A simulation based guide to machinability assessment

Public report

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1 Sammanfattning

Skärande bearbetning spelar en viktig roll inom bilindustrin. En central fråga är skärbarheten av inkommande material (stål, aluminium, gjutjärn etc.). För att möta allt strängare krav på bränsleförbrukning introduceras nya legeringar med förbättrade mekaniska egenskaper men som i allmänhet har sämre skärbarhet. Speciellt påverkas verktygslivslängden och längre bearbetningscykeltider erhålls för bearbetning av nyckelkomponenter som: cylinderblock i gjutjärn/aluminium, vevaxlar och kamaxlar i stål. Vanligtvis upptäcks dålig bearbetbarhet för sent i bearbetningsprocessen.

Projektets syfte är därför att skapa en digital guide för att bedöma skärbarheten hos de inkommande materialen baserad på experimentella- och simuleringsbaserade data sammanställda i en strukturerad databas. Huvudfrågor i projektet handlar om att finna relevanta demonstratorer med tillhörande skärparametrar så att dessa låter sig struktureras med fysiska och simuleringsdrivna skärexperiment i en databas. Databasen tillåts hela tiden ”växa” genom inkorporering av fler och fler data för prediktering med Machine Learning (ML). På så sätt förbättras hela tiden vår modell i takt med att utökade data erhålls. Två demonstratorer, en för face-turning, och en för face-milling operationer, har utvecklats. Den senare demonstratorn är kopplad till en strukturdynamisk modell för prediktion av vibrationer på grund av t ex håltagningar och skillnader i material etc.

Detta synsätt har arbetats fram i projektet genom att succesivt adressera modelleringsfrågor kopplat till relevanta skärexperiment, först i 2D och sedan i 3D (för face turning/milling). Totalt har vi passerat 6 på förhand definierade milstolpar. Bl a har en materialmodell för duktil skadeutveckling under höga deformationshastigheter och förhöjd temperatur i arbetsmaterialet utvecklats. Vi har även studerat effektiv kalibrering av materialparametrarna. Detta för att kunna utveckla databasen med simuleringsdata på ett tillförlitligt sätt.

Sedan har vi landat i iden till skärbarhetsguiden med data för skärkrafter, spånbildning och verktygsslitaget under olika skärhastigheter och matning. Syftet är att förbättra kvaliteten på producerade komponenter, och att förkorta ledtiden vid införande av nya material i produktionen. Därmed bestämmer guiden skärbarheten från bearbetningsparametrarna via verktygsgeometri, arbetsmaterial och bearbetningssystem. Ingångsparametrarna redovisas i simuleringarna genom att modellera de mekaniska, termiska och materialinteraktionerna i bearbetningen.

Tillsammans utgör databasen tillsammans med det ML-baserade predikteringsverktyget en värdefull grund för vidare modellutveckling. Vi bedömer att projektet tagit oss avsevärda steg mot en ökad förmåga att simulera skärprocessen. Projektarbetet har även resulterat i en generellt ökad kompetensnivå kring modellering och simulering av skärande bearbetning hos medverkande projektparter.

Eftersom den experimentella ansträngningen som krävs för att bedöma bearbetbarheten är enorm så är simuleringsdrivna skärdata nödvändiga för att komplettera databasen. Simuleringarna är dock fortfarande begränsade i sin predikteringsförmåga, speciellt när det gäller vissa skärkrafter. Således, återstår viktig forskning och samverkan innan industrin har full förmåga att utveckla den simuleringsdrivna delen av guiden. Detta innefattar både en ytterligare höjning av kompetensnivån hos industriföretagen, men också fortsatt forskning för att adressera kvarstående forskningsfrågor.

2 Summary

The project concerns the development of a machinability guide implemented as a digital twin based on virtual simulations and machining experiments. In fact, short tool life and/or long machining cycles due to conservative range of cutting conditions represent key challenges in reducing lead times in the production lines. This problem becomes particularly important when new material grades are to be introduced to meet the present-day design targets - typically related to reducing the weight of engine components. The simulation-based guide thereby represents a generic tool to transfer simulated machinability data to the production. The new tool enables the industrial end-users to significantly shorten the lead-time associated with the introduction of new materials and management of materials variation in production. If the guide is properly implemented, a signficant reduction of

experimental trial-and-error work in production shopfloors is expected. This is why robust integration of reliable CAE approaches in symbiosis with experimental methods is so important to reduce the time and costs needed for the process planning. Moreover, increase in the quality of production of engine critical components will be attained, given the capability to accurately predict and optimize the machining operations. In the development of the guide, inter-disciplinary research in the areas of metal cutting, machining-system dynamics and computational material science has been integrated. The guide consists of two separate implementations, one for the face turning demonstrator focused on cutting forces, tool wear and chip formation based on steel material. The digital twin implementation consists of a structured data from machining experiments and simulations combined with a machine learning methodology to predict machinability. The other one is focusing on the process machine interaction applied to a face milling demonstrator. The simulation tool considers the presence of holes and slots, geometric errors in the machine tool mechanics combined with the existence of vibrations during cutting.

The project is carried out by a consortium of four industrial partners, AB Volvo, VCC, Powertrain Engineering Sweden AB (Aurobay), Scania CV AB and AB Sandvik Coromant, and two main academic partners, Chalmers – MCR and KTH – DMMS. The main applicant is Professor Ragnar Larsson, dept. of Applied Mechanics, Chalmers.

3 Background

Metal cutting processes play an important part in automotive industry. A central issue for the metal cutting is the machinability of the incoming materials. To meet increasingly tighter standards on fuel consumption, new materials with enhanced mechanical properties are introduced. These new materials are generally “difficult to cut”, associated with reduced tool life and longer machining cycle times for the machining of key components such as: cast iron cylinder blocks and heads, crankshafts, camshafts and gears. Typically, poor machinability is often detected too late in the machining process. The challenges with the incoming workpiece materials (i.e. new high strength materials and property variations of existing materials) in the production require a huge experimental effort to assess the machinability. This is generally associated with excessive costs, time and waste.

Thereby, the major incentive for this project is the need to reduce the experimental cost in real production lines by developing a *simulation based machinability guide* to assess machinability of new incoming materials. The purpose and aims are thus: (1) to improve the quality of produced components, and (2) to shorten the lead-time when introducing new materials into production. The guide should include cutting forces, chip formation and tool wear under various cutting conditions when machining new grades of steel and aluminum. Thereby, the guide determines the machinability and it is evaluated from the output machining process parameters as obtained via simulation of input parameters like tool geometry, workpiece materials and machining system. The input parameters are accounted for in the simulations by modelling the mechanical, thermal, and material interactions in the processing. By new incoming materials, we mean here workpiece materials where our challenges involve: different aluminum alloys for cylinder blocks and heads, challenging specifications for forging steel for crankshafts, camshaft, gears, cast iron material for cylinder blocks and heads.

Here, it may be remarked that the project is completely in-line with the digitalization trend. As the machinability guide has been developed in the project, the guide is formulated around typical machining operations (face turning of steel and milling of aluminum, gray cast iron), where experimental and modeling developments are motivated and collected. Machinability predictions including both the FE-modeling and experimental development are then being made based on a machine learning algorithm. The developments are in-line with a number of previous projects carried out via the MCR environment at Chalmers. In this context we also mention our consortium at Chalmers-MCR and KTH-DMMS, focusing on material modeling issues of the cutting zone in symbiosis with the experimental technology, (1) (2) (3) (4) (5) (6) (7) (8) (9), as well as machining system dynamics, (10) (11) (12) (13). In particular, the application of FE-based approaches has also been extensively addressed in international research and development, e.g. Birmingham University (14), the WZL-lab of RWTH Aachen University (15), the group in Mondragon University (16) (17) and the research at LTU, cf. Lindgren et al. (18).

4 Purpose, research questions and method

The purpose of the project has been to develop a machinability guide based on virtual simulations and experiments for selected machining operations, integrating inter-disciplinary research in the areas of metal cutting, machining-system dynamics and computational material science. The idea with the new tools is to enable the industrial end-users to significantly shorten the lead-times associated with the introduction of new materials, machining processes, and management of materials variation in production.
The following research questions are addressed:

- How to design a material model for the prediction of cutting forces, temperatures and chip formation close to real life production? The model is to be used for FE-modelling of representative workpiece materials combined with the prediction tool wear.
- How to generate the experimental data necessary for calibration/validation of the material model including tool wear. Also machining process calibration is considered.
- How to incorporate geometric nonlinearities and multi-material surfaces in real life workpieces into the modeling of machining processes.
- A major challenge is the efficient process discretization allowing for the handling of sufficiently accurate virtual process data generated during the cutting process.
- How to develop of demonstrators that are capable of handling representative cutting parameters, leading to cutting forces and temperatures that can be validated from virtual simulation.
- How to develop a machinability guide capable of handling the cutting response (e.g. forces and temperatures) for selected variation of the controlled cutting parameters. The delivery of the guide is made for a selected material based on Al-alloys, steel and cast iron central to all the involved project partners.

4.1 Method

In order to handle the research questions above, the project is subdivided from the outset into three main development processes:

- material modeling and calibration campaign, establishing the representative material model, calibrated against e.g. crankshaft steel from orthogonal cutting tests.
- machinability parameter study campaign, carrying out process parameter studies using a simulation tool for a suitably chosen machining operation with respect to the material parameter variation developed in the material modeling and calibration campaign. A milling and/or face turning operation is taken for demonstration.
- studies of forced vibration spectra in relation to varying machining parameters in geometrical nonlinear workpieces with multi-material surfaces. A dedicated simulation framework incorporating relevant machine tool characteristics relevant to machining quality is developed.
- machinability guide development campaign, collecting data into a structured database, describing key machinability parameter variations from virtual simulations and experiments of the chosen demonstrator. In this campaign, effects of tool wear as well as effects of the machining system will also be included.

The different campaigns are further subdivided into work packages defined by

WPA, Material modeling and simulation
Work-package leader Ragnar Larsson, Chalmers MCM

In this WP the modeling of the workpiece material in the cutting zone has been addressed. Key research issues are degradation of the material at ductile thermomechanical failure conditions while preserving a FE-mesh objective energy dissipation. Figure 1 shows the details of a split-Hopkinson tensile bar test based on a novel thermal ductile damage formulation produced in the scope of the project. Also, FE representation of chip formation and its dependence on the cutting parameters is dealt with. In these developments, we have passed our SOTA via milestone M1: *ductile thermomechanical failure assessment with preserved mesh objective energy dissipation*.

Another issue of this WP is the cutting force/tool wear interaction problem, strongly coupled to the heat generation and temperature assessment in the cutting zone. The coupling between the advanced thermo-mechanical material model development and the cutting force/tool wear analysis has passed our SOTA, via our milestone M2: *coupling between thermo-mechanical material modeling and force/tool wear interaction*.

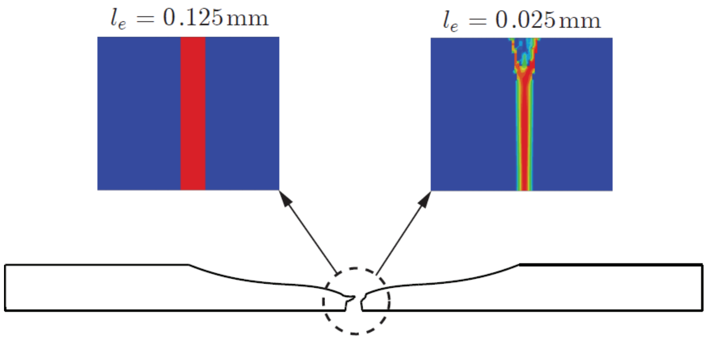

Figure 1 Details of a ductile split-Hopkinson tensile bar fracture for the finest FE discretization $l_e = 0.025$mm. The initial temperature is 300℃. The close-ups show the captured damage pattern for the coarsest and finest FE discretizations. Here, "red" means fully developed damage. From (21).

WPB, Material testing and model calibration

Work-package leader Amir Malakizadi Chalmers – MOT

In this work-package extensive testing has been carried out at different turning operations in order to activate the representative workpiece material behavior. A number of orthogonal and face turning cutting tests have been carried out for different cutting controls (such as cutting speed and feed rate) and the responses (such as the cutting forces, chip thickness, tool-chip contact length and cutting temperature) have been measured experimentally for each cutting experiment. Tool life testing to generate data for tool wear model calibration and validation has also been carried out. Here, we have focused on: measurements of flank wear, and investigations of the dominant wear mechanism using Scanning Electron Microscopy (SEM) and X-ray dispersive spectroscopy of the temperature and cutting force variations as the tool wear develops. Tailored cutting inserts with in-built holes were used to measure the temperature using thin thermocouples (0.25 mm in diameters). The position and depth of the holes were identified using FEM to ensure that we obtain sufficiently large differences in temperature readings for inverse identification of heat flux. In these developments we have passed our SOTA via our milestone M3: *temperature assessment via modeling and experimental verification*.

Related to the testing campaign and for the guide development, an efficient and robust material parameter calibration is important for speed-up of the process for new incoming materials. Various numerical and semi-analytical procedures, based on 2D orthogonal cutting tests including tool wear (1), have been examined and developed. In particular, an efficient semi-analytical calibration technology of the constitutive parameters (for a Johnson-Cook based material model, (19) (20) has been developed. In these developments we have passed our milestone M4: *dissipation objective material model combined with efficient parameter identification at continuous chip formation*.

WPC, Machining system simulation

Work-package leader Andreas Archenti, KTH Production Engineering

The goal of WPC is the development of a novel simulation approach for the Process-Machine-Interaction (PMI). Most existing models aim at predicting cutting forces based on analytical formulations of the chip formation. However, in industrial applications, the formulation of these equations is challenging due to possible discontinuities in the workpiece, e.g. holes and slots, and challenging geometries, e.g. free-form surfaces, geometric errors in the machine tool mechanics and the existence of vibrations during cutting. The developed framework combines the dynamic and kinematic machine tool characteristics with a geometric description of the cutting tool and the workpiece based on robust algorithms from computational geometry. The significance of the prementioned effects on the machining depends on the use-case, hence the development focused on the modularization of the machining process. Therefore, the outcomes of WPC are of fundamental interest for further researchers and industrial applicants. Further developments comprise the prediction of the machine tool dynamics withing the work envelope and the acceleration-based surface prediction based on neural networks. The developed methodology consists of several sequential steps: The first step is a discretization of the workpiece based on Computer Aided Design (CAD) data. This is followed by the analytical modeling of the cutting tool and the machine tool kinematics. The geometric machine tool errors are superimposed on the derivation of tool trajectories derived from standard G-Code. During each timestep, the framework then calculates the Tool-Workpiece-Engagement (TWE) and predicts the cutting forces based on a mechanistic cutting force model. Incorporating a model of the machine tool dynamics, these forces are used to calculate the Tool-Center-Point (TCP) deviation from the nominal trajectory. The modified engagement geometry is finally mapped onto the generated surface of the discretized workpiece. For process planners, the resulting force spectra, surface patterns and achieved machining accuracies are invaluable indicators of the machinability of new processes.

With these developments we have passed our milestone M5: *methodology for assessing influence of machining system on machinability*.

WPD, demonstrators and machinability guide development
Work-package leader Goran Ljustina, VCC, Powertrain Engineering Sweden AB

In this WP two demonstrators have been developed. One demonstrator is related to face turning for camshaft steel and the other demonstrator considers a milling process for different grades of aluminum and gray cast iron. The demonstrators summarize the results from WPA-WPC and serve as the basis for the machinability guide development. No such digital demonstrator for machinability predictions has existed before. Hence, in this development, we have passed our current SOTA, stated in milestone M6: *machinability guide generation by process parameter variations*.

5 Main project goals

The main goal of the project is to:

- to devise a machinability guide that can be used with confidence to predict the machinability of the workpiece material geometry for a selected machining operation.

To approach the main goal, the following sub-goals (=milestones) are formulated:

- develop a model for the workpiece material behavior in the cutting zone for ductile thermomechanical failure assessment with preserved mesh objective energy dissipation.
- sort out the key machining parameters and their range through representative physical workpiece material testing of selected machining operations.
- develop an efficient calibration strategy for material parameter identification at continuous chip formation.
- incorporate the coupling between thermo-mechanical material modeling and cutting force/tool wear interaction, enhanced by elevated temperatures.
- develop a computational efficient methodology for predicting the Process-Machine-Interaction based on structural dynamics and virtual process cutting forces.
- assess the temperature and its distribution in the cutting zone via modeling and experimental verification.
- to propose a methodology for process-machine interaction based on structural dynamics involving virtual process generated cutting tool forces.

6 Results and fulfilment of goals

6.1 Project results

The most important results from the project are summarized related to how we have passed the *milestones 1-6* per work package.

WPA, Material modeling and simulation

Related to *milestone 1* we have made significant developments summarized in papers (21) , (22), (23) and (24). In (21), an approach to ductile failure modeling is derived based on continuum thermodynamics and damage. A continuum damage enhanced formulation of the effective material is used to describe the degradation of the response. From the thermo-mechanically motivated dissipation rate, a novel damage driving energy that involves both stored energy and dissipative contributions due to inelasticity is presented. This damage driving energy is combined with a damage threshold that controls the onset of inelastic damage driving dissipation. As main prototypes for the effective material and damage threshold, the Johnson–Cook continuum and failure models are exploited. From the verification examples, satisfactory convergence properties of the model are obtained. The model capabilities to represent real thermodynamic ductile failure processes are demonstrated for a specimen made of a ductile Weldox steel subjected to tensile split-Hopkinson Tension Bar tests. The model is computationally efficient and shows well controlled damage progression in the FE-application, cf. Figure 2.

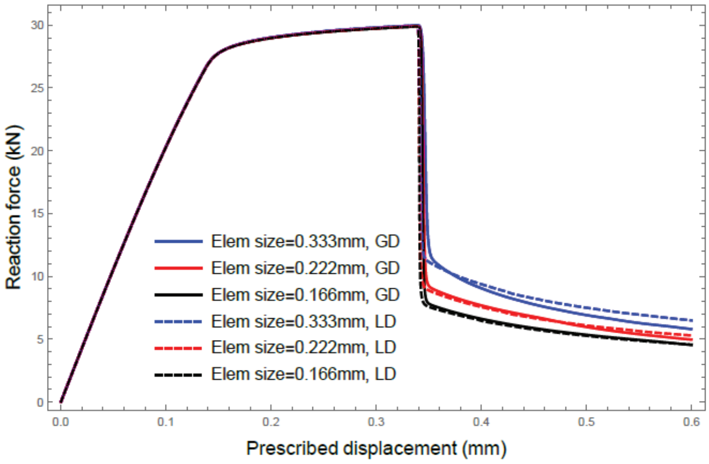

Figure 2 Mesh convergent behavior of proposed damage evolution used to be used in machining modeling and simulation.

An extension is developed in refs. (5), (22), (23) to include gradient-enhanced damage model for ductile fracture modeling, describing the degraded material response coupled to temperature. Again, the viscoplastic Johnson-Cook constitutive model serves as prototype for the effective material. A novel feature is the damage-driving dissipation rate, allowing for elastic and plastic components separated by a *global damage threshold* for accumulation of inelastic damage-driving energy. In the application to a dynamic split-Hopkinson test and two quasi-static tensile tests, the gradient damage model is compared with the corresponding local model. For isothermal conditions, the examples show that both damage models exhibit mesh convergent behavior when using the global damage threshold.

As to *milestone 2*, a novel model for rigid viscoplastic flow and continuous damage evolution is proposed for the modeling and simulation of chip formation of the Alloy 718. The model in ref. (25) advances purely dissipative flow stress problems in the DEFORM 2D™platform. Onset of damage evolution is controlled by a modified Cockcroft-Latham failure criterion, facilitating a flexible modeling of serrated chip formation. By comparing the proposed continuous damage degradation model to the damage drop method in DEFORM 2D™, the role of ductile failure on the chip formation is investigated. The model is calibrated and validated against experimental machining tests, where both continuous and serrated chip formation is observed for the Alloy 718 depending on the cutting speed. From the experiment, cutting forces, chip shapes and tool-chip contact lengths were analyzed and compared to the model response, cf. Figure 3. A good agreement between model and experimental results is obtained.

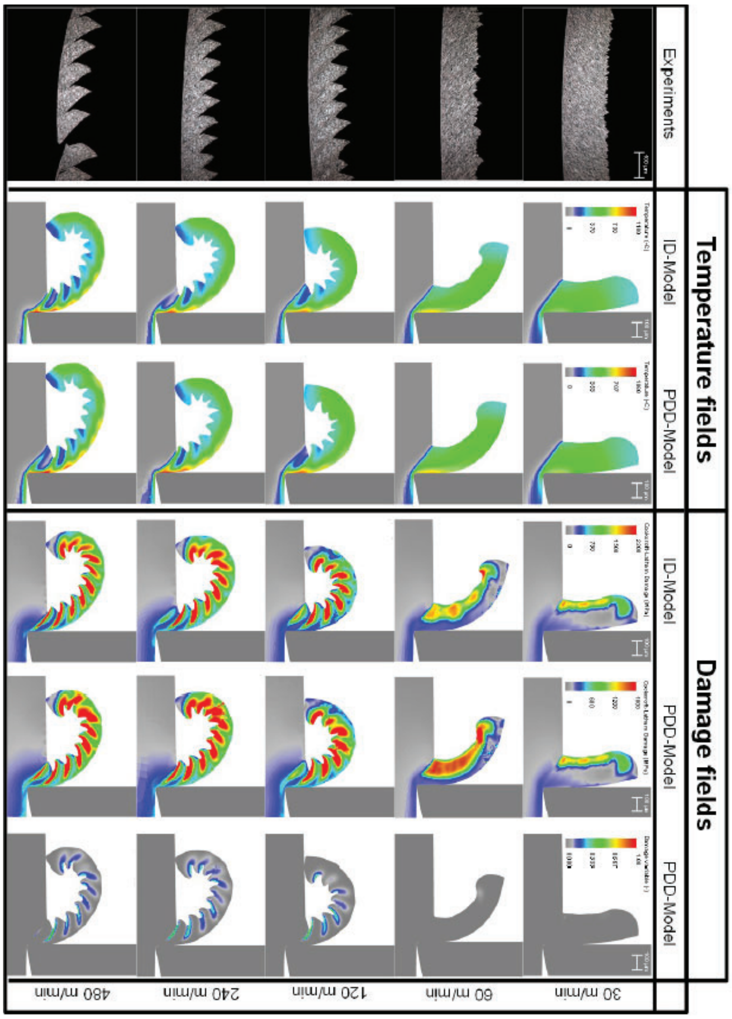

Figure 3 Comparison between temperature and damage fields for the modeling of chip formation at different cutting speeds. The workpiece material is Alloy 718. Note that serrated chips are predicted from $120m/min$.

WPB, Material testing and model calibration

Related to *milestone 3*, extensive testing has been carried out for different turning operations. In particular, we are considering thermal investigation of turning processing. The work is summarized in paper (26). The paper considers temperature measurement of the setup (main results), thermal simulations (modeling, steady state and transient), calibration of heat flux related to temperature distributions. Main results are shown in Figure 4Figure . The temperature measurements are used for calibration of time dependent heat flux. The calibrated heat flux is validated through machining simulations. Key machining parameters such as the heat transfer friction coefficients are, in turn, determine on the time dependent heat flux.

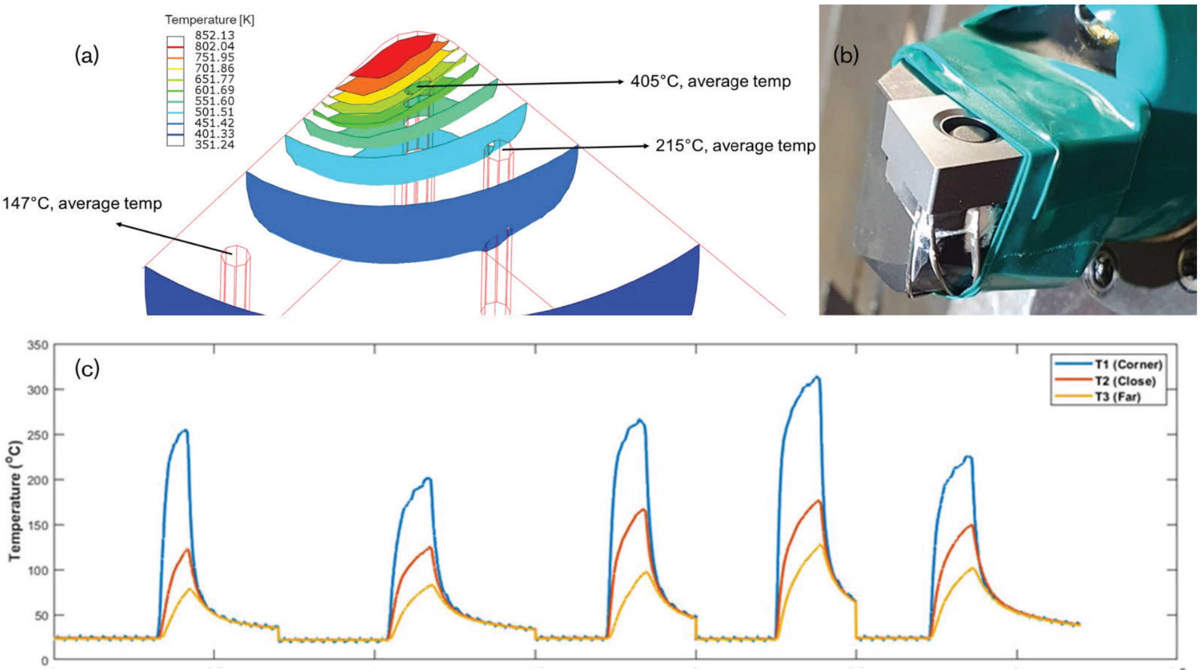

Figure 5 FE- assisted identification of thermocouple positions for inverse assessment of heat flux in cutting (a), the experimental set-up including three thermocouples attached to cutting insert (b), temperature readings from each thermocouple at different cutting conditions.

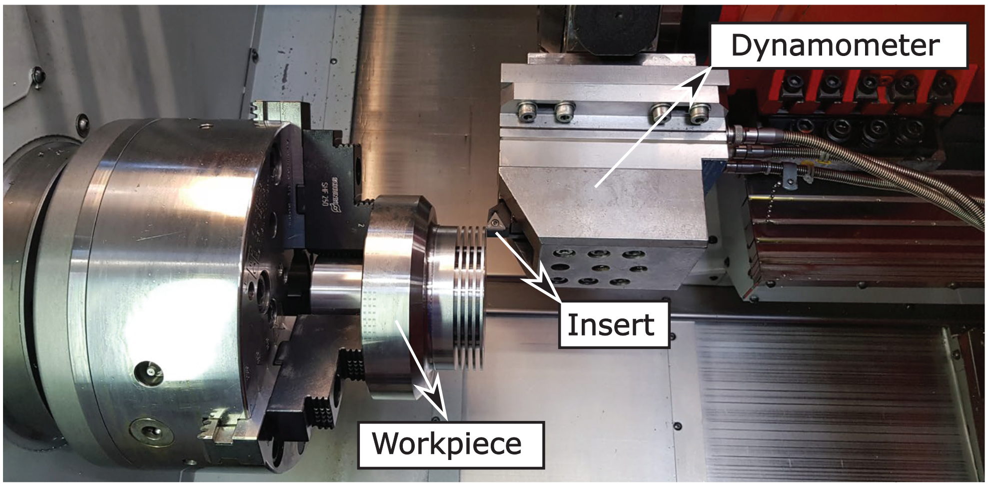

Figure 4 Set-up used for orthogonal cutting tests to calibrate the flow stress models and to validate the results

Related to *milestone 4*, a novel thermomechanically coupled distributed primary deformation zone model has been developed in (19) to assist the inverse identification of Johnson-Cook material parameters to be used for machining simulations. The experimental set-up is shown in Figure 5. A special feature of the enhanced model is that the assumed stress field is temperature-dependent, where the thermomechanical coupling governs the stress and temperature distributions across the primary shear zone to describe the thermal softening effect. By using stress, strain, strain rate, and temperature distributions from the thermomechanically enhanced model, Johnson-Cook material parameters are calibrated for orthogonal cutting tests of C38, 42CrMo4, and AA6082 materials where continuous chip formation prevails. The performance of the parameters is compared with that of a wider set of cutting tests using finite element simulations. The results show that the thermomechanically motivated model yields closer results to experiments in terms of cutting force and chip thickness (9% and 34% difference, respectively) compared with the original thermally uncoupled model (47% and 92% difference, respectively). Identification of the material parameters by this method focuses directly on the orthogonal cutting test and it does not require many experiments or simulations. In fact, the proposed methodology is computationally robust and cost-efficient which makes it preferable compared with other methods which are more accurate but highly time-consuming.

WPC, Machining system simulation

In order to approach *milestone 5*, “methodology for assessing influence of machining system on machinability”, the modular node-based software platform SharpCut (#cut) has been developed. The platform follows a sequential modeling approach modularizing the manufacturing processes using nodes. The considered machine tool characteristics are the geometric errors and the dynamic behavior of the machine tool. First part of the simulation is the accurate and numerically efficient prediction of the Tool-Workpiece-Engagement as summarized in (8).

The model of the machine tool kinematics uses Homogenous Transformation Matrices (HTMs) and Look-Up-Tables (LUTs) of the kinematic errors (27). In this project, we measured the positioning accuracy, straightness, and squareness of the lab machine demonstrator AFM Baca R1000, ANDRYCHOWSKA FABRYKA MASZYN DEFUM S.A., POLAND with a XL-80 laser system, RENISHAW PLC, WOTTON-UNDER-EDGE, UNITED KINGDOM. At industrial applicants, these measurements are often available due to frequent machine tool calibrations. The discretization of the workpiece uses the multi-axial depth-element (Dexels) approach (28). This approach reduces the memory storage of the three-dimensional workpiece surface to a one-dimensional representation. Finally, the cutting edge of the tool is discretized via an adaptive triangulation for a better approximation of smaller nose radii. This discretized edge is moved along a predefined toolpath generated from standard ISO 6983 G-Code and repeatedly checked for interference with the discretized workpiece. The cutting chip detection is based on a vectorized Havel-style ray-triangle intersection and outsourced onto the simulation machine’s GPU if available. Further improvements of the numerical efficiency result from the storage of the workpiece data into a spatial index, i.e. a quad tree. Figure 6 shows examples of the prementioned calculation steps and results.

Once a cut is detected, the chip intersection is transformed into the 2D plane of the insert’s rake face. As the scattered point cloud is not always convex, an alpha shape algorithm is used to detect the boundary of the intersection. Additional filters based on sweeping lines clean up the result. The resulting chip is then discretized using an algorithm similar to (29). From there, a mechanistic cutting model is employed to calculate the cutting forces in the insert coordinate system based on the unified cutting force model for turning, boring, drilling, and milling operations presented by (29). The resulting normal and tangential forces are finally transformed back into the machine tool coordinate system to predict the global forces on the structure.

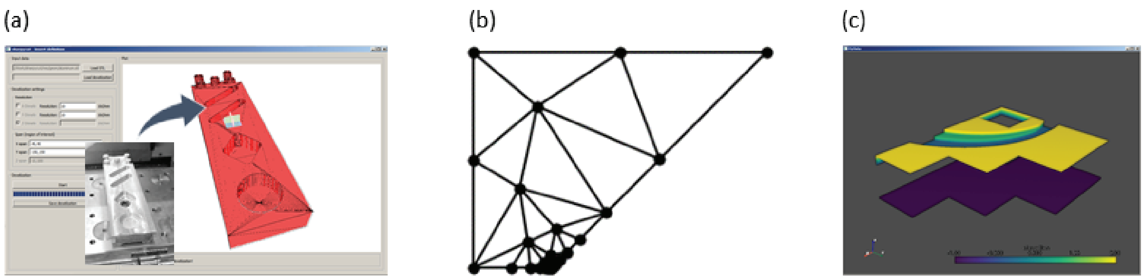

Figure 6 Machining system simulation: a) Graphical User Interface implementation of the discretization of the aluminum test workpiece, b) triangulation of one cutting insert, c) detected Tool-Workpiece-Engagement

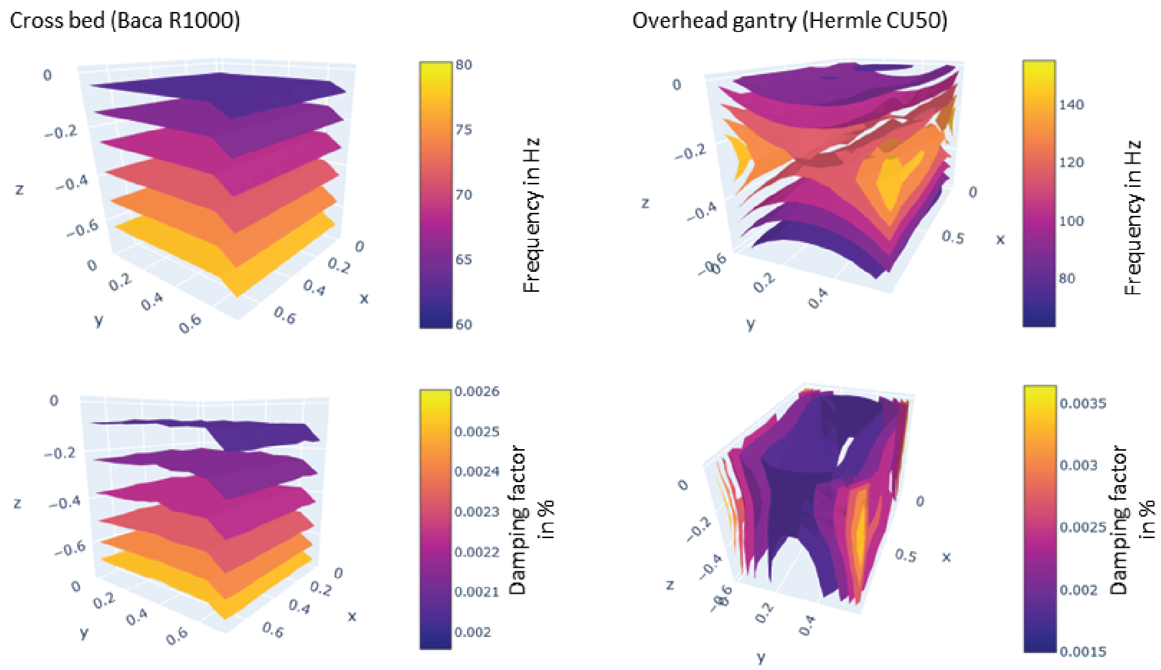

Figure 8 Spatial dependency of the dynamic behavior of a Baca R1000 and Hermle CU50 type machine tool. Values displayed are for the first vibrational mode.

The last step in the simulation of the PMI is the accounting for the dynamic behavior of the machine tool structure, as the cutting forces deflect the cutting tool during the cutting process. Research was performed on the application of the Algorithm of Mode Isolation (AMI) for the semi-automatic detection of the structural dynamics, i.e. modal parameters, of machine tools (30). In a naïve approach, the acquired values are gathered in a LUT and queried depending on the position of the Tool-Center-Point (TCP). They are used to form a Zero-Pole-Gain model which allows for the integration of displacements in the fixed timesteps, cf. (31). Additionally, we explored another path based on the modeling of the machine tool dynamics with machine learning. (32) and the surface reconstruction based on a prediction of the periodic force spectrum (33). Figure 7 displays the derived dynamic spatially dependent modal parameters for the first machine tool mode in a Hermle CU50 and a Baca R1000 type machine tool.

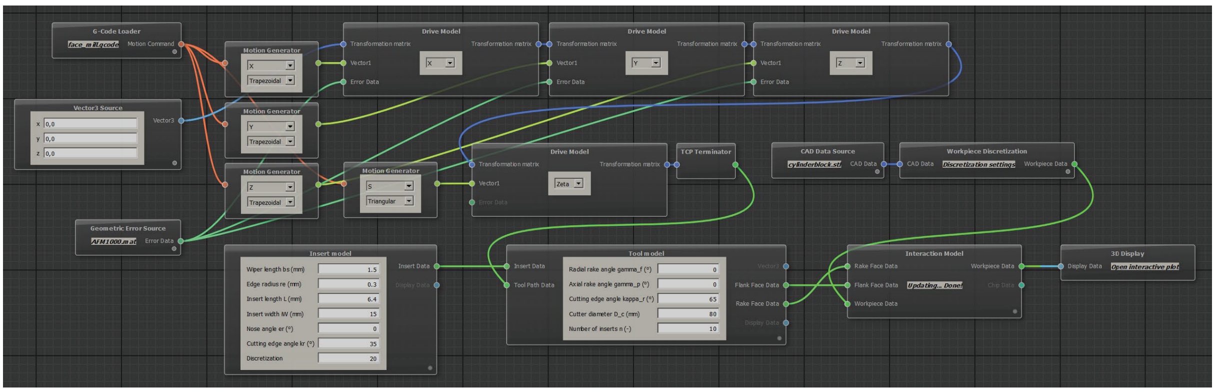

Figure 7 Graphical node editor for the modelling of the Process Machine Interaction; implementation of a three-axis Baca R1000 milling machine tool

One major strength and novelty of the WPC result is the open and modular design in all parts of the framework. SharpCut is completely written in the free programming language Python and uses only libraries with a permissive license. That way commercial entities such as industrial applicants as well as non-profit organization and researchers can build their models atop of this basis. To further encourage the usage of the developed framework in an industrial context, a graphical node editor was implemented as a graphical abstraction of the prescribed modules. That way, the modules can be visually connected to from, e.g., different machine tool kinematics or simulate batches of process parameters. Figure 8 displays the editor and shows the implementation for the lab machine tool demonstrator Baca R1000 including its kinematic errors.

The source code is available in a GitHub repository. A publication in the Journal of Open Source software is in the pipeline (34). The framework is accompanied by an extensive documentation as well as tutorials accessible under the following link.

- Documentation and tutorials: https://gits-15.sys.kth.se/pages/bpeuke/sharpycut/
- Source code: https://gits-15.sys.kth.se/bpeuke/sharpycut

WPD, demonstrators and machinability guide development

Related to *milestone 6*, the machinability guide is developed as digital twins of the *face turning* and *face milling* demonstrators.

The ***face turning demonstrator*** is shown in Figure 9. A machine learning based implementation summarizes all the experimental and simulation data related to the testing materials and cutting parameters. The main steps of the machinability guide development are listed as in terms of "off-line" development and "on-line" machinability prediction as follows

Figure 9 Face/longitudinal turning demonstrator with measurements of cutting forces and tool wear related to cutting parameters summarized in terms of the equivalent chip thickness h_e. Workpiece material is C38 steel with Sandvik 4325 inserts.

- Off-line development of the guide:
  - Perform physical machining tests in concert with simulations of the face turning demonstrator. This has been developed in WPA-B. Note, the material change is considered for a limited number of tool life experiments.
  - Store the data from the testing in a structured format (=data base) to be used for machine learning interpolations.
  - Create a 3D simulation model in the software "Deform" of the face turning demonstrator based on work done in WPA-C.
  - Carry out simulations from the "Deform model" to validate the results from the physical testing with the and FE-simulations.
  - Carry out the simulations to complete/extend the data base for the machinability guide.
- On-line machinability prediction based on the guide:
  - Use the digital twin to predict the machinability response for the considered face turning operation using machine learning interpolations.

The implementation is made using the *XGBoost* ML software (35) using a Python implementation.

- The software along with the cutting data and instructions are available under the GitHub.

In order to describe the on-line machinability prediction using the guide, let us consider the following force and wear estimations: As to prediction of cutting forces, estimation of cutting-, feed- and passive forces are made at the beginning of the cut, when major tool wear has not developed. As an example, a portion of the developed cutting forces from the experimental program are shown in Figure 10. Figure 11 shows the graphical interface involving the input cutting parameters. For smart representation, the control variables are linked into a common, equivalent, chip thickness h_e defined as

$$h_e = \frac{a_p f}{r \cos^{-1}\left(\frac{r - a_p}{r}\right) + \frac{f}{2}}$$

where a_p is the depth of cut, f is the feed rate and r is the nose radius. Results from the *XGBoost* ML prediction is shown in Figure 12 in terms of predicted cutting and passive forces.
To further describe the guide, cutting hold-time dependent wear and cutting forces are considered. In this case the cutting data are extended to include the time (or cutting hold time) effect with respect to the forces and flank wear as shown in Figure 13a. Here, the data concerns the C38 steel in combination with Sandvik 4325 uncoated inserts. The GUI for the ML implementation covers flank wear and cutting force predictions with respect to a given cutting speed, $200m/min$ as in Figure 11. As another options, the limiting cutting speed v_c related a critical (max) flank wear is predicted. a shows the first case with evolving flank wear up to $v_b = 0.16$ after 1 hour hold time along with the other cutting parameters in Figure 11. Figure 13b shows the predicted max cutting speed v_c for a limit on the flank wear $v_b = 0.2$.

	A	B	C	D	E	F	G	H	I	J
1	no	vc [m/min]	f [mm/rev]	ap [mm]	r [mm]	kr [degree]	cf [N]	ff [N]	pf [N]	note
2	1	150	0.1	1	0.4	91	331.9	244.8	56.53	chalmers-uncoated wear
3	2	150	0.2	1	0.4	91	588.2	349.3	102.5	chalmers-uncoated wear
4	3	200	0.15	1	0.4	91	433.2	266.8	73.36	chalmers-uncoated wear
5	4	250	0.1	1	0.4	91	321.1	224.6	54.83	chalmers-uncoated wear
6	5	250	0.2	1	0.4	91	577.6	322.8	99.38	chalmers-uncoated wear
7	6	350	0.1	1	0.4	91	308.6	204.9	53.45	chalmers-uncoated wear
8	7	100	0.1	1	0.4	91	356.2	279.7	65.15	chalmers-uncoated wear 1pass
9	8	100	0.1	1	0.4	91	354.6	275	65.35	chalmers-uncoated wear 1pass
10	9	150	0.1	1	0.4	91	343.4	253	60.5	chalmers-uncoated wear 1pass
11	10	150	0.1	1	0.4	91	347.6	258.6	63.27	chalmers-uncoated wear 1pass
12	11	200	0.1	1	0.4	91	344.2	243.1	60.49	chalmers-uncoated wear 1pass
13	12	200	0.1	1	0.4	91	355.2	255.3	61.45	chalmers-uncoated wear 1pass
14	13	250	0.1	1	0.4	91	334.8	228.1	55.88	chalmers-uncoated wear 1pass
15	14	250	0.1	1	0.4	91	344	237.4	56.29	chalmers-uncoated wear 1pass
16	15	300	0.1	1	0.4	91	330.6	222	53.43	chalmers-uncoated wear 1pass
17	16	300	0.1	1	0.4	91	338.3	223.1	54.39	chalmers-uncoated wear 1pass
18	17	350	0.1	1	0.4	91	327.8	214.8	51.87	chalmers-uncoated wear 1pass

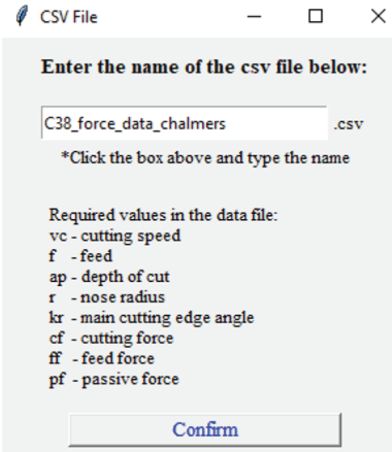

Figure 10 Created cutting force data based on experimental and simulation campaign for the chosen face turning operation: a) chosen section of data. Here, cf is the cutting force cutting force, ff is the feed force and pf is the passive force for a set control, b

no	vc [m/min]	f [mm/rev]	ap [mm]	r [mm]	kr [degree]	t [min]	vb [mm]	cf [N]	ff [N]	pf [N]	note
19	275	0.1	1	0.8	72.5	0	0	265.627	116.28515	159.6282	sandvik
19	275	0.1	1	0.8	72.5	4	0.132	284.1256	128.04657	168.3113	sandvik
19	275	0.1	1	0.8	72.5	8	0.144	273.4363	106.64103	152.0587	sandvik
19	275	0.1	1	0.8	72.5	12	0.144	281.3821	111.66951	158.3569	sandvik
19	275	0.1	1	0.8	72.5	16	0.151	284.5998	109.62288	157.8222	sandvik
19	275	0.1	1	0.8	72.5	20	0.15	286.2231	111.35619	158.6521	sandvik
19	275	0.1	1	0.8	72.5	24	0.15	284.7561	111.02322	157.1667	sandvik
19	275	0.1	1	0.8	72.5	28	0.156	286.4729	110.49446	158.5233	sandvik
19	275	0.1	1	0.8	72.5	32	0.158	286.3508	110.72525	156.3571	sandvik
19	275	0.1	1	0.8	72.5	36	0.166	282.8987	111.25536	156.1755	sandvik
19	275	0.1	1	0.8	72.5	40	0.169	290.5275	111.67517	158.9587	sandvik

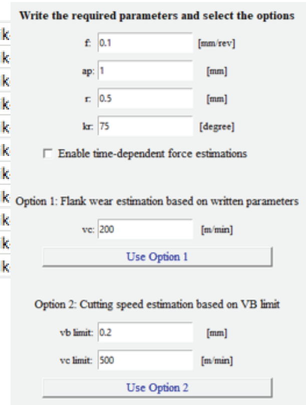

Figure 11 Machining guide data for C38 steel and Sandvik 4325 inserts: a) time dependent cutting data generated for the guide based on experimental and simulation program. Wear is represented by the flank wear and time. b) GUI for different options.

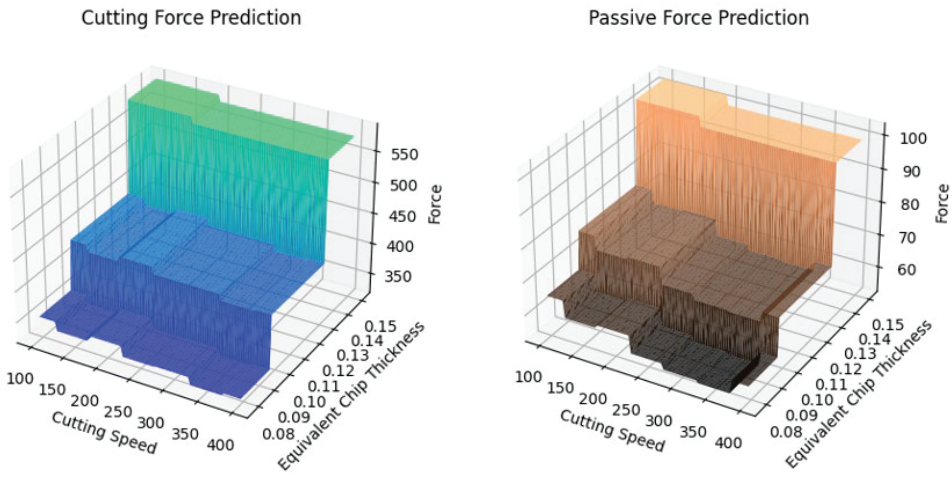

Figure 13 Cutting force cf[N] and feed force predictions ff[N] from the XGBoost interpolation.

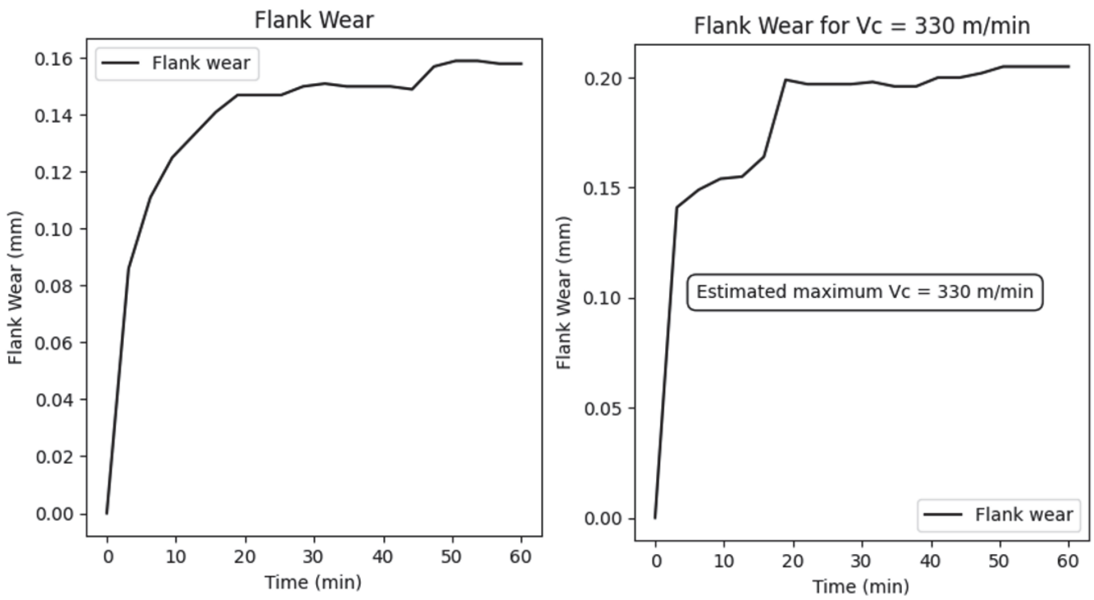

Figure 12 Guide prediction of time dependent response data: a) predicted evolved flank wear based on given cutting speed (200m/min) and other cutting parameters. b) predicted critical cutting speed based on a limiting value of the flank wear, $v_b = 0.2$.

As for the face turning demonstrator, the machinability guide for ***face milling demonstrator*** requires “off-line” calibration for the “on-line” predictions.

- Off-line development of the guide:
  - Perform physical face milling machining tests and measure the resulting cutting forces. This step is unique for each tool-workpiece combination and needs to be repeated for each new combination.
  - Assess the dynamic behavior of the machine tool using the developed semi-automated algorithms of WPC. In case of large parts, use the machine learning based prediction of the spatially changing dynamic behavior.
  - Calibrate the mechanistic cutting force model by deriving the cutting coefficients. This is automated within #Cut by using a standard `fmin` search.
  -
- On-line predictions:
  - Create and load a 3D representation of the uncut workpiece. This is typically available in the Computer-Aided-Manufacturing (CAM) department of the applicants.

- Select the time step size and workpiece/tool discretization resolution depending on the requirements and available computational resources.
- Predict the cutting forces, vibration spectra, and/or surface roughness of new process parameters.

As a demonstrator tool, the indexed CoroMill 245, Sandvik Coromant, Sandviken, Sweden, was chosen. The demonstrator part is an aluminum cylinder head. The first step of the off-line calibration is the identification of the cutting force parameters. These was done with the partner Sandvik Coromant. The test campaign included the machining of aluminum and cast iron supplied by the partner Volvo Cars and Volvo Trucks. The #Cut framework was then used to recreate the cutting experiments and compare the results with the established analytical models of the cutting forces. It is denoted that the calibration did not include the effects of the machine tool dynamics. *Figure 14*shows the prediction of the aluminum cutting forces in comparison with the experiments. The average prediction deviation is at most 12,4%.

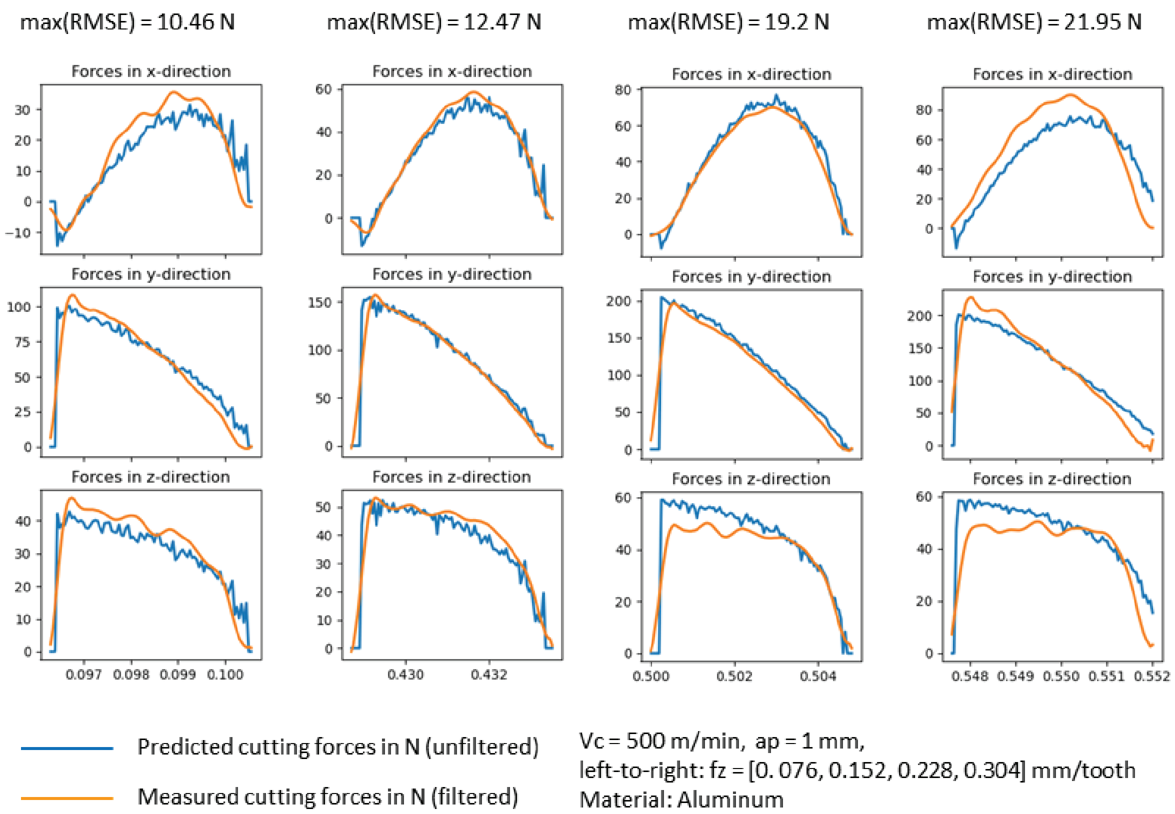

Figure 14 Comparison of predicted and measured cutting forces for aluminum workpieces.

The second part of the off-line development was performed at the partners Volvo Trucks and Volvo Cars. In the test campaign, the machine tool dynamics of the horizontal machining centers Grob G500, GROB-WERKE GmbH & Co. KG, Mindelheim, Germany, and a92 by the company Makino, Mason, Ohio, USA, were measured at the Tool-Center-Point along several positions within the machine tool's work envelope. By using the prescribed AMI, modal parameters were extracted and used to build the structural dynamics model for the simulation of the PMI. With that in place, a prediction of the vibration spectrum, as well as the surface roughness, was performed. Figure 15 shows the measured and simulated vibration spectra for the aluminum test piece machined at VCC displays the predicted average surface roughness Ra in comparison to the measured values. The maximum error to the performed measurements is 18% in this demonstration.

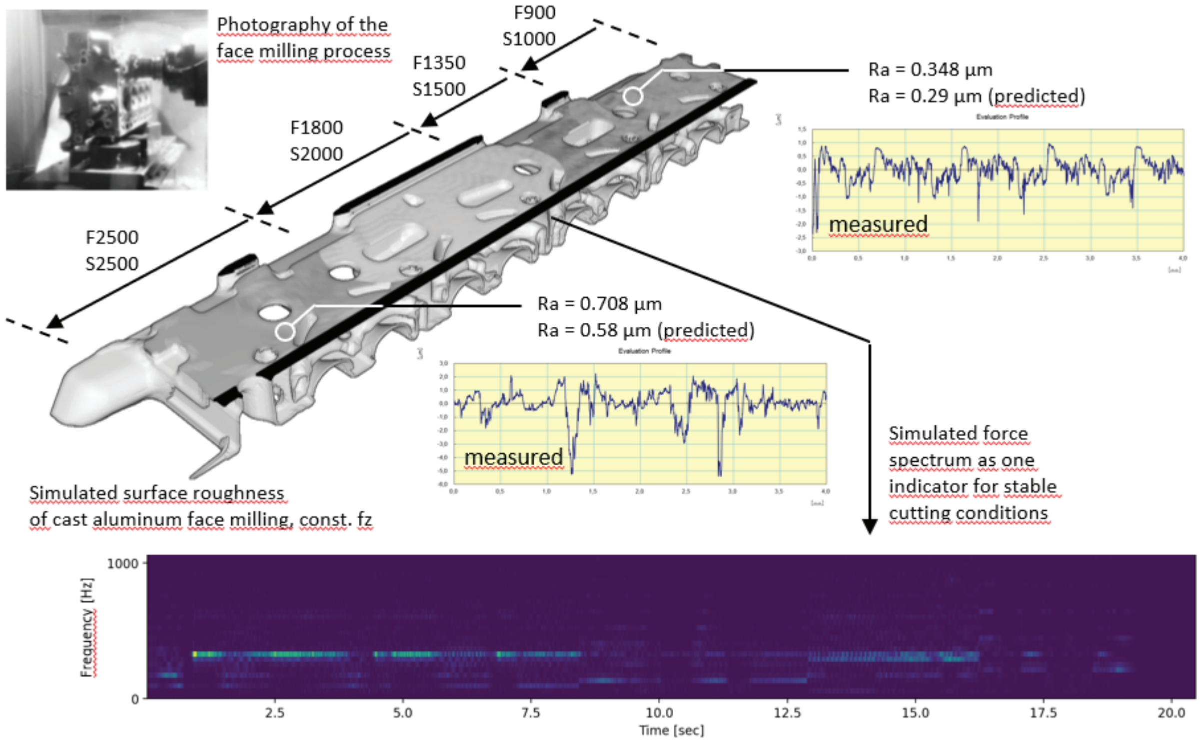

Figure 15 Predicted surface roughness and process vibration spectrum.

6.2 Project goal fulfilment

Primary goal

The prime goal of the project has been to develop a machinability guide that can be used with confidence to predict the machinability of the workpiece material for a selected machining operation. In order to accomplish this goal, a number of milestones were defined with more detailed gates to passed based on our (at the project start) SOTA. From the outset the contours of the machinability guide were a bit diffuse. With time and with the development of the project, the guide has crystallized into its present format. Finally, we have developed a prototype to a guide based on a combination of experimental and modeling/simulation efforts made in the project. A structured database has been set-up for different material grades, different cutting tools, spanned by data from the experiments and the simulations. The data contains controlled cutting parameters (speed, feed and type of tools) and response variable (forces, tool wear and chip thickness). The database is linked to a machine learning implementation that can be used with confidence to make fast evaluations (from efficient interpolation in the database) of machinability. We emphasize that the guide is a generic prototype that could (and should) to be filled with more data in terms of the data-span (e.g. the range of cutting speed) more materials, other machining operations involving other more advanced mechanisms such as serrated chip formation.

Milestones

The associated milestones have been passed to the level as described in the previous section. Also, for some of the milestones, more work is needed. For example, a detailed assessment is required for temperature and heat transfer properties of metal cutting processes for better accuracy of the simulations. Some experimental effort has been made to investigate the temperature levels and distribution of it on the tool surface. However, the experimental work needs to be widened to different cutting conditions and tools. Moreover, simulations need to be performed and to be validated by the experiments. By doing so, heat transfer properties of different metal cutting processes can be estimated. In addition to the temperature assessment, the crucial requirement for mesh objective FE-simulations is still not fully resolved. From the results, we can handle mesh objective simulations only for isothermal conditions in the current SOTA. Furthermore, the calibration method of the material model used in the simulations can be improved with consideration of different shear zones and assumptions that represent the machining deformation mechanism in a more accurate way.

6.3 Contribution to FFI goals

The project has been based on the cooperation between Volvo, Volvo Cars, Sandvik Coromant and Scania CV together with Chalmers and KTH. We have studied relevant problems in the industrial production comprising disciplines of “mechanics based material and structural modeling”, “material science” and “system based structural dynamics”. Thereby, the project results have a sound scientific basis, which is an important prerequisite for the sustainability of the methods proposed. The milestones and deliverables concern both methodologies and competence developments supporting the machinability guide.

The project is well fitted in ”FFI-sustainable production”, primarily from ”flexibility and quality” through the development of the machinability guide promoting decision making at early stages and “shorted lead-times” through the model-based machinability guide reducing the experimental effort speeding-up a new material introduction. We also have synergistic effects considering the shift towards ”model-based” and digitized industry as a key element for manufacturing in high-wage countries.

According to milestones of the project, main deliveries are:
Increased knowledge in the industrial production related to new models, implementations for validation and simulation of cutting processes and machining systems. In particular, the development of a dedicated simulation framework incorporating relevant machine tool characteristics relevant to machining quality.
Dissemination in terms contributions to journals and conferences. The contributions are both local and international levels. We may mention for example, the Swedish manufacturing R&D cluster at Katrineholm. We mention Ph.D and licentiates Engineering theses and exams at Chalmers-MCR have been conducted within the scope of the project.

Tools to be used and further developed by industry and the involved academic partners: A digital guide to machinability assessment for face turning and face milling operations has been developed. The face turning guide is developed in the form of a structured database of cutting data along with a machine learning implementation to make predictions of cutting force and tool wear. The data concerns cutting data C38 steel and Sandvik uncoated inserts. In this development, all partners have been involved in the developments. In particular, all partners have been involved in the experimental program for producing all data to the database. In addition, a structural dynamics-based implementation for handling forced vibration spectra in relation to varying machining parameters in geometrical nonlinear workpieces with multi-material surfaces has been developed.

The project has been affected by the pandemic starting in the beginning of 2020. The experimental work in the project has been significantly delayed due to layoffs and other constraints applied to the partners. The project has been delayed with one year and three months. Overall, the pandemic has made it difficult work-up all costs in the project. Nevertheless, the project results are considered to be positive. We believe that the quality of the project has benefitted from the delay, especially in modelling, simulation and prediction.

7 Dissemination

7.1 Knowledge and results dissemination

To avoid confusion by translation, the table below has been filled in Swedish.

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	Nya, förbättrade modeller för att beskriva materialbeteendet i vid skärande bearbetning. Ett koncept för digital representation av skärbarhet har utvecklats. Stark samverkan mellan akademiska och industriella parter har också lett till kompetensöverföring i båda riktningar viket stärkt den gemensamma kunskapen.
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	Även om resultaten är lovande, så krävs fortsatta forskningsinsatser för att nå hela vägen till full industriell användning. Därför initieras nu en fortsättning på projektet med flertalet av de parter som ingått i konsortiet.
Föras vidare till produktutvecklingsprojekt	X	Ej fullt moget ännu.
Introduceras på marknaden	X	Ej fullt moget ännu.
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut	X	Ej tillämpbart.

7.2 Publications

Licentiate Engineering and Ph.D theses

- Ertürk, A. S. FE-Simulation of Metal Cutting Processes. u.o. : Chalmers University of Technology, 2021. Lic. Eng. thesis.
- Razanica, S. Ductile damage modeling of the machining process. u.o. : Chalmers University of Technology, 2019. PhD thesis. 978-91-7597-884-0.

Journal papers

- Mesh objective continuum damage models for ductile fracture. Larsson, R., Razanica, S. och Josefson, B. L. 2015, International Journal for Numerical Methods in Engineering, Vol. doi: 10.1002/nme.5152.
- A ductile fracture model based on continuum thermodynamics and damage. Razanica, S., Larsson, R. och Josefson, B. L. 2019, Mechanics of Materials.
- FE modeling and simulation of machining Alloy 718 based on ductile continuum damage. Razanica, S., Malakizadi, A. och Larsson, R. 2020, International Journal of Mechanical Sciences, Vol. 171.
- Gradient-enhanced damage growth modelling of ductile fracture. Larsson, R. och Ertürk, A. S. u.o. : Wiley, 2021, International Journal for Numerical Methods in Engineering, Vol. 10.1002/nme.6768.
- A thermomechanically motivated approach for identification of flow stress properties in metal cutting. Ertürk, A. S., Malakizadi, A. och Larsson, R. 3-4, International Journal of Advanced Manufacturing Technology, Vol. 111.
- Validation of the ductile fracture modeling of CGI at quasi-static loading conditions. Razanica, S., Josefson, B. L. och Larsson, R. 2021, International Journal of Damage Mechanics.

Conference papers

- A simulation based guide to machinability assessment, R. Larsson et al., Klusterkonferens 2019, The Swedish Manufacturing R&D Clusters, Katrineholm. 2019.
- A simulation based guide to machinability assessment, MCGUIDE, R. Larsson et al., annual conference 2020, The Swedish Manufacturing R&D Clusters, Katrineholm. 2020.
- A modular node-based modeling platform for the simulation of machining processes. Peukert, B. W. och Archenti, A. 2021. euspen's 21st International Conference & Exhibition.

- Gradient enhanced damage growth modelling of ductile fracture. Larsson, R. och Erturk, A.S. [red.] A. Corigliano. Milano: u.n., 2021. 25th International Congress of Theoretical and Applied Mechanics. s. 1830.

Papers in the "pipe-line"

- Thermal investigation of turning processes. Erturk, A. S., Malakizadi, A. och Larsson, R. 2022. Work in progress.
- Bernd Peukert, Markus Zink, Andreas Archenti, Mapping the time-variant structural dynamics of machine toolsusing machine learning. Work in progress – available upon request
- Bernd Peukert, Adithya Rengaraju, Andreas Archenti, In-situ prediction of the spatial surface roughness profile during slot milling. Work in progress – available upon request
- Bernd Peukert, Andreas Archenti, A modular node-based simulation framework for the prediction of machining processes. Work in progress.

8 Conclusions and further research

The project has resulted in improved modelling and parameter calibration of the workpiece material in cutting processes. The sound thermomechanical formulation including damage yield consistent FE-mesh objective results. In the FE application novel results have been presented for chip formation at different cutting speeds. Efficient calibration assist has been developed for identification of Johnson-Cook material parameters. The material parameters identified focus directly on the orthogonal cutting test and it does not require many experiments. The material model is shown to behave well for idealized load cases, and also competes well with other existing damage models.

However, complete machining simulations in 3D are computationally costly. In addition, the results are not always completely convincing related to issues like passive and feed forces. Hence, additional research to improve the FE-modeling is warranted. Here, key parameters are contact tool/workpiece interaction including contact and heat transport. Moreover, the material flow typically involves significant shearing and material degradation in the primary shear zone. Here, a major incentive to improve our modeling and simulation capability to make faster assessments of the cutting conditions for specific operations (like face/longitudinal turning and milling) with a direct link feedback to enlarge the cutting database. Hence, we need to develop technology that gives (qualitative and quantitative) fast direct assessment of e.g. cutting forces, temperatures and tool wear with respect to changes in cutting speed, feed rate etc. This technology must also be synchronized with experimental procedures for machining different grades of materials.

On the system level, the project has improved the modelling of machining capabilities and their assessment. The semi-automated modal identification using the AMI as well as the implementation of machine learning models for the spatial prediction of modal parameters within the machine tool's work envelope enables the simulation of the dynamic PMI also for larger parts. The modularization of the developed framework encourages industrial applicants to build suitable machining simulations with a set of predefined building blocks. The results show, that the resulting cutting forces and force spectra can be predicted with great accuracy after an initial calibration test. However, the calculations of the resulting surface roughness show room for improvement, mainly due to the missing inclusion of tool wear and the performance of the Computer-Numerical-Control within the machining system.
As with the FE-simulations, the presented calculations are computationally expensive. Major speed improvements were achieved by outsourcing the expensive algorithms to the GPU, but an additional cost comes from the internal data handling of the discretized workpiece. Hence, further research is needed to enable for smaller time steps and higher workpiece discretization resolution. Additionally, thermal effects as well as the CNC performance are not considered in the framework which can significantly contribute to the machining accuracy.

The two major outcomes of the project are the guide to machinability assessment for a face turning operations as well as the modularized simulation framework for the prediction of machining capability incorporating the prementioned models. The guide is in the form of a structured database of cutting data along with a machine learning implementation to make predictions of cutting force and tool wear. The data concerns cutting data C38 steel and Sandvik uncoated inserts. The major part of the data is based on the experimental observations. The range of applicability of the guide is limited to the experimental investigation. Clearly, the range of data can be increased and complemented by FE-simulations, in-particular, with respect to limiting cutting conditions in terms of e.g. speed and feed rate. To do this, further research and extensive collaboration between academia and industry is needed. The project has also led to a raise of competence level when it comes to the industrial modelling and experimental verification of machining, mainly through the large investment in time put on the demonstrator testing.

All in all, the project has taken significant steps towards a digital assessment of machinability. The main steps towards this goal the consistent work on modeling/simulation and experimental verification. This has lead to the set-up of key control and response machining parameters in a structured data base. The machine learning is based on this database and can be further improved with more data related to the range of the parameters but also with the range of material considered. Hence, there is also remaining research to be made before the models and methods developed in this project can be fully adopted in industry.

The database alongside the prediction tool for machinability assessments have been made available to the project partners via the link

- https://ragnar60@bitbucket.org/ragnar60/mguide-face-turning-digital-twin.git .

The framework is accompanied by an extensive documentation as well as tutorials accessible under the following link.

- Documentation and tutorials: https://gits-15.sys.kth.se/pages/bpeuke/sharpycut/
- Source code: https://gits-15.sys.kth.se/bpeuke/sharpycut

Through the project, we believe that the consortium has established a leading position on machining research in Europe. This has been achieved through well-recognized journal publications and conference presentations.

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