and Materials Science (IMS), Chalmers University of Technology.

2. Sammanfattning på svenska

Projektet fokuserar på utveckling av en guide till skärbarhet genom att utveckla ett ramverk för en digital tvilling som integrerar virtuella simulationer med empiriska skärandebearbetningstester. En central drivkraft bakom detta arbete är de återkommande utmaningarna att säkerställa konsekvens i produktionens ledtid och verktygslivslängd. Dessa utmaningar härstammar till stor del från variationer i mikrostruktursegenskaper hos insatsmaterial mellan olika batcher. För att hantera osäkerheterna som skapas av batch-till-batch variationerna, använder sig komponenttillverkarna oftast av konservativa skärdata vilket medför ekonomiska förluster, minskad global konkurrenskraft samt i många fall ökande energikonsumtion och miljöpåverkan.

För att möta dessa utmaningar kan den föreslagna integrerade experimentella och simuleringsbaserade skärbarhetsplattformen tjäna som ett generaliserat verktyg för att översätta simulerade data till användbara insikter för produktionsmiljöer. Utvecklingen av denna skärbarhetsplattform bygger på tvärvetenskaplig forskning som omfattar grundläggande metallerbearbetning, avancerad materialkaraktärisering och beräkningsbaserad materialvetenskap. Genom att utnyttja detta verktyg förväntas industrins aktörer kunna hantera de utmaningar som materialvariationer mellan batcher medför längs hela värdekedjan. När plattformen implementeras till full effekt, minimeras beroendet av omfattande experimentella trial-and-error-processer på verkstadsgolvet betydligt. Den framgångsrika integrationen av pålitliga och robusta fysikbaserade modeller och metoder med experimentella angreppssätt är därför avgörande, då detta möjliggör effektivare processplanering samtidigt som kostnader och miljöpåverkan reduceras. Vidare förväntas möjligheten att förutsäga och optimera bearbetningsoperationer med hög noggrannhet förbättra kvaliteten på kritiska komponenter för drivlinor och motorer. Dock kräver den komplexa – och i vissa fall stokastiska – naturen av verktygsförslitning vid bearbetning (t.ex. flisning av egg och verktygsbrott) en parallell utveckling av pålitliga system för övervakning av verktygsförslitning som kompletterar det föreslagna fysikbaserade ramverket.

Med denna bakgrund har vi utvecklat och implementerat två distinkt skilda men kompletterande lösningar:

- En, i framkant, fysikbaserad plattform för modellering och simulering av verktygsförslitning vid bearbetning, anpassad för de tydligaste förändringarna i mikrostruktursegenskaper för kolstål och gjutjärn.
- Pålitliga och robusta system för övervakning av verktygsförslitning baserade på olika sensorer (t.ex. accelerometer, kraft, akustisk emission och mikrofon) samt signalbehandlingsmetoder, anpassade för skärande och slipande processer.

Tillsammans visar dessa implementationer på potentialen som den integrerade WEAR-FRAME-plattformen har att möjliggöra robust, datadriven beslutsfattning i avancerade tillverkningsmiljöer. Projektet har genomförts av ett konsortium bestående av fyra industriella partner: AB Volvo, Scania CV AB, Seco Tools AB, Gnosjö Automatsvarvning AB, en nationell branschförening som representerar cirka 90 små och medelstora företag inom skärteknik — Skärteknikcentrum Sverige (SKTC) — samt två institutioner vid Chalmers tekniska högskola: a) Institutionen för industri- och materialvetenskap (IMS), som koordinator, och b) Institutionen för mikro- och nanoteknologi (MC2), som akademiska forskningspartners. Huvudansvarig sökande är Dr. Amir Malakizadi vid IMS, Chalmers tekniska högskola.

3. Background

In today's manufacturing environment, sustainable machining processes requires robust predictive models and simulation tools that can effectively manage "batch-to-batch" material variations in production lines. Even when materials meet standard specifications, their properties can still fluctuate, creating significant challenges. These variations make it difficult to optimise machining conditions and to accurately schedule tool changes, which in turn can negatively impact production efficiency. The analysis of the data collected [1] on the global use of cutting tools over a one-year period show that in the United States alone 1) incorrect cutting tools were used in production lines in more than 50% of the cases, 2) the tools were not used at the optimum cutting conditions in 42% of applications, and 3) the tools were changed before the end of tool life in 62% of applications. This suboptimal cutting tool utilisation is largely due to 1) the limitations in the presently available empirical methods for tool life prediction and process planning and 2) the inconsistencies in the workpiece material properties – known as batch-to-batch material variation effects – which hinder the full exploitation of recommended tooling solutions.

By improving the predictability of tool change intervals, manufacturers can increase productive machining time, leading to better Overall Equipment Effectiveness (OEE) – a key metric in lean and sustainable manufacturing practices. WEAR-FRAME aimed to advance the understanding of the role of batch-to-batch material variations on the tool performance during machining and grinding processes. One of its key outcomes is the development of a platform that models the evolution of flank and crater wear over machining time. This platform is designed to account for variations in material properties that arise, for example, from the steelmaking process and subsequent operations like forging and heat treatment. To date, the recommendations by the leading tool manufacturers such as Seco Tools cannot account for the complex and ever-changing batch-to-batch material variation effects. This is because the batch variations associated with the non-metallic inclusions have only minor impacts on the mechanical properties like macro-hardness and tensile properties, which are traditionally taken as material property indicators for machinability assessment and tool life recommendation. Our analysis of research published in literature also indicated a lack of systematic investigation on the role of inclusions and other microstructural properties on tool wear in machining. Obviously, without a thorough understanding of the overlapping and complex mechanisms involved, there are no comprehensive modelling platform currently available for simulating tool wear in machining that is adaptive to the microstructural changes. We can however name major attempts in scientific communities for developing the integrated wear models. Kramer and his co-workers [2-4] were among the first to propose a unified physics-based model for evaluating the effectiveness of various coated tools for machining steels and titanium alloys, taking into account the role of abrasion and dissolution wear mechanisms. This approach has been extended in recent years by others [5, 6]. Various Finite Element (FE)-based approaches have also been proposed in the recent years, facilitating the evaluation of tool performance in different machining operations. For example, an investigation by Malakizadi et al. [7] has shown that the wear measurements at only one cutting condition would suffice to predict the dissolution/diffusion dominated tool wear progression at a wide range of cutting conditions, thanks to reliable thermodynamic predictions using CALPHAD approach combined with the validated FE predictions of tool-workpiece interface temperature. Different teams in France [8, 9], Italy [10] and Germany [11-14] proposed FE-based methodologies for wear prediction in metal cutting. Nevertheless, the aforementioned models and methods largely rely on costly and inefficient FE simulations to obtain the thermo-mechanical loads on the tool surfaces necessary for the wear predictions. Resolving this challenge was one the major development in WEAR-FRAME leading to the advent of robust hybrid-FE approach for prediction of temperature and stress distribution on the tool surface. Despite these improvements, the complexity of tool wear mechanisms necessitates the development of monitoring solutions in parallel – a direction we also pursued in this project, with significant implications for industrial application as a complementary approach.

4. Purpose, research questions and method

The primary aim of this project has been to develop a comprehensive platform for machinability assessment capable of capturing the effect of batch-to-batch material variations based on a combination of virtual simulations and experimental studies for selected machining operations. This work integrates interdisciplinary research spanning metal cutting, advanced characterisation, and multi-scale modelling and simulations. The goal of this platform is to empower industrial end-users to significantly reduce lead times associated with the introduction of new materials, machining processes, and the management of material variation in production. The project addresses the following critical research questions:

- How do the batch-to-batch material variations influence the tool wear in machining and what are the underlying tribological mechanisms when machining carbon steels and cast irons?
- How can the efficiency and reliability of the models and methods be improved for wear prediction in cutting?
- What steps shall be taken to generate the reliable experimental datasets for wear predictions?
- What steps shall be taken to include the history of the material processing (e.g., forging and heat treatment) into considerations for wear predictions during machining?
- What steps shall be taken to develop automated approach to quantify the major microstructural variations with a large impact on tool wear in machining?
- Can reliable tool wear monitoring solutions be developed to bridge the gap where physics-based approaches fall short in accurately predicting tool wear?

To address these questions, we executed the research & development activities through five WPs.

4.1. WP1: Industrial data collection and analytics

WP1 aided the industry 4.0-driven analytics to support the project by identifying the requirements of each use-case and understanding the microstructural aspects that can be measured and modelled for evaluating machinability & grindability. Industrial data collection & analytics on material variations (e.g. chemical composition, microstructure and manufacturing history), process data (e.g. cutting data and tool change intervals) and machine outputs (e.g. through suitable portable or integrated sensor solutions) are measured and monitored in production lines (OEMs: Volvo Group, Scania and SME: Gnosjö Automatsvarvning). The goal was to find patterns in collected data using supervised & unsupervised Machine Learning (ML) methods which could explain the batch-to-batch variations in machinability of specific material grades (e.g. in alloying elements, manufacturing history). These datasets also paved the path towards taking more industrially relevant developments for tool failure prediction and detection (classification: failed/not failed tools) in shopfloor. The goal for the data analysis was to provide a structure for development of physics-based machinability & grindability assessment (wear) models sensitive enough to batch variation effects, along with/prior to the fundamental developments in WP4. This WP was led by Seco Tools– Adj. Professor Rachid M’Saoubi.

4.2. WP2: Experimental machining tests

WP2 dealt with lab-scale machining and grinding experiments. The experiments are divided in four scenarios, each one focusing on a particular steel or cast iron grade and machining process at different levels of applied research and small-scale prototypes in lab environment (TRL3-4). The tasks include the cutting force measurements and temperature measurements using thermal imaging (IR Thermography). The obtained data were used to provide input for modelling of cutting processes and for calibration & validation of the physics-based wear models and integrated software-package in WP4. In parallel, sensor-based tool conditioning monitoring methods are developed for detecting the state of the tool (and wheel) in cutting and grinding using vibration, acoustic emission, sound pressure and force signals. This WP is led by Chalmers IMS – Professor Peter Krajnik.

4.3. WP3: Material characterisation

WP3 is concerned with the characterisation of the work material prior to tool life tests and worn tools after machining tests in WP2. This WP also supports the data analytics of WP1 by characterising different steel batches fed to production lines and worn tools taken from end-users. Optical and scanning electron microscopy (OM/SEM) and Energy-dispersive X-ray spectroscopy (EDS) by AZtecSteel® software are used to determine the type, size, amount and distribution of the non-metallic inclusions, carbide and nitrides and other microstructural features within the selected materials for each case study. The worn and unworn tool surfaces were analysed using advanced techniques, such as SEM/EDS, EBSD and AES to understand the underlying wear mechanisms during machining. These characterisation outputs provided essential inputs for development and implementation of physics-based wear models and machinability & grindability assessment in WP4. This WP is led by Chalmers IMS – Professor Uta Klement.

4.4. WP4: Modelling & simulation – software integration

WP4 dealt with simulation and software integration using the “material” inputs from DFT calculations (properties of non-metallic inclusions) and CALPHAD models (hardness and solubility) estimations, prediction of the thermo-mechanical loads on the cutting edge by means of a Hybrid-FEM, mechanistic and semi-analytic approaches. A MATLAB-based platform is developed to predict the tool wear response and for setting guidelines for machinability and grindability assessments. A focus was placed on implementation of a hybrid approach (FEM/mechanistic/semi-analytic) for cutting temperature predictions and more reliable cutting force predictions with less computational time. Meta models and supervised learning methodologies combined with FE modelling and analytic/mechanistic approaches were developed for a more robust and cost-effective wear predictions. This WP is led by Chalmers IMS – Dr. Amir Malakizadi.

4.5. WP5: Demonstration

WP5 dealt with demonstration & validation of the predictions and recommended guidelines of the physics-based integrated software-package i.e. tool life estimations including the batch variation effects & machinability & grindability assessments in lab-environment. Materials from a given batch were sorted and fed to the production lines, providing a baseline for assessing the applicability of developed methods and solutions. The material data for the wear estimations – specific to the given batches – were provided by Chalmers (Characterisation, CALPHAD dataset and inclusion properties). Further, the successes of tool condition monitoring algorithms were tested under industrial environment. This WP is led by Scania, Dr. Martin Selin.

5. Objective

The primary objective of the project was to develop an integrated methodology that combines simulation-based (specifically, physics-based) and experimental approaches for evaluating the machinability and grindability of carbon steels, with a particular focus on tool life. This methodology aims to support informed decision-making in two critical areas: (1) the procurement of input materials, and (2) the management of batch-to-batch material variability resulting from inherent differences in steelmaking processes and/or subsequent thermo-mechanical treatments within the production line. The envisioned integrated approach was designed to be robust, reliable, and adaptable to variations in both input materials and the tooling used in machining operations. During the course of our investigations in Work Package 1: Industrial Data Collection and Analytics, it was observed that in several targeted operations, stochastic wear mechanisms – particularly cutting-edge chipping – were the predominant tool wear types. This insight provided new motivation to expand the project scope by developing sensor-based tool condition monitoring solutions to complement the existing WEAR-FRAME platform, which originally concentrated on physics-based modelling techniques. In addition, Volvo AB introduced a new use case involving the machining of nodular cast irons, thereby broadening the scope of knowledge development within the project. The newly developed sensor-based monitoring solutions contribute to a significant reduction in scrap rates by enabling real-time detection and management of complex, stochastic wear phenomena. On the other hand, the physics-based models facilitate a deeper understanding of how the microstructural properties of individual material batches influence tool wear progression during machining. Together, these advancements support improved process control and increased productivity by enhancing the adaptability of machining operations to material and tool variability.

6. Results and deliverables

6.1. WP1: Industrial data collection and analytics

The data analytics have been done primarily on the data collected from material certificates to see, whether it is possible to group the materials with respect to the variations in their chemical composition and also their thermo-mechanical history, e.g., the variations may be introduced during forging process. In this WP, the focus was placed on C38 micro-alloyed steels being used for manufacturing crankshafts at Scania. The analysis of the material certificates showed that C38 steels are provided by four material suppliers to two forging companies (referred to A and B). The forging companies were provided with different batches of steel from these four material suppliers over the investigation period. Artificial Neural Network (ANN) algorithm with 8 hidden layers was then used for clustering the data and pattern recognition. 60% of data was used as the training dataset, 20% as validation dataset and 20% as test dataset. We have confirmed the following:

- It is possible to determine the forging company based on the chemical composition of input materials in 99% of the cases. There are differences in steels supplied to the forging companies A and B.
- It is possible to determine the steel company based on the chemical composition of input materials in 99% of the cases. There are differences in steel compositions specific to the steel mill.
- It is possible to determine the steel company based on the type/amount of oxide micro-inclusions in 98% of the cases. There are differences oxide type/amounts specific to the steel mill.

- It is possible to determine the steel company based on the hardenability data according to DIN EN ISO 642 i.e. hardness values at various length of Jominy bar in 96% of the cases. There are differences in steel compositions specific to the steel mill, or grain size, that leads to differences in hardenability of steels.

An in-depth analysis of the material certificates showed that:

- Up to 17% variation in yield strength (Rp0.2)
- Up to 15% variation in tensile strength (Rm)
- Variations in hardness
- Variations in oxide type/amount according to ASTM E45
- Variations in amount of carbo-nitride former elements

This agrees with our qualitative thermodynamics and kinetic calculations using ThermoCalc® and TC-Prisma®. We have performed thermodynamic and kinetic simulations to determine the variations in the amount of (V,Ti)(C,N) precipitates for 20 randomly selected batches of C38 steel with varied grain size, strength and hardness as well as strain hardening responses. These factors can all influence the machinability of this grade of steel, as they dictate the amount of heat generated in the cutting zone [15]. Similarly, the type, size and volume fraction of inclusions can have a large impact on tool wear when machining various grades of steels [16, 17]. Hence, in WP4, we have developed a modelling framework to simulate the impact of these variations on the machinability of plain carbon and medium carbon micro-alloyed steels as well as the cast irons. This approach can be extended to other material groups upon interest.

Additionally, worn cutting inserts supplied by Scania's production line were examined to identify the predominant wear mechanisms occurring during the specified machining operation. Inspection of these specimens revealed multiple wear patterns, with chipping and fracture representing the principal failure modes (Fig. 1). Such failures are of stochastic nature and principally attributable to chip jamming and variations in depth of cut caused by forging tolerances in the workpiece. Considering the inherently unpredictable nature of these tool failures, the development of a robust, online tool-wear monitoring system – employing sensors analogous to those evaluated herein (WP2) – was deemed essential as a complement to the physics-based WEAR-FRAME methodology. Implementation of this monitoring system would enable real-time detection of emerging failures and timely notification for tool changes, thereby enhancing the resilience of the production line.

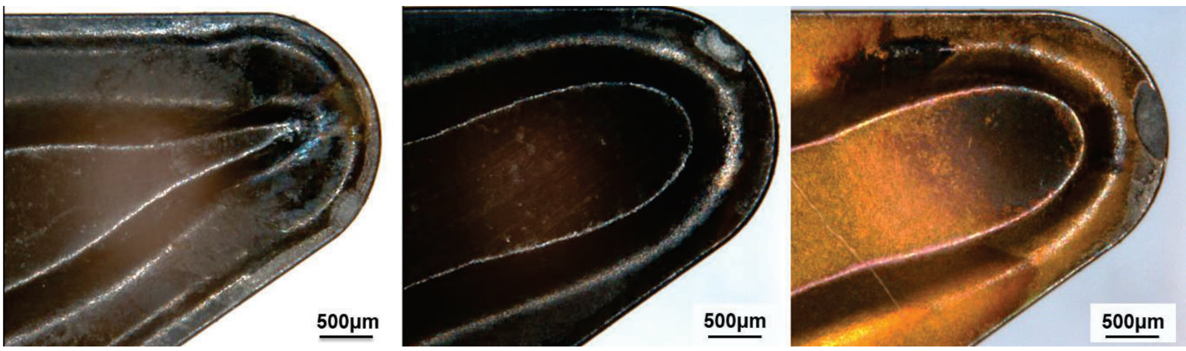


Fig. 1. Inserts of different grades were collected from the production line and analysed to reveal the dominant wear type and mechanism.

6.2. WP2: Experimental machining tests

Related to WP2, numerous machining experiments have been conducted, presented herein according to the workpiece materials they were conducted on. These experiments allowed us to confirm the role of batch-to-batch variations – in agreement with the data analytics performed in WP1 – and generate input for developing physics-based models and sensor-based tool condition monitoring solutions for industrial implementation.

Machinability of C38 Steel (Scania)

To gain a better understanding of how microstructural batch variations correlate with differences in machinability, face turning operations of two different batches of C38 steel were performed on the EMCO 365 turning lathe, mounted with a dynamometer for three-axis force measurements (shown in Fig. 2). For this material, two sets of tests were conducted: tool life tests and constant spiral cutting length tests, both with the same tool type (DCMT11T304-M3 with grade TP2501).

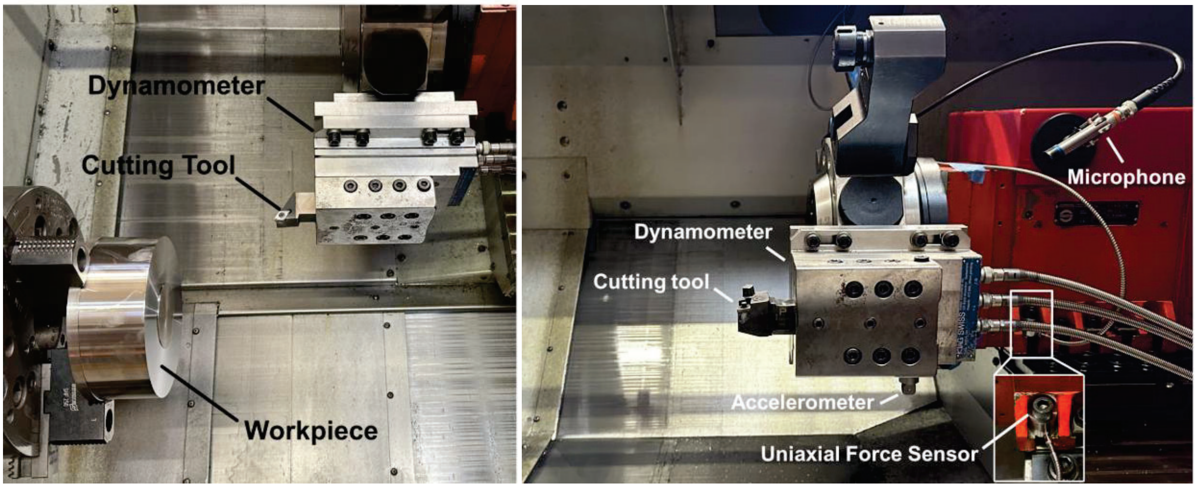


Fig. 2. Experimental setup used for the facing SCL-tests of C38 steel (left), the same set-up equipped with various sensors to for tool wear monitoring (right).

First, the tool life tests were conducted to evaluate and compare how differences in material properties between the batches affect the overall tool life during machining. The cutting conditions were varied in terms of cutting speed (300-500 m/min) and feed (0.10-0.20 mm/rev) in order to obtain a large set of tool wear data in the industrially relevant cutting condition window. As evident in Fig. 3, for all the cutting conditions examined, machining Batch A resulted in a shorter tool life compared to Batch B [18].

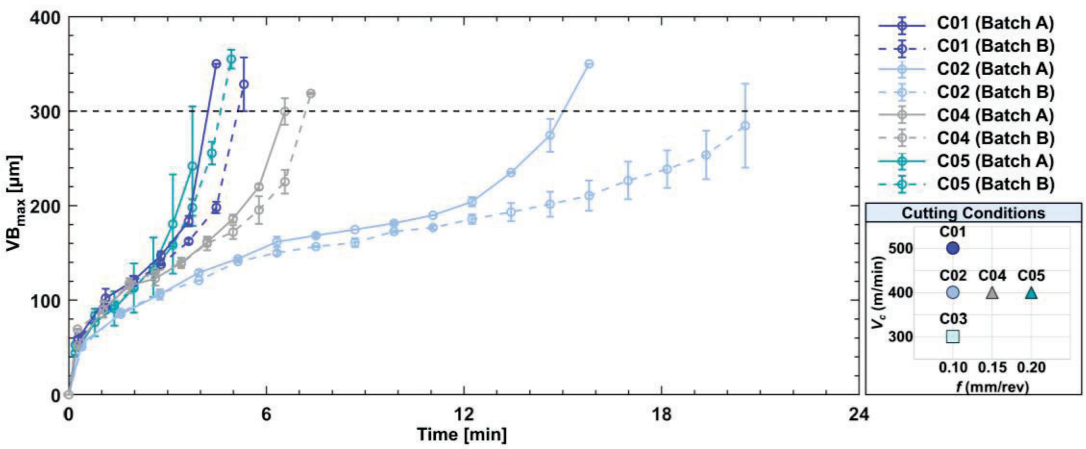


Fig. 3. Flank wear width (VB_{max}) progression for batches A and B at the different cutting conditions [18].

Second, the constant spiral cutting length tests allowed a fair comparison of the wear states after a constant machining length of 1200 m for each insert. These SCL-tests would allow a more in-depth analysis of the active wear mechanisms compared to the tool life tests. For these tests, the feed and depth of cut were kept constant at 0.1 mm/rev and 1 mm respectively, while the cutting speed was varied at 300, 400 and 500 m/min. For statistical relevancy, three repetitions of every cutting test were conducted.

Similar to the tool life tests, it is evident that, after machining the same spiral cutting length (1200 m), the tools used on Batch A experienced significantly more wear than those used on Batch B, as shown in Fig. 4. The maximum flank wear (VB_{max}) for insert 3A was 146 µm, while insert 3B showed 29% less wear with a VB_{max} of 105 µm. Similarly, insert 2A exhibited a maximum flank wear of 172 µm, whereas insert 2B had 18% less wear at 141 µm for the same cutting length. Lastly, insert 1A had a maximum flank wear of 315 µm compared to 201 µm for insert 1B. Additionally, the spalling observed on the rake face of insert 1A suggests the presence of plastic deformation wear at this cutting condition, which was not observed in insert 1B. Further, EDS elemental maps confirm the presence of adhered workpiece material in higher concentrations on the rake and flank surfaces of the inserts used for Batch A compared to Batch B.

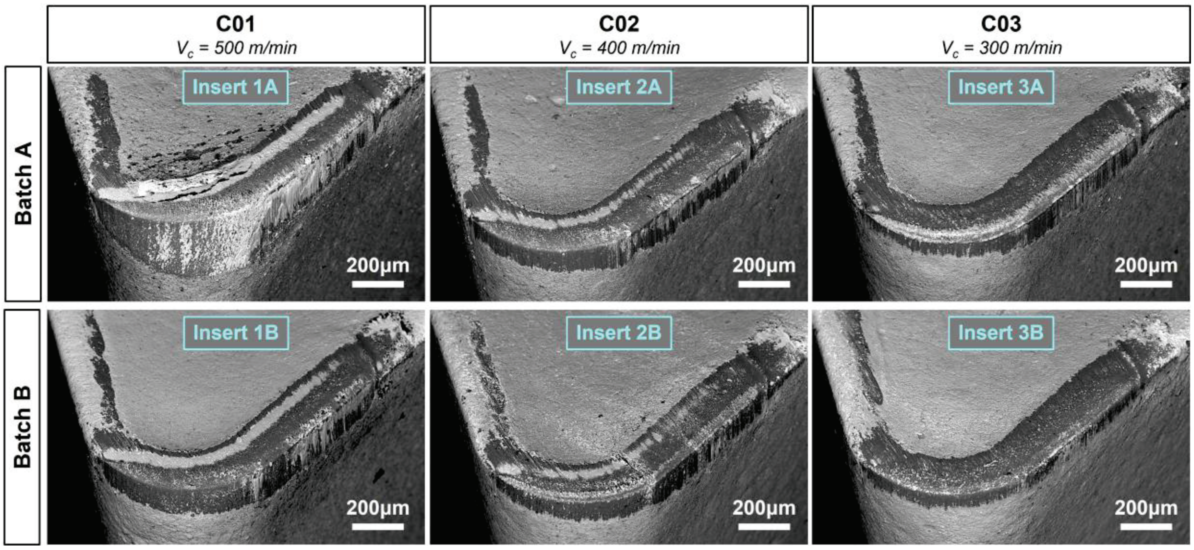


Fig. 4. SEM micrographs showing the worn tools after SCL of 1200 m machining both Batch A and B under the different cutting conditions (obtained using BSE at an acceleration voltage of 20 kV) [18].

Machinability of V2158 Steel (Volvo)

Similar to C38 steel, the material supplied by Volvo – V2158 steel – was also supplied in two batches. Thus, turning tests were conducted for a constant spiral cutting length of 1200 m to compare the tool wear response of these two batches. In this case, longitudinal turning was conducted instead of facing using DCMT11T304-M3 with TP2501 grade. The cutting conditions investigated were the same as those for C38 – 300, 400 and 500 m/min cutting speeds at a constant feed (0.1 mm/rev) and depth of cut (1 mm). Two repetitions of each cutting condition were conducted to ensure statistical relevance. Fig. 5 presents the difference obtained in maximum flank wear for both batches A and B. As evident, Batch A exhibits less flank wear compared to Batch B for all investigated cutting conditions.

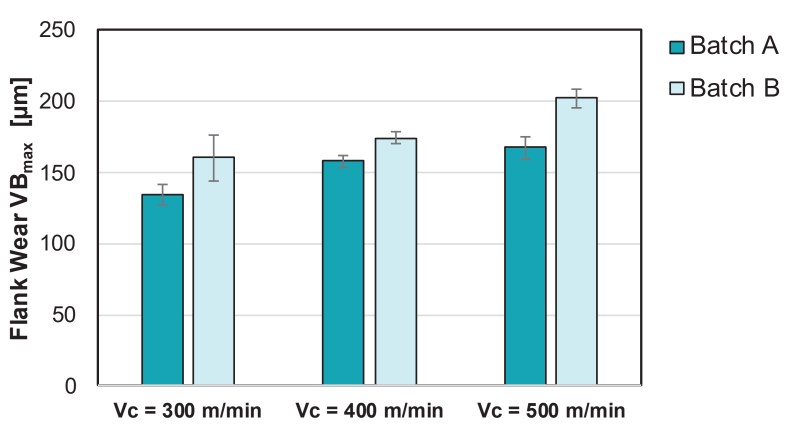


Fig. 5. Comparison of maximum flank wear for the different cutting conditions of different batches of V2158.

A dedicated analysis of the worn tools was also conducted to reveal the active wear mechanisms for each batch. The inserts used for V_c = 500 m/min are presented in Fig. 6, where it is evident that the wear for Batch A is less advanced than that for Batch B. While the tungsten carbide substrate is exposed in both inserts, the area of exposed substrate in Batch B is notable higher than that in Batch A. Similarly, larger areas of the titanium carbonitride coating (light grey) are exposed in the cutting zone of Batch B compared to Batch A, indicating more advanced tool wear in B. These trends hold for all investigated cutting conditions, emphasising the enhanced machinability of Batch B compared to A.

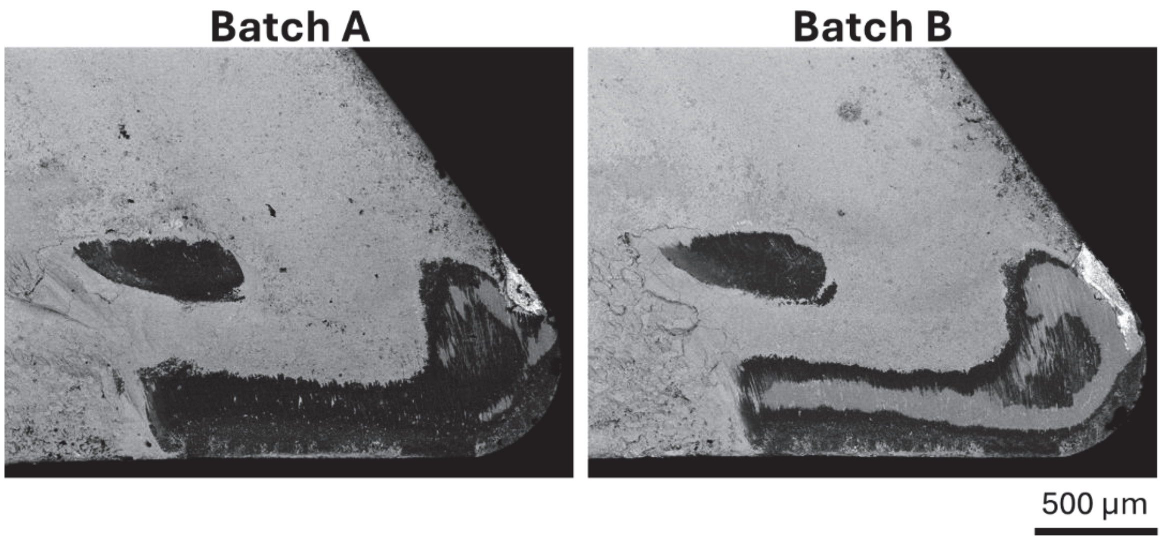


Fig. 6. Comparison of cutting inserts used for Batch A and B for Vc = 500 m/min

Machinability of 100Cr6 Steel (Gnosjö)

The bearing steel 100Cr6 was provided in three batches: two nominally-identical batches of high sulphur content (Batches A and B) and one of lower sulphur content (Batch C). Additional to the workpiece variation, this part of the research introduced a variation on the tool side as well by utilising five different tools. The tools all possessed the same tungsten carbide substrate but were either (1) uncoated or coated with (2) coarse-grained TiCN, (3) fine-grained TiCN, (4) TiCN + Al_2O_3 or (5) pure Al_2O_3. These tools were varied in order to gain insight into the different tool-workpiece interactions present during the machining of 100Cr6. Constant spiral cutting length tests were conducted in order to compare the flank wear, as presented in Fig. 7 for the cutting condition of V_c = 200 m/min and f = 0.1 mm/rev. As is evident, the tool wear response varies significantly not only between different batches, but also between different tools.

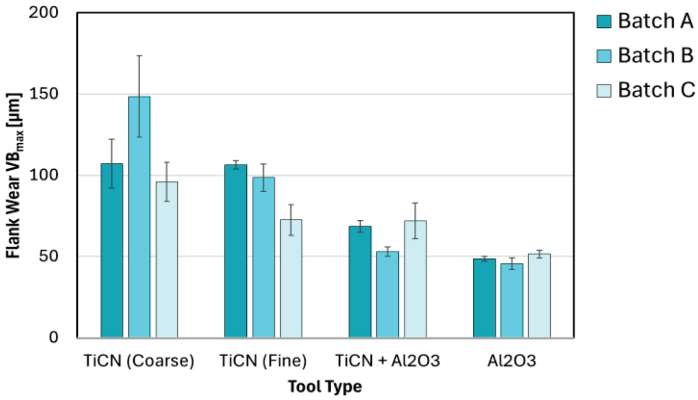


Fig. 7. Comparison of obtained flank wear VBmax for the different cutting tools and material batches at Vc = 200 m/min and f = 0.1 mm/rev.

The analysis of the worn tools has been conducted to reveal the active wear mechanisms and interaction between the workpiece and tools. A dedicated analysis was conducted on the alumina-coated tools, including SEM, EDS and AES analysis. The rake and flank SEM images of the worn tools used for V_c = 200 m/min are presented in Fig. 8. In addition, a complementary series of cutting tests was conducted at Seco Tools, where cutting temperatures in the cutting zones were measured during orthogonal turning with the different tool-workpiece combinations. These measured cutting temperatures provide insight into the thermal conditions present at the cutting zone for each of these workpiece-tool combinations. This is presented in WP5.

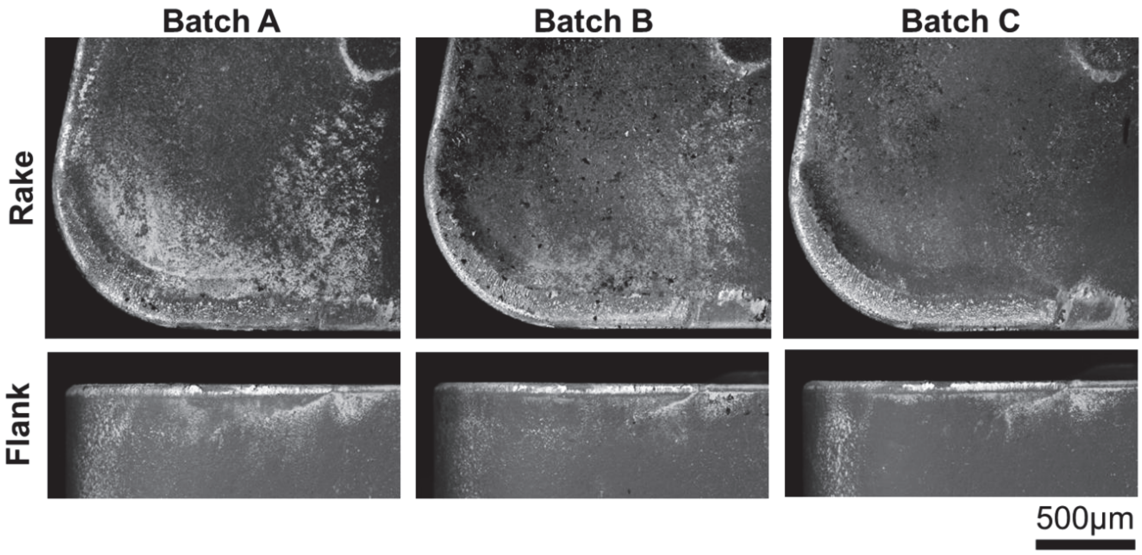


Fig. 8. SEM images of the alumina-coated tools used for batches A, B and C (Vc = 200 m/min)

Orthogonal turning tests were conducted at Seco Tools AB, Fagersta, using a combination of three variations of 100Cr6 and the five different tool grades named above. During the cutting tests, an infrared (IR) camera was used to obtain thermal images of the cutting zone to determine the temperature of the tool. The purpose of these tests was on one hand to provide insight into the thermomechanical loads experienced by each tool-batch combination, thus providing further clarity into the active wear mechanisms during the machining process and potential insight into the difference between the three batches. On the other hand, these temperature profiles were used to validate the temperature models developed in this work as discussed in WP4. Fig. 9 shows the raw thermal image obtained from the IR camera and the extracted tool temperature profile using MATLAB. Specifically, the highlighted points on the tool profile were used for the validation of the temperature models.

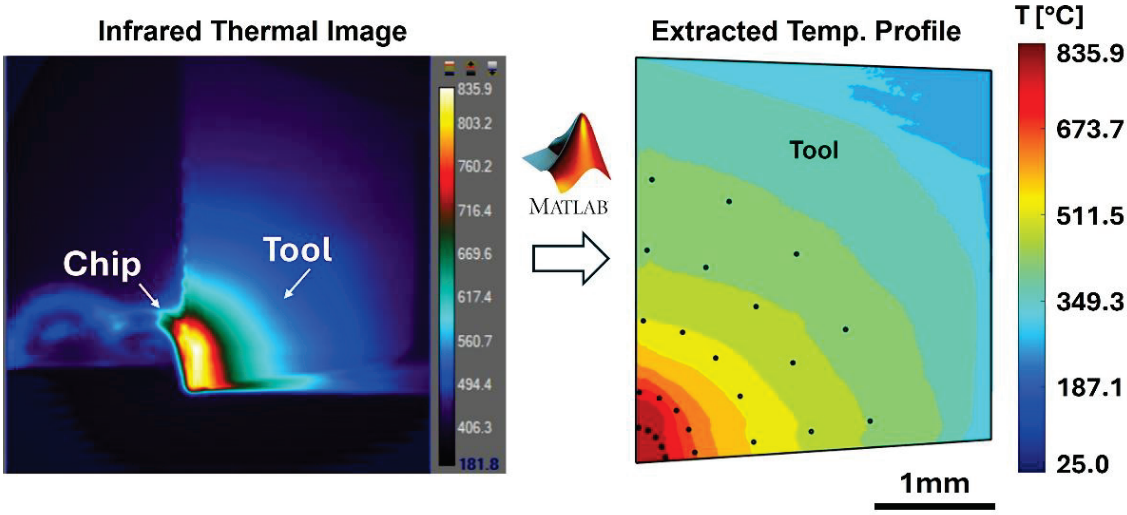


Fig. 9. Extraction of temperature profile of the tool from the thermal image obtained during orthogonal turning.

Machinability of Nodular Graphite Iron (NGI)

A batch of nodular graphite iron (NGI) was supplied by Volvo as cast tubes. The tubes included three grooves present along the length of the workpiece, with the purpose of introducing intermittency during turning to more closely represent the actual cutting conditions in production lines. Face turning tests were run in the EMCO-CNC turning machine under dry cutting conditions. This work also investigated the use of various cutting tools to compare their robustness in machining a given batch of NGI. The aim of this part of the work was to improve the understanding of the machinability of these types of materials and further investigate the batch-dependent material properties and characteristics that could influence the active wear mechanisms when machining these grades. The tested tools were: two grades of coated cemented carbide, four grades of ceramic tools (Cer), and two grades of cubic boron nitride (CBN). The feed and depth of cut were kept constant for all tests at 0.25 mm/rev and 2 mm respectively, while the cutting speed was varied. The measured flank wear at cutting speed 650 m/min for the ceramic and CBN tools after a spiral cutting length of 1100m can be seen in Fig. 10. As evident, the tools exhibit widely differing tool wear for the same conditions and workpiece material. For instance, ceramic insert D exhibits higher wear at an SCL of 550 m than ceramic B does at an SCL of 1100 m. This highlights the importance of specific cutting tool properties in determining the machinability of a specific material.

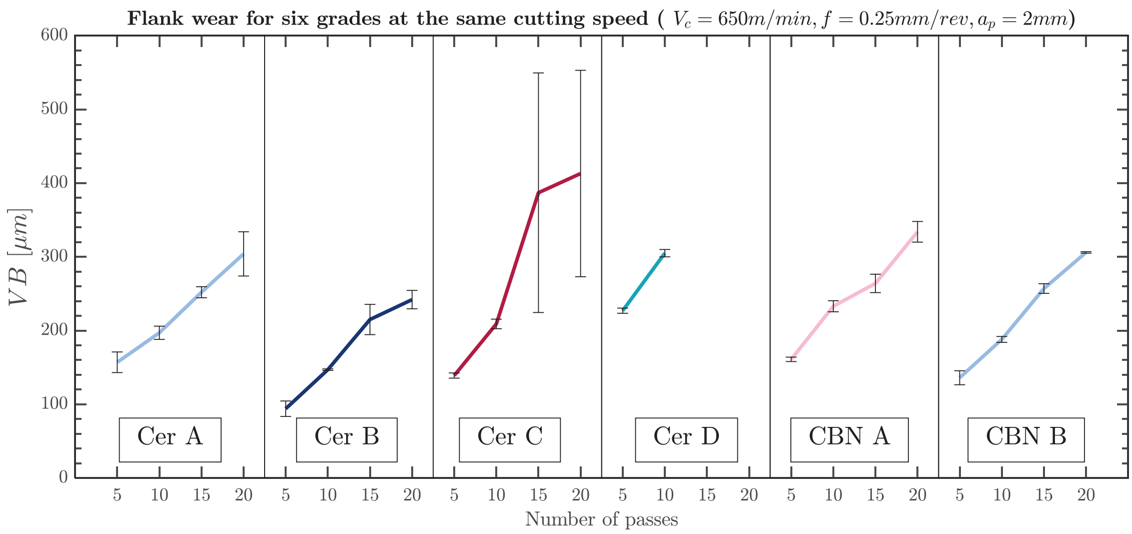


Fig. 10. Flank wear width at cutting speed 650 m/min for six different tool grades.

Sensor-based monitoring in turning in lab environment

The monitoring of tool wear in a production line is essential to optimising its productivity. The success of such monitoring depends on a plethora of factors, including but not limited to the types of sensors used, their placement within the machinery, as well as the post-processing algorithms applied. To evaluate the effectiveness of various sensors and post-processing algorithms, controlled experiments were conducted in a lab environment at Chalmers under this WP, using a CNC lathe for dry longitudinal turning of a case-hardening steel [19]. These tests involved capturing data from a 3-axis dynamometer, 3-axis accelerometer, and microphone to record machining conditions and assess the sensor's robustness in detecting tool wear using different post-processing algorithms. The cutting speed was fixed at 150 m/min with a depth of cut of 1 mm, while the feed rate was varied at 0.20, 0.25, and 0.30 mm/rev. Further, the used tools were in various wear conditions, including new tools and tools with moderate (VB = 220 ± 20 μm) and more severe (VB = 340 ± 20 μm) flank wear.

A sensitivity study was conducted on the placement of accelerometers and microphones within turning CNC machines. It was determined that the accelerometer must be mounted as close as possible to the cutting zone in order to capture vibrations, while ensuring its protection from the high heat and aggressive chip flow in the cutting zone. In contrast, since microphones capture sound without direct physical contact, they are non-invasive and could be placed at a distance from the machining area without interfering with the process.

After running the cutting tests, the signals were analysed using the Hilbert-Huang Transform and the Discrete Wavelet Transform. The signals from the accelerometer and microphone were decomposed into wavelets or intrinsic mode functions (IMFs) to extract relevant features such as root-mean-square (RMS) values and instantaneous energy, which were then used to distinguish ranges between worn and sharp tools, as shown in **Error! Reference source not found.**. This study found that the identification of worn tools varied depending on the sensor and signal processing technique used. Cutting force measurements successfully identified tool wear through increases in cutting, feed, and passive forces, especially as wear progressed. However, while the DWT method showed limited success in detecting worn tools from acceleration and sound signals, the HHT method performed significantly better. The HHT analysis of the microphone data identified worn tools with a success rate of up to 78% using the 3rd IMF function, and the acceleration data (particularly in the passive direction) also showed promise, with a success rate of up to 100% in certain cases.

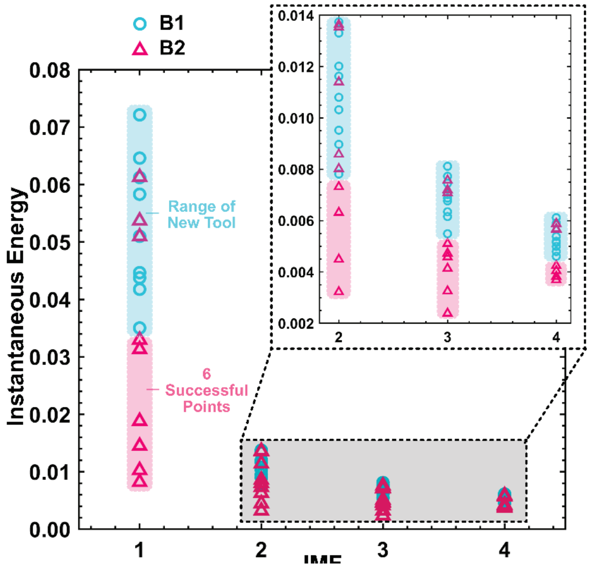


Fig. 11. HHT analysis of microphone signals for cutting conditions B1 (new tool) and B2 (worn tool) [19].

Grinding tests in lab environment

Similar to turning processes, grinding processes in production lines could benefit greatly from wear monitoring, which, if successful, would allow the optimisation of wheel-dressing strategies and thus enhance productivity and improve workpiece surface quality. Additionally, differences in batch grindability may lead to variations in wheel wear progression which would be detected by the appropriate sensors. In order to investigate wheel wear monitoring in grinding, some grinding tests were conducted at Chalmers, which assessed the capability of dynamometers (forces) and acoustic emission sensors. For this purpose, two sets of grinding tests were run: first, no-dress tests to monitor wheel wear progression for two different batches of C38, and second, grindability tests to investigate and evaluate the sensors' capabilities on a larger test matrix, as described below.

No-Dress Tests

The focus of this no-dress test was to determine potential force and acoustic emission features that are sensitive to wheel wear during grinding. For this purpose, workpieces from batch A (and B) were ground using a sharp grinding wheel for a large number of passes, allowing the wheel to wear without intermittent dressing. AE signals and grinding forces were recorded at various intervals S1 to S5 during the grinding process to capture any differences in the signals as the wheel wore. Each segment S1 to S5 included 3 seconds of active grinding. The experimental grinding setup is shown in Fig. 11(a), while Fig. 11(b) shows the force measurements for Batch A during the grinding, with sections S1-S5 highlighting the approximate locations where the AE signals were extracted and processed. As evident, the normal force exhibits a slight increase with wheel wear progression, while the tangential force seems to remain stable all along the grinding.

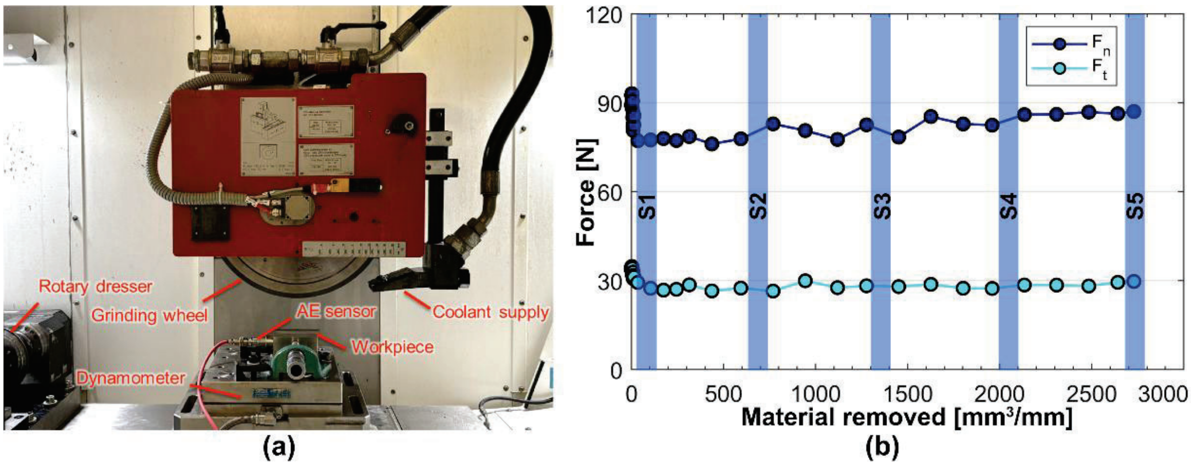


Fig. 11. (a) Grinding setup and (b) normal and tangential force measurements during grinding showing sections S1-S5 where the AE signals were extracted (section widths not to scale)

The recorded AE signals were then processed using frequency-domain techniques such as Fast-Fourier (FFT) and frequency-time-domain techniques such as Hilbert-Huang Transforms (HHT) analysis. The progression of the instantaneous energy of each Intrinsic Mode Function (IMF) generated by the HHT method are shown in **Error! Reference source not found.**. Evidently, the instantaneous energy of each IMF(1-4) exhibits an increase as the wheel wear progresses. In fact, when analysing the frequency spectrum of these IMFs, it was further shown that the IMF mean

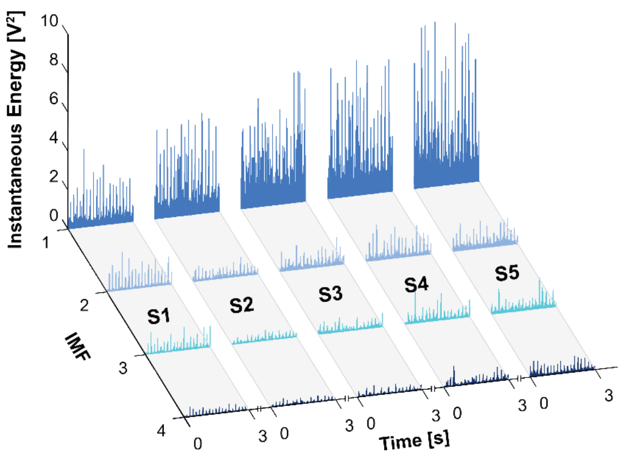


Fig. 13. Comparison of the HHT mean instantaneous energy of the various IMF functions of the AE signals for batch A for the different grinding segments S1-S5.

energy showed a clear progressive increase in all frequency bins within the spectrum as the wheel wear progressed. In terms of distinguishing batches, another feature that was extracted from the AE signals of both batches was the normalised entropy, shown in Fig.11, which shows a notable distinction between the two batches. Further analysis and repetitions are required to assess the overall industrial applicability and repeatability of such features; however, the clear distinction observed between batches A and B signifies a promising initial result.

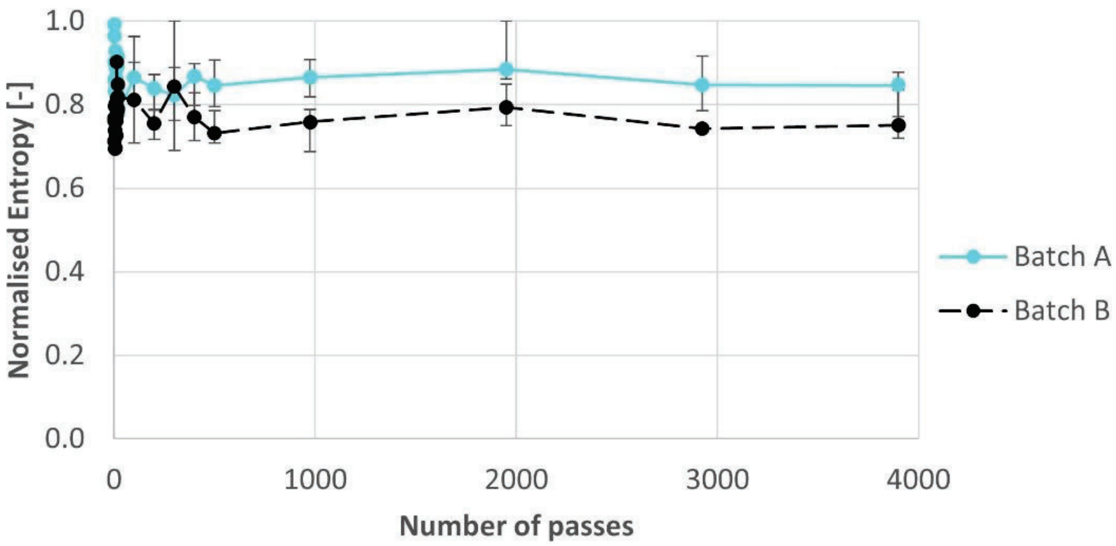


Fig. 12. Comparison of the normalised entropy of AE-signals between both batches during grinding

Grindability Tests

Additionally, some grindability tests were run where the grinding wheel was subjected to three different dressing conditions to control its micro-topography and simulate various states of wheel wear as follows: U_d = 3.5 (sharp micro-topography), 7.0 (medium micro-topography), and 10.5 (dull micro-topography). After initially dressing the wheel to these micro-topographic conditions, 20 grinding passes were performed for each wheel state on both batches for three different aggressiveness numbers by varying the depth of cut. AE emissions and grinding forces were measured during these tests, providing insight on how the dressing condition affects both the wheel's performance and the interaction with the workpiece. For instance, Fig. 13 shows the comparison of normal and tangential forces during grinding for both batches at different dressing wheel conditions and cutting conditions. The general trend observed is a slightly higher force for Batch B in all tested wheel and cutting conditions compared to Batch A. The distinction in forces between the wheel wear states is also evident.

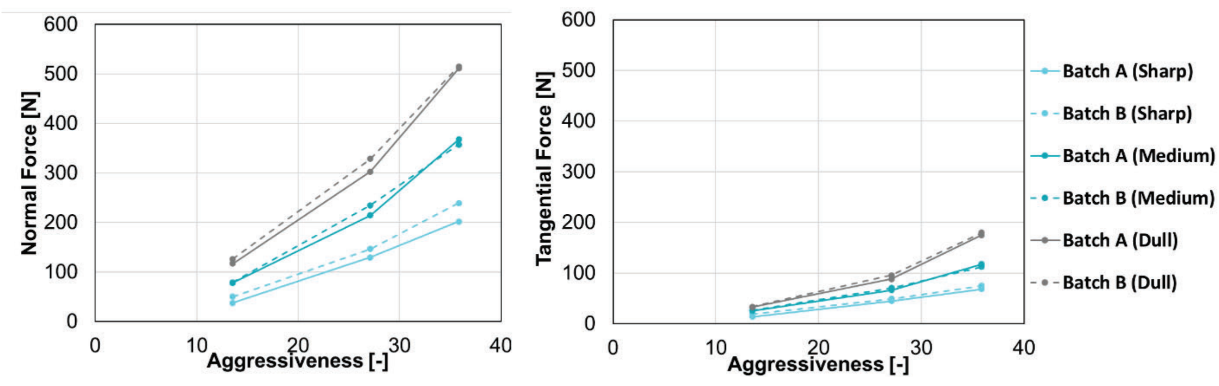


Fig. 13. Comparison of normal and tangential cutting forces between the two batches for different dressing conditions.

In regard to the AE signals, the mean instantaneous energy of the HHT IMFs was determined to be a successful parameter in distinguishing the different wheel micro-topographies. As evident in Fig. 14, the dull wheel consistently led to the highest mean energy of IMFs 1-4, followed by the medium dull wheel then by the sharp well, for all investigated aggressiveness conditions.

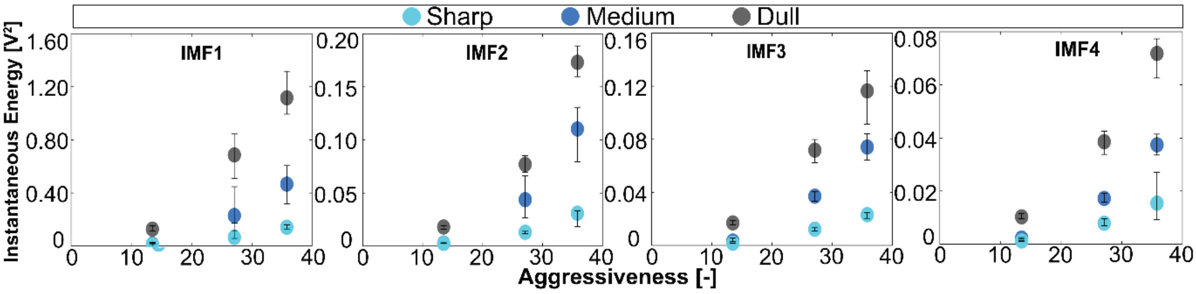


Fig. 14. Mean energy of IMFs 1-4 for various wheel conditions at different aggressiveness numbers.

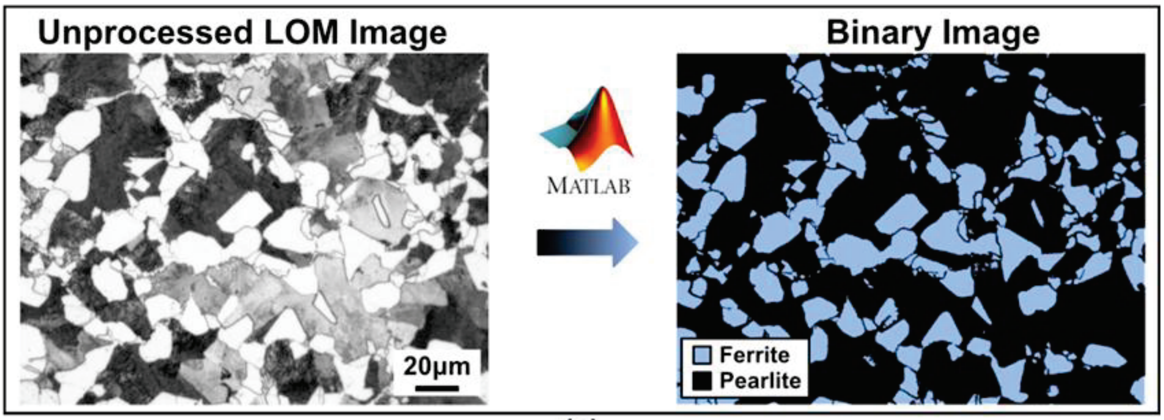
6.3. WP3: Material characterisation

To better understand the reasons behind the observed differences in machinability between the batches, it is essential to evaluate the microstructural variations between them. Therefore, in the framework of WP3, an in-depth characterisation of the workpiece materials was performed, concentrating on micro-hardness, phase fractions and properties, as well as non-metallic inclusions as well as the worn tools. In this WP, an ***automated application*** was developed using MATLAB based in order to convert images – taken either using scanning electron or light optical microscopy – to binary images and quantify the phase volume fractions and pearlite lamellar spacing, as shown in Fig. 15. These characteristics have a major impact on strength, hardness and strain rate hardening rate of the carbon steels. In parallel, the non-metallic inclusions are analysed and classified using a scanning electron microscope equipped with an EDS detector and AztecSteel® add-on module.

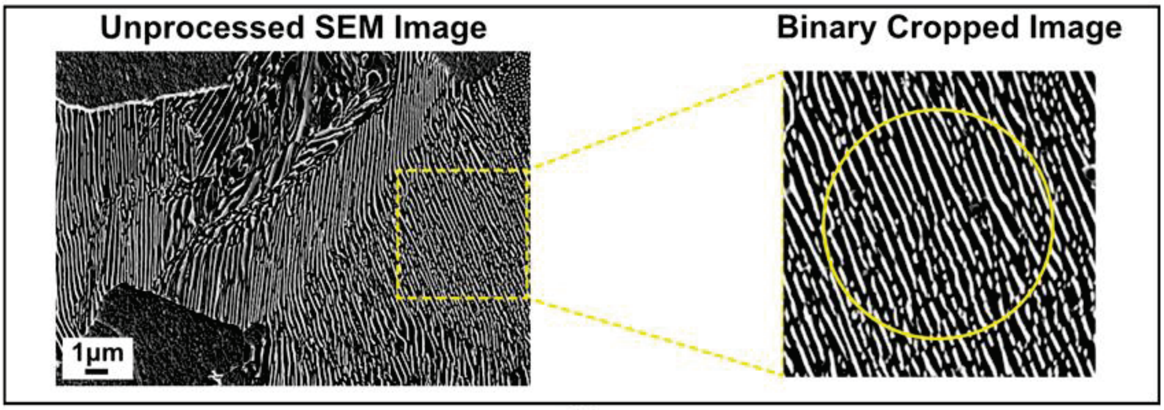
C38 Steel (Scania)

Metallographic samples were extracted from both inner and outer radial locations of the workpieces to detect any differences in the material's microstructure along the radial direction. Automated Vickers hardness testing (10 kgf test load) revealed that both batches had nearly identical hardness in the internal samples, with Batch A being just 1% lower. However, at the outer radius, Batch A's hardness was 8% higher than that of Batch B, which may contribute to Batch B's enhanced machinability. It was thus determined that Batch B has a notably higher volume fraction of the softer ferrite in its microstructure as opposed to a higher volume fraction of the harder pearlite in Batch A, again suggesting a better machinability for Batch B. Further microstructural characterisation was performed to assess the pearlite interlamellar spacing. The analysis showed that both batches exhibited similar average values of the true lamellar spacing.

A comparative analysis of the inclusions, covering an area of 22 mm² for each batch, is summarised in Fig. 16 and Table 1. Several key differences emerge when comparing the quantities, area (or volume) fractions, mean areas, and mean aspect ratios of inclusions between Batch A and Batch B. Notably, Batch B has significantly more, smaller, and more globular manganese sulphide inclusions than Batch A (Table 1), all of which suggest an enhanced machinability for Batch B. Also noteworthily, (Mn,Ca)S sulphides occupy 53% less area in Batch B compared to Batch A. A similar disparity exists for titanium nitride inclusions, with Batch A having 49% higher area fraction of these abrasive particles compared to Batch B, suggesting more aggressive abrasive wear in Batch A.



(a)



(b)

Fig. 15 (a) Conversion of LOM images to binary using MATLAB for the quantification of microstructures and (b) the calculation of pearlitic lamellar spacing using binary image conversion.

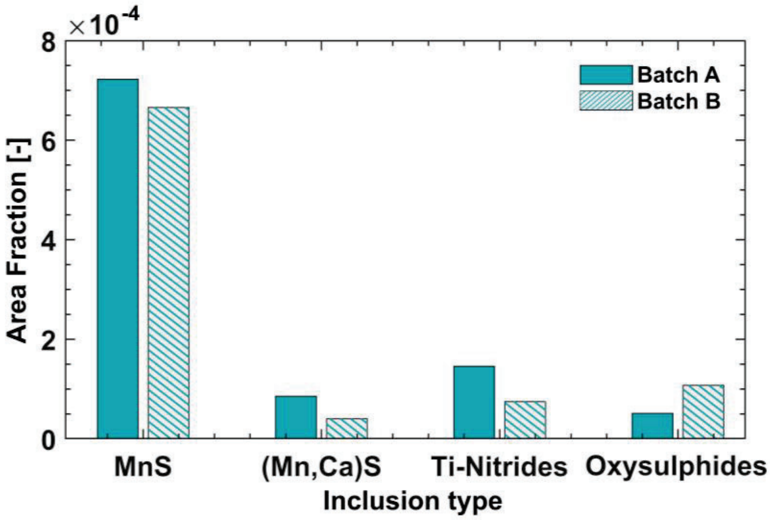


Fig. 16. A comparison of the area fraction (i.e., volume fraction) occupied by the different non-metallic inclusion classes between Batch A and B (scanned area is 22 mm^2 per batch).

Regarding oxysulphides, Batch B possesses more than double the area fraction of these inclusions compared to Batch A (110% higher) and also nearly double the quantity (77% higher). The influence of these oxysulphides on the steel's machinability is complex and demands a deeper investigation into their chemical composition. For this insight, the inclusions identified by AztecSteel® are mapped onto pseudo-ternary phase diagrams to give an indication of their deformability and ability of forming protective layers on the tool's surface. For this work, the $CaO-MgO-Al_2O_3-SiO_2$ system was selected with 10 wt% MgO, as shown in Fig. 17.

Table 1. Comparison of different properties of each class of non-metallic inclusions in batches A and B.

Constituent	Property	Batch A	Batch B
	Quantity	2541	8236
MnS-	Mean area [μm^2]	6.2	1.7
	Mean aspect ratio [-]	2.9	2.3
	Quantity	599	451
(Mn,Ca)S-	Mean area [μm^2]	3.1	2.0
	Mean aspect ratio [-]	1.9	2.1
	Quantity	1431	1046
Ti-Nitrides	Mean area [μm^2]	2.2	1.5
	Mean aspect ratio [-]	2.4	2.4
	Quantity	383	675
Oxysulphides	Mean area [μm^2]	3.0	3.5
	Mean aspect ratio [-]	1.5	1.5

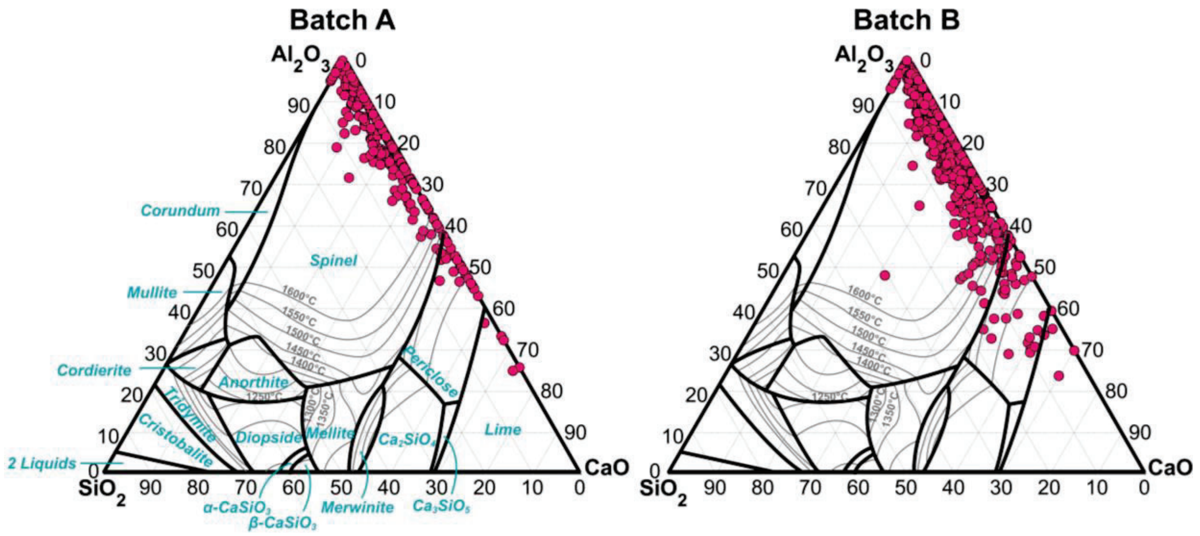


Fig. 17. The pseudo-ternary phase diagram of $CaO-Al_2O_3-SiO_2$ system containing 10 wt% MgO showing the compositions of the oxysulfide inclusions within the investigated steel batches.

V2158 Steel (Volvo)

A similar in-depth characterisation of the workpiece materials received from Volvo, V2158, was carried out to obtain a comprehensive understanding of the differences between both batches. For instance, the non-metallic inclusion distribution, shown in Fig. 18, establishes that Batch B has a notably higher percentage of MnS, (Mn,Ca)S and oxysulphides compared to Batch A.

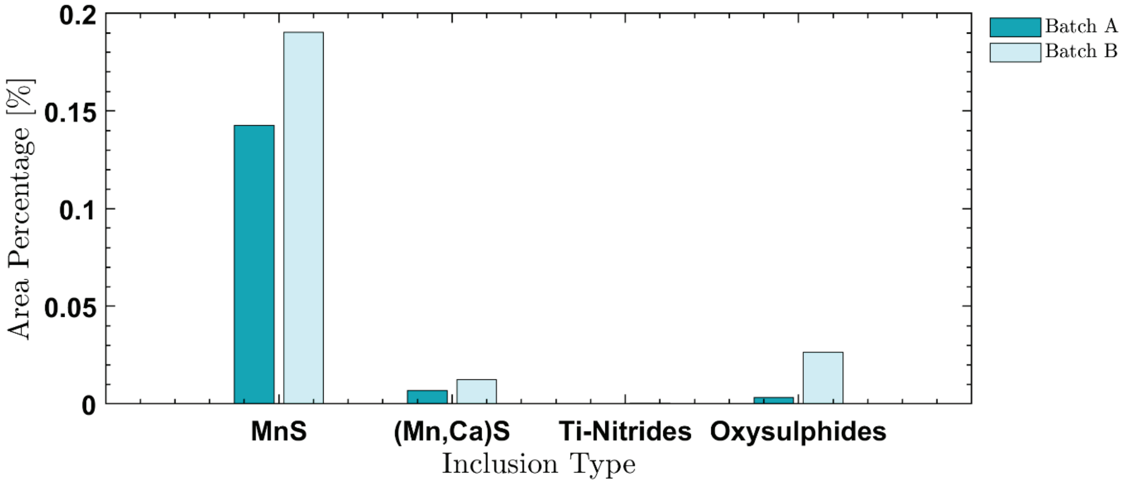


Fig. 18. A comparison of the area percentage (i.e., volume percentage) occupied by the different non-metallic inclusion classes between Batch A and B (scanned area is 2 mm^2 per batch).

Ternary plots were also generated for the sulphides in the various batches, as shown in Fig. 19, providing information about their chemical composition. The ternary plot for Batch B shows a more noticeable presence of points extending towards the Ca-axis, which suggests that the sulphides in Batch B are richer in calcium compared to Batch A. Sulphides rich in calcium are generally recognized for improving machinability and influencing chip formation.

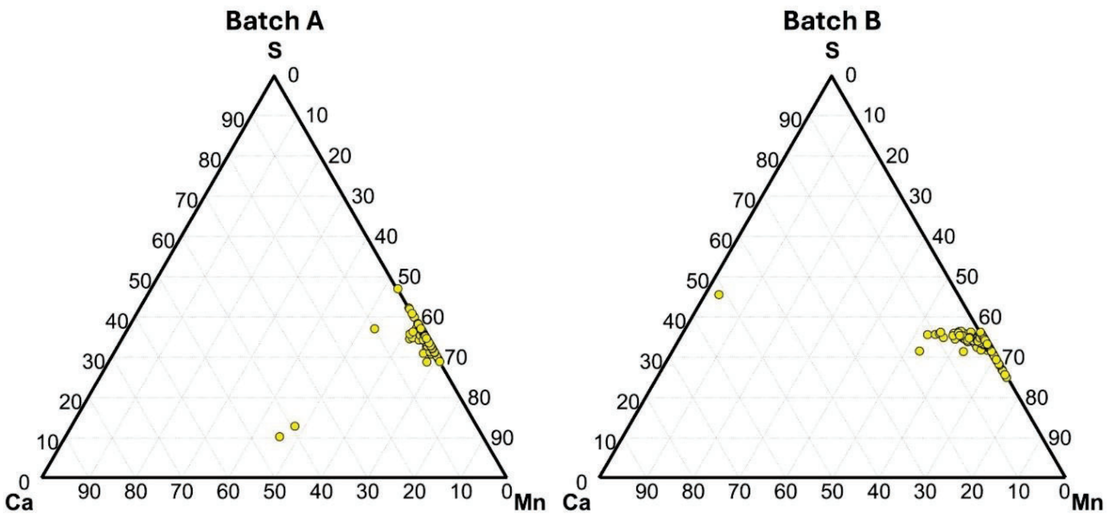


Fig. 19. The pseudo-ternary phase diagram of Ca-Mn-S system showing the compositions of the sulphide inclusions within the investigated steel batches.

100Cr6 Steel (Gnosjö)

Similar to the other workpiece materials, an in-depth characterisation of the different batches of 100Cr6 was performed. Batches A and B are nominally identical high-sulphur batches while Batch C has a slightly different chemical composition, mainly due to its lower sulphur content. Fig. 20 shows a comparison of the different non-metallic inclusion classes between these batches, showing a clear distinction in the quantity and area percentage of the NMIs. For instance, Batch B possesses the highest quantity and area percentage of MnS sulphides as well as Ti-nitrides. Batch C, while having lower sulphur content, exhibits the highest quantity and area percentage of oxysulphides compared to Batches A and B.

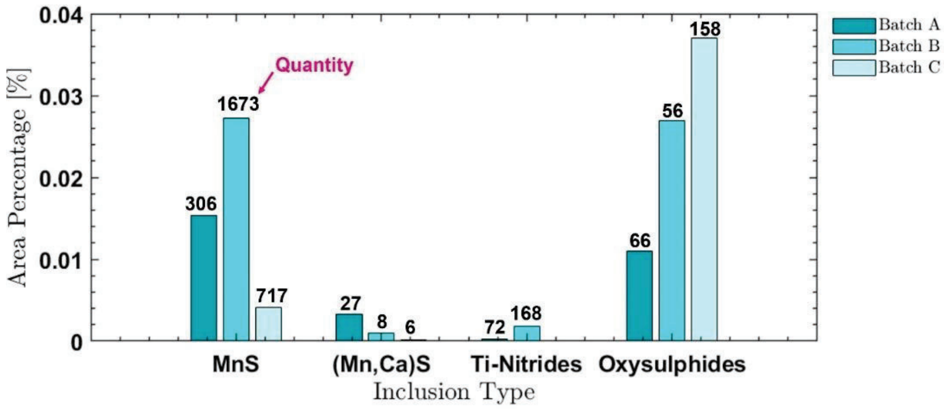


Fig. 20. A comparison of the area percentage (i.e., volume percentage) occupied by the different non-metallic inclusion classes between Batch A, B and C (scanned area is 4 mm^2 per batch)

Nodular Cast Iron (Volvo)

Similarly to the other studied materials, the cast investigated nodular cast iron grade (NGI) was analysed using advanced characterization techniques. An important factor influencing the mechanical properties of cast irons is the morphology of the graphite present in the material, commonly represented by the graphite nodularity. The nodularity in the workpiece material was determined by a combination of light optical microscopy and image processing using MATLAB. In the case of the nodularity, large variations were detected within one workpiece, indicating that the mechanical properties might not be homogenous within one workpiece or across different workpieces. Further, an investigation of the non-metallic inclusions present in the workpiece was conducted using AztecSteel®. The results from this investigation are shown in Table 2. Some of the found inclusion groups, mainly nitrides and oxides, are known to act abrasively on the cutting tool during machining, often acting as major contributors to wear.

Table 2. Groups of inclusions and their properties found in the SGI workpiece material.

Main Constituents	Property	
(Mg,Si,Ca)O	Quantity [-]	1082
	Area Fraction [%]	0.133
	Mean Area [μm^2]	10.8
	Mean Aspect Ratio [-]	1.95
(Mg,Si)S	Quantity [-]	523
	Area Fraction [%]	0.116
	Mean Area [μm^2]	11.6
	Mean Aspect Ratio [-]	1.31
(Mg,Si)N	Quantity [-]	318
	Area Fraction [%]	0.039
	Mean Area [μm^2]	11.63
	Mean Aspect Ratio [-]	1.75
(Ti,Nb)C	Quantity [-]	47
	Area Fraction [%]	0.00249
	Mean Area [μm^2]	4.99
	Mean Aspect Ratio [-]	2.64
Ti:O	Quantity [-]	26
	Area Fraction [%]	0.00328
	Mean Area [μm^2]	11.88
	Mean Aspect Ratio [-]	2.18

6.4. WP4: Modelling & simulation – software integration

This WP dealt with developing models and methods for machinability assessment. The activities in this WP were divided into four sub-activities: 1) developing database for the hardness properties of the inclusions present in the workpiece materials using density functional theory (DFT), 2) developing physics-based (dislocation-based and microstructure-sensitive) flow stress models required for process simulation, 3) developing efficient and reliable analytical and hybrid-FEM models for estimation of stress and temperature estimation on tools and thus tool wear, 4) software integration to deploy an open-access platform for industrial use.

Estimation of hardness

We have developed atomistic models and methods to estimate the hardness properties of the inclusions in the workpiece materials, allowing us to rank their relative impact on abrasive wear [20]. The inclusions that are soft, may either form a protective layer on the tool surface and thus enhance the tool life [16, 20], or react with the coating material and substantially increase the wear rates [17]. The hard inclusions can, however, abrade the tools under the extreme tribological conditions (high shear and normal stresses and temperatures) on the sliding surfaces. Hence, it is vital to estimate the deformability and hardness of the particles. Here, we have developed a hardness database for the oxide, carbide and nitride inclusions using two approaches. One method relies on the estimation of hardness and ductility based on the DFT calculations of elastic properties [21], and the second approach includes other properties such as electronegativity, number of valance electrons and charge density [22, 23] for the hardness estimations [24, 25].

Physics-based flow stress properties

In order to estimate the thermo-mechanical loads on the tool surfaces, it is vital to provide the finite element (or analytical) models with reliable flow stress data – accounting for the material behaviour at high strain rates and temperature. Most often, the phenomenological models like Johnson-Cook and its modifications have been calibrated using either inverse approaches or based on high strain rate and high temperature data (e.g. those data obtained using SHPB or Gleeble tests). A major limitation in application of these phenomenological models is that the material model should be re-calibrated for a new microstructure obtained, e.g., using a different heat treatment process of the same material. This requires repeating the costly and time-consuming experiments to obtain the raw data for the new microstructure. To overcome this limitation, we have, developed and extended [26] the existing dislocation-based models in literature which are sensitive to variations in microstructural features and chemical composition [27, 28].

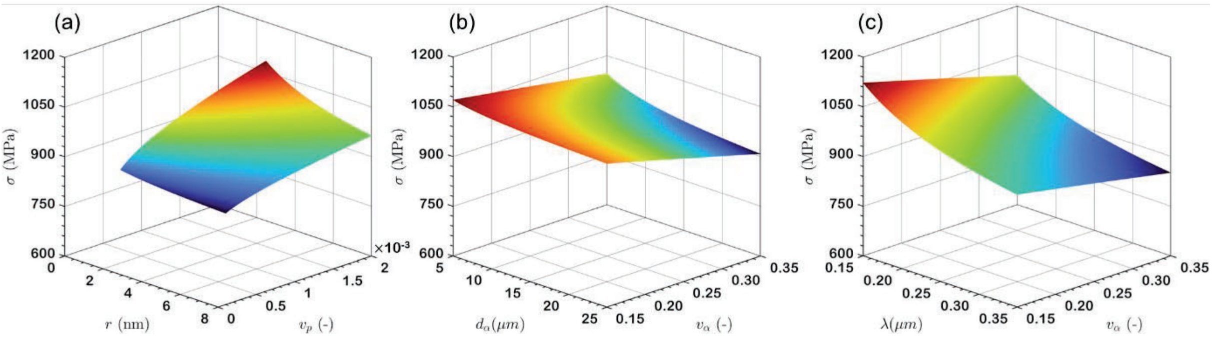


Fig. 21. The influence of precipitate size and volume fraction on flow stress at 20% deformation for a pearlitic-ferritic microstructure with $\lambda = 0.2$ μm, $d_\alpha = 15$ μm, and $v_\alpha = 0.3$ (a), the influence of ferrite grain size and volume fraction on flow stress at 20% deformation for a pearlitic-ferritic microstructure with $\lambda = 0.2$ μm, $r = 5$ nm, and $v_p = 0.001$ (b), the influence of ferrite grain size and pearlite interlamellar spacing on flow stress at 20% deformation for a pearlitic-ferritic microstructure with $d_\alpha = 15$ μm, $r = 5$ nm, and $v_p = 0.001$ (c). Temperature and strain rate were assumed constant.

A particular focus was placed on developing and extending available flow stress models [29] for materials with heterogeneous microstructures that include constituents with a significantly different strength and ductility such as pearlitic-ferritic micro-alloyed steels. For instance, Fig. 21 shows the estimated flow stresses at a constant strain, strain rate and temperature (room temperature) as a function of microstructural characteristics of micro-alloyed medium carbon steels, such as pearlite interlamellar spacing (λ), volume fraction (v_p) and size (r) of (V,Ti)(C,N) nano-size precipitates, the volume fraction (v_α) and size of ferrite grains (d_α).

Hybrid semi-analytical and FE-based models – tool wear estimation

Tool wear in machining involves various complex mechanisms: mechanically-induced processes like abrasion and adhesion and thermally-induced mechanisms such as dissolution-diffusion and oxidation [30]. In order to have reliable predictions, it is, therefore, vital to adopt a wear model that can account for the most dominant mechanisms at given tribological conditions (e.g., temperature, stress and sliding velocity). Such a wear model should be responsive to the variations in the workpiece material, e.g. the composition and the volume fraction/type/size of non-metallic inclusions, and the properties of the tool, e.g. coating composition and hardness. We have, therefore, extended and further developed physics-based models that account for abrasion and dissolution-diffusion mechanisms [2-4, 7]. To obtain a reliable prediction of tool wear – efficient, yet reliable, estimations of stress and temperature distributions on the tool rake and clearance surfaces are required.

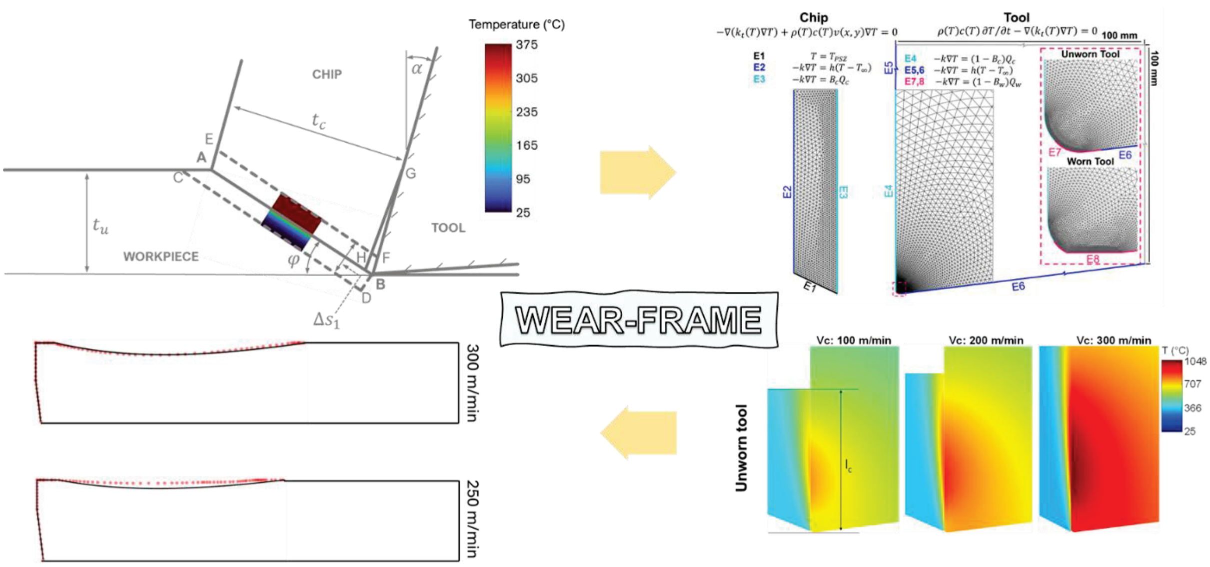


Fig. 22. The Developed hybrid approach for predicting tool wear and thus assessing machinability of a given material.

To this end, enhanced semi-analytical [31] and hybrid FE-based approaches are developed. This development allows us to obtain the temperature and stress distributions on the tool surfaces quite efficiently (in scale of minutes) as compared to the alternative approaches in literature (normally a couple of hours for chip formation simulations using FEM [32]), with cutting forces, chip thickness and contact length as the input parameters. Such inputs can be obtained readily using simple experimental procedures. Once the temperature and stress distributions are known, it is then possible to predict the tool wear using the adopted physics-based model. The steps are shown in Fig. 22.

Software integration

The models and methods are combined and integrated in a stand-alone pilot MATLAB-based software. A snapshot of this software – currently under development – is shown in Fig. 23. This software package takes some inputs from thermodynamic and kinetic calculations using the associated software like ThermoCalc® and TC-Prisma® and is equipped with the hardness database, physics-based flow stress and advanced wear models that are developed in WEAR-FRAME project and the hybrid FE-based models for temperature and stress estimation and ultimately flank and crater wear predictions.

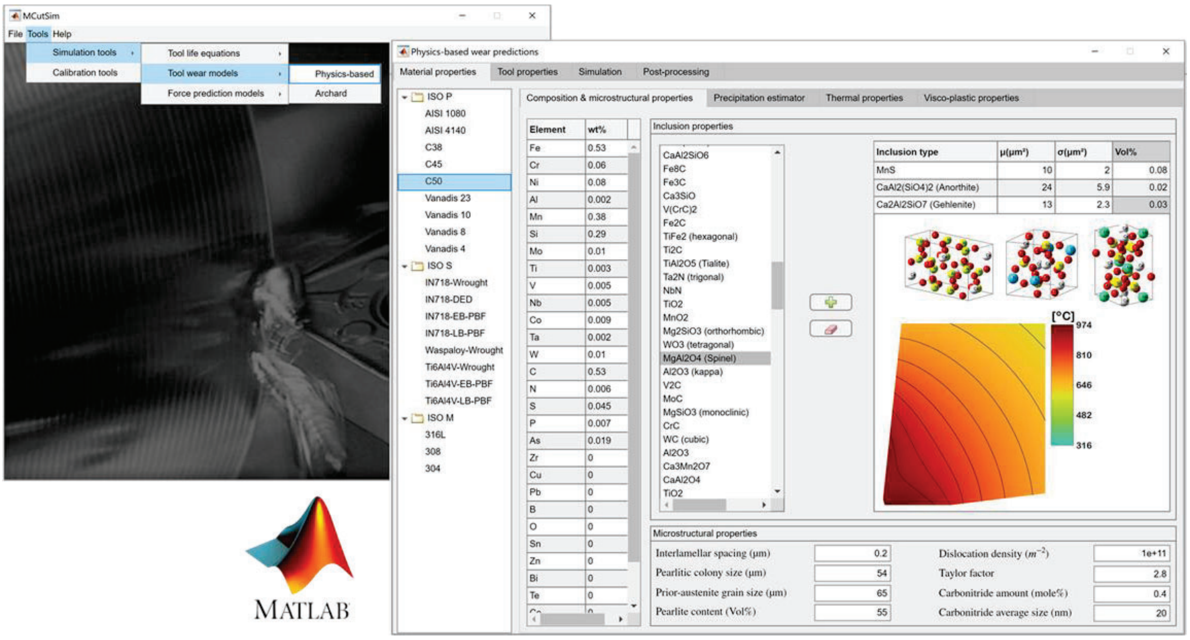


Fig. 23. MCutSim pilot software – open-access.

6.5. WP5: Demonstration

In the context of WP5, various tests were carried out in both turning and grinding processes within industrial production lines at Scania, Volvo, Gnosjö Automatsvarvning AB and Seco Tools. The purpose of these industrial tests was multifaceted: to support the results obtained in a controlled lab environment and assess their applicability on an industrial scale as well as provide inputs and validate the simulation results developed in this project.

Sensor-based monitoring in turning production lines (Scania)

Data acquisition from production lines plays a central role in Industry 4.0. To this end, a variety of sensors (accelerometer and microphone) were installed inside turning machines at the crankshaft production lines at Scania, Södertälje and the signals were acquired, filtered and post-processed to determine any correlation between batch variations and tool wear progression.

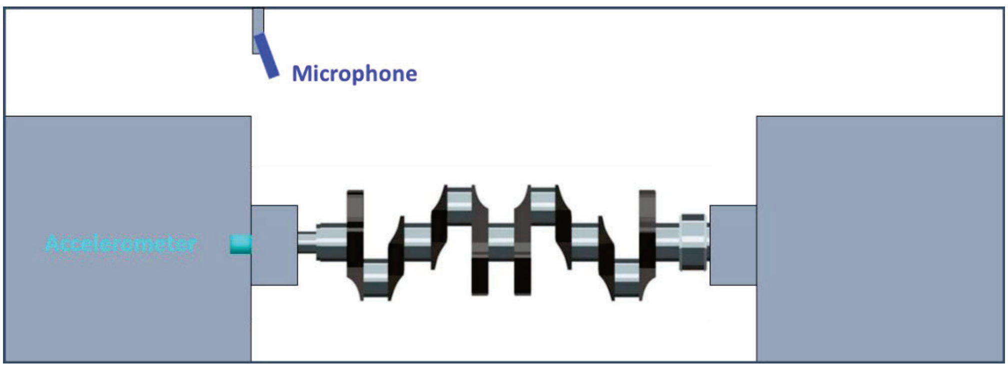


Fig. 24. A schematic representation of the accelerometer and microphone placement within the Scania crankshaft production line

The analysis of the raw acquired signals using Wavelet and FFT methods did not reveal any distinction between the different batches fed into the production line. This is primarily because the variations in the tool geometry and other source of variations could overpower the slight impacts the small variations in the chemical composition or the type, size and volume fractions of the oxides and nitrides could possibly have on the measurable signals. These factors however could have significant impact on tool life and wear progression.

Grinding tests - crankshaft (Scania)

To evaluate the grindability of different steel batches, a series of tests were conducted at Scania, where various batches of crankshafts (C38 steel) were subject to grinding. During these tests, several key data inputs were collected to examine the potential of identifying variations between the batches based on their grinding behaviour. The industrial grinding tests included 3 series of tests conducted in a crankshaft production line at Scania in Södertälje, Sweden. Each test series comprised dressing of the CBN grinding wheel followed by grinding 20 crankshafts without re-dressing the grinding wheel. A number of in-process and post-process quality control measurement data were recorded and included in the analysis. During grinding, the spindle power was recorded. Subsequently, these ground crankshafts underwent inspection including measurement of surface roughness, form, and Barkhausen noise of the ground crankpin and main surfaces. In this way, the effect of progressing grinding wheel wear on crankshaft quality metrics was evaluated. Furthermore, as varying steel batches were contained in the crankshafts of each test series, the effect of batch-to-batch variations on wheel wear (and part quality) was investigated.

Fig. 27 exemplifies form changes due to grinding wheel wear. Due to wear in longitudinal direction of the grinding wheel, the widths of crankshaft mains and pins get slightly smaller. During production, a G-code compensation is adopted in order to take this change into account and stay within allowable tolerance. The comparison in Fig. 27 shows a clear difference between test 1 and test 2. The results indicate that grinding the specific steel batches in test series 2 led to faster progression of wheel wear and hence faster reduction of crankpin and main width. This further emphasises the need to monitor wear progression in production lines in order to avoid large variations in the resulting workpiece.

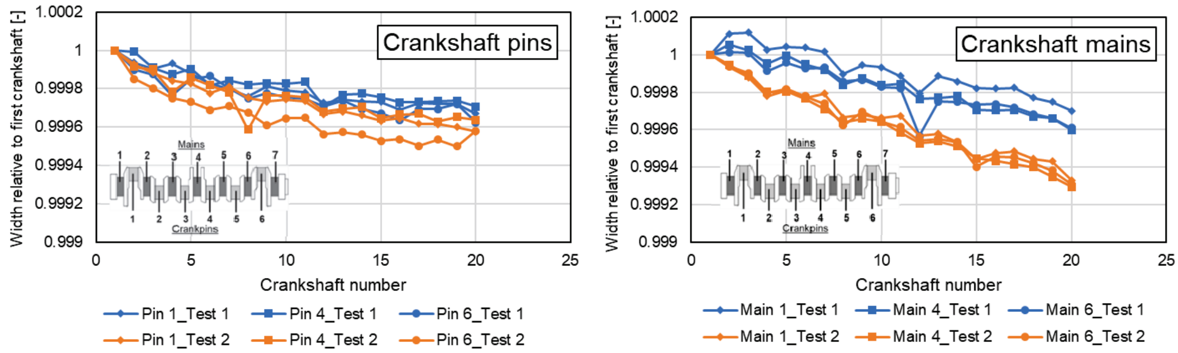


Fig. 27. Grinding wheel wear and its effect on form changes on crankshaft pins and mains as function of number of crankshafts ground after dressing of grinding wheel.

Turning tests – gear blanks (Volvo)

To investigate the effects of batch-to-batch variation in an industrial line, machining tests were conducted on two batches of steels at Volvo and tools were collected at various intervals to be investigated at Chalmers. The benefit of such industrial tests is because it is difficult to reach such high material removal rates in lab environments, given the limitation in workpiece quantities among other factors. Thus, a more complete representation of the active wear mechanisms can be assessed in industrial tests such as this. Fig.28 shows SEM images of a worn tool obtained after the machining of (a) 120 workpieces and then (b) 240 workpieces for a single batch, Batch A. In fact, this batch showed enhanced machinability compared to Batch B in the production line. The flank wear in Batch A reached 206 µm while for Batch B, the flank wear reached 276 µm. The workpiece materials from the same batches used for these tests were sent to Chalmers for characterisation. An in-depth characterisation of material batches in terms of ferritic area fraction, pearlite lamellar spacing, non-metallic inclusions and hardness, showed clear correlations regarding the difference in machinability between both batches based on our developed methodologies.

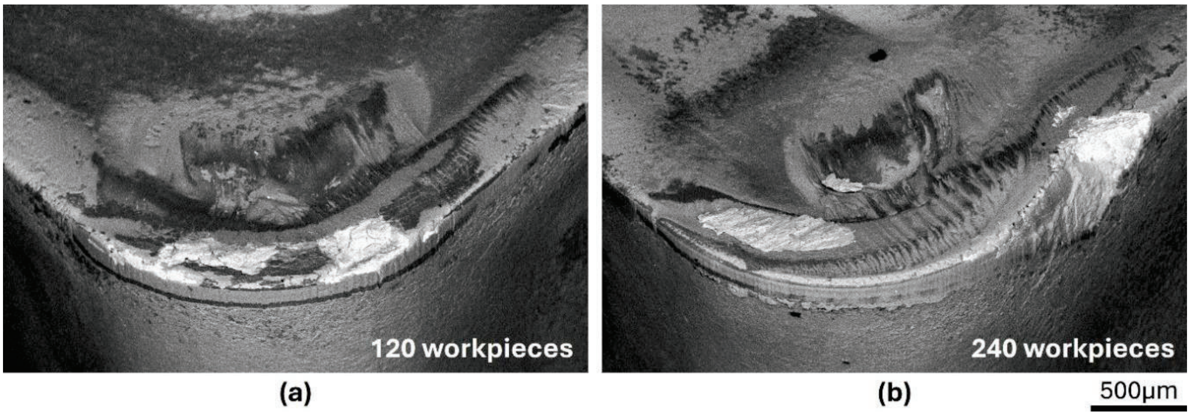


Fig. 28. SEM images of worn tools in production line at Volvo after production of (a) 120 and (b) 240 workpieces.

Turning tests (Gnosjö)

Machining tests were conducted on a batch of 100Cr6 steel and tools were collected from the production line. The HV10 hardness of the workpiece was shown to be constant along its radial direction, averaging at 252 kg/mm^2. Additionally, Fig.29(a) shows an SEM image of the microstructure of the 100Cr6 workpiece, showing a spheroidal microstructure. Using image processing in MATLAB, the area percentage of these spheroids was characterised and determined to be 16.5%. Fig. 29(b) presents the inclusion analysis, where the quantity and area percentage of each inclusion class is presented, showing a high quantity and area percentage of MnS inclusions.

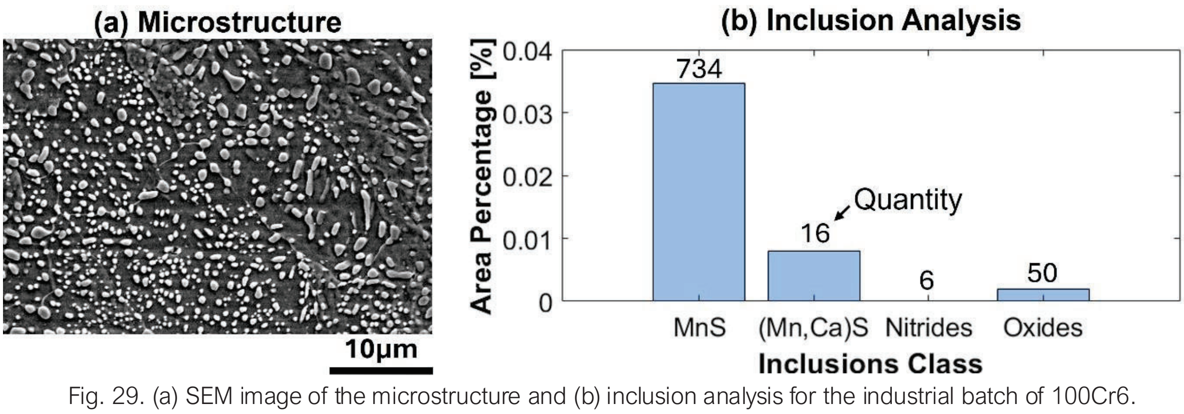


Fig. 29. (a) SEM image of the microstructure and (b) inclusion analysis for the industrial batch of 100Cr6.

In parallel, the cutting tools used in production were collected for characterisation. Fig. 30 presents two of the investigated tools, which show vastly different wear levels despite being used to machine the same material under identical cutting conditions. Specifically, the wear at the cutting edge and flank side of the tool seem to be considerably more advanced in Tool A compared to Tool B, where larger areas of the coatings and substrate are exposed. Such behaviour can be well explained based on the variations in micro-constituents in the workpiece materials.

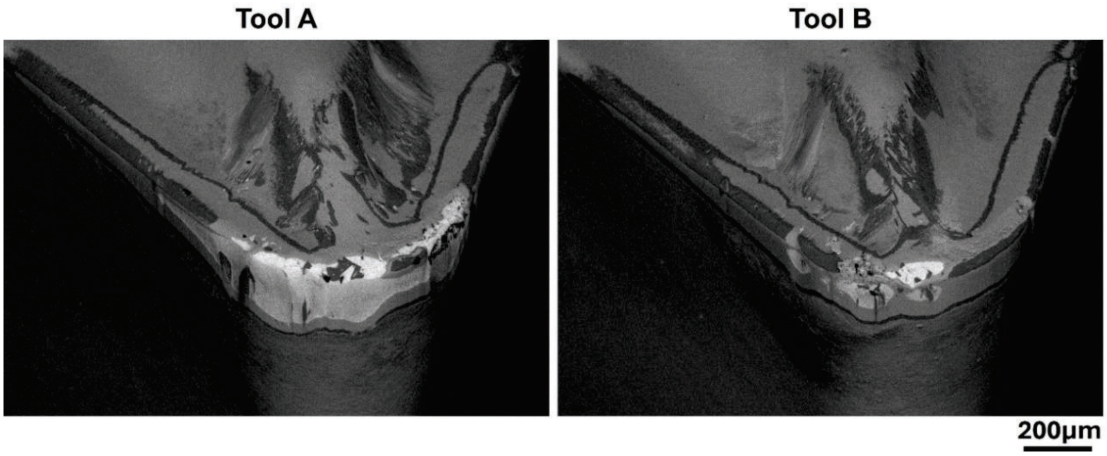


Fig. 30. Comparison of two tools machined to the same spiral cutting length under identical cutting conditions.

Sensor-based monitoring (Gnosjö)

To investigate the applicability of sensor-based monitoring of tool wear in production lines, different sensors were tested in the production line at Gnosjö Automatsvarvning AB. For instance, Fig. 31 shows the installation of the accelerometer on the outer surface of a machine in the production line. Despite its external placement, the accelerometer was successful in identifying the tool wear, as seen in the spectrograms. Evidently, certain frequencies gain power as the wear progresses. Thus, the average power of different frequency bins could be a successful extracted feature in identifying tool wear in industrial applications. Of course, the details of such sorting algorithms would largely depend on the specific application and would need to be tailored to the specific machine being investigated.

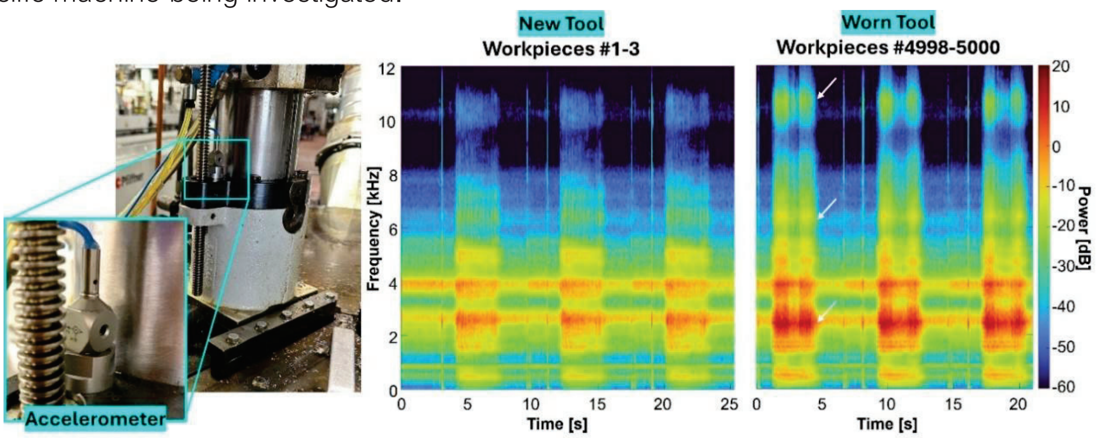


Fig. 251. Comparison of spectrograms of accelerometer signal for a new and worn tool in production line.

7. Dissemination and publication

7.1. Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	State-of-the-art models to describe the material behaviour in cutting process, adaptive to the variations in the material batches are developed. A concept for digital representation of machinability has been further developed. Strong collaboration between academic and industrial partners has also led to competence transfer in both directions, which has strengthened the common knowledge.

Be passed on to other advanced technological development projects	X	The results are promising, with continued research efforts required to reach full industrial use (above TRL 5). Therefore, a continuation of the project is now being initiated with the majority of the parties in the consortium.
Be passed on to product development projects		
Introduced on the market	X	Some of the functionalities of the open-access pilot software are currently available to the industrial partners using GUI. The rest are available as MATLAB codes and need to be integrated with the pilot software for full functionality. The database and models will be extended together with the partners through bilateral and multilateral collaborations at Chalmers Centre for Metal Cutting Research.
Used in investigations / regulatory / licensing / political decisions		

We have also presented WEAR-FRAME methodologies in national and international industrial and scientific communities to increase the awareness on the challenges associated with batch-to-batch material variations and the industrialisation of our integrated approach and tool-condition monitoring systems:

- C. Salame and A. Malakizadi, A framework for the physics-based estimation of tool wear in machining process, Manufacturing R&D clusters conference, Södertälje, 2023-05-09.
- A. Malakizadi, Towards physics-based machinability assessment of metallic alloys, CIRP Winter Meetings, Technical presentation, Paris, Feb. 2023.
- C. Salame, A. Malakizadi, On the effects of variable heat flux on tool temperature in machining, Oral presentation, EuroMat, Sep. 2023
- A. Malakizadi, Physics-based simulation of flow stress properties of alloys, Oral presentation, EuroMat, Sep. 2023
- A. Malakizadi, Resilient material supply chain – modelling of the batch-to-batch material variation effects, MCR-DMMS annual conference, Göteborg, Dec. 2023.
- C. Salame, Sensor-based identification of tool wear in turning process, MCR-DMMS annual conference, Göteborg, Dec. 2023.
- A. Malakizadi, WEAR-FRAME: A framework for the physics-based estimation of tool wear in machining process, Online presentation (recorded) for SMEs, Skärteknikcentrum Sverige, Dec. 2024.
- A. Malakizadi, WEAR-FRAME, Manufacturing R&D clusters conference, Göteborg, 2025-05-15.

7.2. Publications

- **Salame C**, Rapold R, Tasdelen B, **Malakizadi A**. Sensor-based identification of tool wear in turning. Procedia CIRP. 2024; 121:228-33.
- **Salame C**, **Malakizadi A**. An enhanced semi-analytical estimation of tool-chip interface temperature in metal cutting. Journal of Manufacturing Processes. 2023; 105:407-30.
- **Malakizadi A**, Saelzer J, Berger S, Alammari Y, Biermann D. A physics-based constitutive model for machining simulation of Ti-6Al-4V titanium alloy. Procedia CIRP. 2023; 117:335-40.

- **Salame C**, **Malakizadi A**, **Klement U**. On the influence of batch-to-batch microstructural variations on tool wear when machining C38 micro-alloyed steel. Wear. 2025; 562:205632.
- Singh D, Shukla V, Khossossi N, **Hyldgaard P**, Ahuja R. Stability of and conduction in single-walled Si 2 BN nanotubes. Physical Review Materials. 2022; 6(11):116001.
- Shukla, V., Jiao, Y., Lee, J.H., Schröder, E., Neaton, J.B. and **Hyldgaard, P.**, 2022. Accurate nonempirical range-separated hybrid van der Waals density functional for complex molecular problems, solids, and surfaces. *Physical Review X*, *12*(4), p.041003.
- Frostenson CM, Granhed EJ, Shukla V, Olsson PA, Schröder E, **Hyldgaard P.** Hard and soft materials: putting consistent van der Waals density functionals to work. Electronic Structure. 2022; 4(1):014001.
- Shukla V, Jiao Y, Frostenson CM, **Hyldgaard P.** vdW-DF-ahcx: a range-separated van der Waals density functional hybrid. Journal of Physics: Condensed Matter. 2021; 34(2):025902.
- Racioppi S, Lolur P, **Hyldgaard P**, Rahm M. A density functional theory for the average electron energy. Journal of Chemical Theory and Computation. 2023;19(3):799-807.
- Racioppi S, **Hyldgaard P**, Rahm M. Quantifying Atomic Volume, Partial Charge, and Electronegativity in Condensed Phases. The Journal of Physical Chemistry C. 2024 128(9):4009-17.
- Schröder E, Quintero-Monsebaiz R, Jiao Y, **Hyldgaard P.** Optimally tuned range-separated hybrid van der Waals density functional for molecular binding and quasiparticle characterizations. Journal of Physics: Condensed Matter. 2025;37(21):211501.

In addition, 2 M.Sc. theses and one licentiate thesis are published:

- Salame, C, An Integrated Framwork for Enhanced Machining: Machinability Analysis, Thermal Modelling and Sensor Based Monitoring, Lic. Eng. thesis, Department of Industrial and Materials Science, Chalmers University of Technology, 2024.
- Rapold, R S, Sensor-based monitoring of tool wear evolution in machining, Executed at Department of Industrial and Materials Science, Chalmers University of Technology under Erasmus programme, ETH Zürich, 2022.
- Andersson, D, Aronsson, M, Machinability of 100Cr6 bearing steels, Master thesis, Department of Industrial and Materials Science, Chalmers University of Technology, 2024.

There are also five publications in progress (submitted for publication or in manuscript):

- Andersson, D, **Malakizadi, A**, TOOL WEAR INVESTIGATION OF COATED CEMENTED CARBIDE INSERTS DURING INTERRUPTED TURNING OF NODULAR CAST IRON, submitted to 18th International conference on high-speed machining, France, 2025.
- **Salame, C**, Hoier, P, **Krajnik, P**, **Malakizadi, A**, MULTI-SENSOR MONITORING OF WHEEL WEAR DURING CBN GRINDING OF CRANKSHAFT STEEL, submitted to 18th International conference on high-speed machining, France, 2025.
- **Malakizadi, A**, **Salame C**, A hybrid approach for predicting tool wear in machining, to be submitted to Journal of Materials Processing Technology.
- **Salame, C**, **Svensson, J**, **Malakizadi A**, Batch-to-batch microstructural variations in automotive gear steels and its influence on machinability, to be submitted to WEAR.
- **Salame, C**, Andersson, D, Aronsson, M, **Klement U**, **M'Saoubi, R**, Vikenadler E., Boing, D., D'Eramo, E, **Malakizadi A.** Behaviour of alumina coated tools when machining 100Cr6 bearing steel. to be submitted to Tribology international.

8. Conclusions and future research

This project has led to significant advancements in the modelling and simulation of cutting process. A robust hybrid FE-based model has been implemented in MATLAB, enabling prediction of cutting temperature and stress distribution on the cutting edge using the measured forces, chip thickness and tool-chip contact length. This approach is significantly more reliable and efficient than the alternative methods such as FE-based chip formation simulations for calculating the distribution of stress and temperature on the tool surfaces when machining (orthogonal cutting-2D). It includes a new method for estimation of heat partition between the tool and chip and temperature dependent thermal properties for temperature calculations. Further, it accounts for the effects of edge radius and flank wear dimensions on heat generation in the vicinity of cutting edge. Hence, it allows for rapid and reliable wear predictions when combined with well-calibrated wear models. This approach is implemented as a stand-alone MATLAB programme – MCutSim V1.0 – available to industrial partners and scientific community on demand. To estimate flank and crater wear, both thermally and mechanically induced wear mechanisms are included: dissolution and diffusion as well as abrasion due to hard oxides and nitrides in the workpiece material. It should be noted that some parts of the MCutSim codes and models are not fully integrated with the GUI – and can only be accessed in command mode (MATLAB codes). An additional effort is required for a complete integration of implemented codes and MATLAB GUI. This software is able to connect to SFTC DEFORM software for more advanced calculations and process optimisation. WEAR-FRAME developments are beyond the state-of-the-art in various ways and can, for example, assist material handling and procurement before execution of machining operations. In particular, the developments by WEAR-FRAME make it possible to plan the machining operations for a given batch of material to determine which batch of material meets shopfloor requirements.

Despite these advancements, however, full three-dimensional machining simulations remain a challenge. Moreover, certain discrepancies persist, particularly in the prediction of wear geometries, due to complex tribological phenomena existing on the tool surfaces. These limitations underscore the need for continued research, particularly in refining key modelling parameters such as tool–workpiece contact interaction and extending them for 3D simulations. There is a strong incentive to further develop modelling and simulation capabilities to facilitate rapid evaluation of machining conditions (e.g., in face turning, longitudinal turning, and milling) and to enable feedback-driven updates to machining databases. To this end, future technologies must offer both qualitative and quantitative real-time assessment of machining outputs – such as cutting forces, temperatures, and tool wear – under varying cutting conditions (e.g., speed and feed). These technologies must also align with experimental methodologies to accommodate diverse material grades.

Nevertheless, these recommended technologies should be viewed as essential pieces of a larger system, i.e. an integrated physics-based and sensor-based tool condition monitoring system – adaptive to variations in cutting allowance for example due to variations in cast or forged workpiece dimensions. This system should also be sensitive to the variations in the tool characteristics and workpiece materials. To this end, we identified the needs for developing tool condition monitoring systems and algorithms in both cutting and grinding – and investigated the feasibility for sensor-based tool wear prediction using advanced signal processing methods. Various sensors are used in this project, including accelerometer, microphone, acoustic emission, and force dynamometer. This development was a vital need since stochastic wear types like chipping are identified in production lines – yet are impossible to simulate using physics-based models. This urges the development of integrated approaches in future endeavours. Our models and methods developed in the lab-environment had different levels of success in the production lines. This is mainly because of the limitations and constraints in industry-relevant environments that need to be revisited. For example, in some cases, the current production strategy is that the input materials are not sorted based on forging or steel supplier and they are instead treated equally in a production line. Upon further developments in the project and the relative success of the Hilbert-Huang Transforms in lab-based tests, further analysis of industrial signals needs to be conducted to determine if worn and unworn tools can be distinguished in production lines using the relatively successful HHT method.

In summary, two major deliverables have emerged from the project:

- A state-of-the-art physics-based platform for modelling and simulation of tool wear in machining adaptive to the major changes in microstructural properties of carbon steels and cast irons.
- Reliable and robust tool wear monitoring solutions which are based on various sensors (e.g., accelerometer, force, acoustic emission and microphone) and signal processing approaches adaptable for metal cutting and grinding processes.

The project has also contributed to capacity building in industrial modelling and experimental validation of machining processes, particularly through the extensive time invested in demonstrator testing. The project represents a significant step toward a digital framework for machinability assessment. The integration of consistent modelling, simulation, and experimental validation has enabled the establishment of key control and response parameters within a structured database. The machine learning components built upon this foundation can be further enhanced by expanding the parameter and material space. Nevertheless, additional research and continued collaboration between academia and industry are essential before the developed models and methods can be fully adopted in industrial practice.

9. Participating parties and contact persons

AB Volvo, Jonas Svensson

- jonas.svensson.8@volvo.com

Seco Tools AB, Rachid M'Saoubi

- Rachid.Msaoubi@secotools.com

Skärteknikcentrum Sverige AB, Ulrika Elmersson

- ulrika@sktc.se

Gnosjö Automatsvarvning AB, Jens Ringborg

- Jens@svarvning.nu

Scania CV AB, Lorenzo Daghini

- lorenzo.daghini@scania.com

Chalmers, MC2, Per Hyldgaard

- hyldgaar@chalmers.se

Chalmers, IMS/MCR, Amir Malakizadi

- amir.malakizadi@chalmers.se

10. References

1. Ivester, R.W., et al., *Assessment of machining models: progress report.* Machining Science and Technology, 2000. **4**(3): p. 511-538.
2. Kramer, B.M. and B.F. von Turkovich, *A Comprehensive Tool Wear Model.* CIRP Annals, 1986. **35**(1): p. 67-70.
3. Kramer, B.M. and P.K. Judd, *Computational design of wear coatings.* Journal of Vacuum Science & Technology A, 1985. **3**(6): p. 2439-2444.
4. Kramer, B.M. and N.P. Suh, *Tool wear by solution: A quantitative understanding.* Journal of Engineering for Industry, 1980. **102**(4): p. 303-309.
5. Tooptong, S., K.-H. Park, and P. Kwon, *A comparative investigation on flank wear when turning three cast irons.* Tribology International, 2018. **120**: p. 127-139.
6. Kwon, P., *Predictive Models for Flank Wear on Coated Inserts.* Journal of Tribology, 1999. **122**(1): p. 340-347.
7. Malakizadi, A., et al., *Physics-based approach for predicting dissolution–diffusion tool wear in machining.* CIRP Annals, 2020. **69**(1): p. 81-84.
8. Methon, G., et al., *Efficient predictive simulation of tool wear in face milling using an advanced 3D numerical approach.* Wear, 2025: p. 205946.
9. Courbon, C., et al., *A 3D modeling strategy to predict efficiently cutting tool wear in longitudinal turning of AISI 1045 steel.* CIRP Annals, 2021. **70**(1): p. 57-60.
10. Attanasio, A., F. Faini, and J.C. Outeiro, *FEM Simulation of Tool Wear in Drilling.* Procedia CIRP, 2017. **58**: p. 440-444.
11. Zhang, N., et al., *Study on the effect of wear models in tool wear simulation using hybrid SPH-FEM method.* Procedia CIRP, 2023. **117**: p. 414-419.
12. Binder, M., F. Klocke, and B. Doebbeler, *Abrasive wear behavior under metal cutting conditions.* Wear, 2017. **376-377**: p. 165-171.
13. Binder, M., F. Klocke, and B. Doebbeler, *An advanced numerical approach on tool wear simulation for tool and process design in metal cutting.* Simulation Modelling Practice and Theory, 2017. **70**: p. 65-82.
14. Binder, M., F. Klocke, and D. Lung, *Tool wear simulation of complex shaped coated cutting tools.* Wear, 2015. **330–331**: p. 600-607.
15. Malakizadi, A., et al., *Post-processing of additively manufactured metallic alloys – A review.* International Journal of Machine Tools and Manufacture, 2022: p. 103908.
16. Hoier, P., et al., *Microstructural variations in 316L austenitic stainless steel and their influence on tool wear in machining.* Wear, 2019. **428-429**: p. 315-327.
17. Bjerke, A., et al., *Onset of the degradation of CVD α-Al2O3 coating during turning of Ca-treated steels.* Wear, 2021. **477**: p. 203785.
18. Salame, C., *An integrated framework for enhanced machining: Machinability analysis, thermal modelling, and sensor-based monitoring*. 2024, Chalmers University.
19. Salame, C., et al., *Sensor-based identification of tool wear in turning.* Procedia CIRP, 2024. **121**: p. 228-233.
20. Hoier, P., et al., *Characterization of abrasion- and dissolution-induced tool wear in machining.* Wear, 2019. **426-427**: p. 1548-1562.
21. Jiang, X., J. Zhao, and X. Jiang, *Correlation between hardness and elastic moduli of the covalent crystals.* Computational Materials Science, 2011. **50**(7): p. 2287-2290.
22. Racioppi, S., P. Hyldgaard, and M. Rahm, *Quantifying Atomic Volume, Partial Charge, and Electronegativity in Condensed Phases.* The Journal of Physical Chemistry C, 2024. **128**(9): p. 4009-4017.
23. Racioppi, S., et al., *A density functional theory for the average electron energy.* Journal of Chemical Theory and Computation, 2023. **19**(3): p. 799-807.
24. Gao, F., *Theoretical model of intrinsic hardness.* Physical Review B, 2006. **73**(13): p. 132104.

25. Gao, F.M. and L.H. Gao, *Microscopic models of hardness.* Journal of Superhard Materials, 2010. **32**(3): p. 148-166.
26. Malakizadi, A., et al., *A physics-based constitutive model for machining simulation of Ti-6Al-4V titanium alloy.* Procedia CIRP, 2023. **117**: p. 335-340.
27. Babu, B. and L.-E. Lindgren, *Dislocation density based model for plastic deformation and globularization of Ti-6Al-4V.* International Journal of Plasticity, 2013. **50**: p. 94-108.
28. Malmelöv, A., et al., *Mechanism Based Flow Stress Model for Alloy 625 and Alloy 718.* Materials, 2020. **13**(24): p. 5620.
29. Allain, S. and O. Bouaziz, *Microstructure based modeling for the mechanical behavior of ferrite–pearlite steels suitable to capture isotropic and kinematic hardening.* Materials Science and Engineering: A, 2008. **496**(1): p. 329-336.
30. Trent, E.M. and P.K. Wright, *Metal cutting*. 2000, Boston: Butterworth-Heinemann.
31. Salame, C. and A. Malakizadi, *An enhanced semi-analytical estimation of tool-chip interface temperature in metal cutting.* Journal of Manufacturing Processes, 2023. **105**: p. 407-430.
32. Malakizadi, A., et al., *An FEM-based approach for tool wear estimation in machining.* Wear, 2016. **368–369**: p. 10-24.