THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN SOLID AND STRUCTURAL MECHANICS

FE-Simulation of Metal Cutting Processes

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An artistic touch; juggling with finite element simulations

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ABSTRACT

Machining a new component or a new material requires the selection of the cutting conditions, the tool material and the tool geometry. The selections should be also optimized for the existing components and materials to improve the quality of the produced components and reduce the cost of production. Selecting the most suitable and optimum conditions for the metal cutting processes can be done by performing finite element (FE) simulations which provide more in-depth and detailed information about the cutting processes and also reduce the experimental effort compared to trial-and-error approach.

In this thesis, the challenges and complexities that are needed to be considered in FE simulations of cutting processes are addressed. Firstly, the type of FE simulation should be selected according to the purpose of performing the simulation. Different types of FE simulations of metal cutting such as chip forming, heat transfer and material flow simulations are discussed while explaining their purpose and advantages. These simulations are also combined with semi-analytical methods and machine learning approaches to improve the performance of the simulations in terms of both accuracy and time consumption. Secondly, the selection of the suitable material model for the workpiece and the identification process of the material model parameters are crucial to obtain realistic results from FE simulations. In this aspect, an efficient and robust method of inverse identification of the material model parameters is presented in the scope of the thesis to improve the results of the metal cutting simulations. This identification approach is also implemented to identify the parameters of different material models to find the best-suited model to represent the behavior of the presented carbon steel workpiece material under different cutting conditions. In addition, different effects such as elastic, plastic, viscous and damage behaviors in the material modeling are also discussed throughout the thesis while touching upon their indicators in metal cutting.

There are many more effects and parameters that can be implemented in FE simulations which make the simulations more in-depth and accurate in exchange for computational time. That is why finding the optimum point between the accuracy and time consumption for metal cutting simulations is of interest to many researchers and engineers. The aim of this thesis is to accomplish this while assessing the different aspects of FE simulations of metal cutting processes and discussing the mentioned challenges and complexities in more detail.

Keywords: Finite element method, Heat transfer, Inverse identification, Machine learning, Machining, Metal cutting

to my dear mother and my dear friends.

PREFACE

This thesis includes my work from 2018 to 2023. During this time, I have involved in two research projects. The first one is titled as ”A simulation based guide to machinability assessment” (project number 2016-05397) which is financially supported by the Swedish national research program Vinnova-FFI (Strategic Vehicle Research and Innovation) and also it received financial support from the Chalmers Area of Advance Production and the Chalmers Centre for Metal Cutting Research (MCR). The second one is titled as ”Micromorphic multiscale modeling of the workpiece material flow during metal cutting” (project number 2021-05583) which is financially supported by Swedish Research Council (VR).

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Thank you, mom, for raising me and supporting my decisions. I miss you a lot. Thank you, my family *Roeland Bisschop* and *Carolyn Oddy*, for being my best friends and taking care of me. I am glad to have you. Without you, I wouldn't enjoy my life in Sweden this much and wouldn't feel at home. Thank you, my dearest friend *Pooria Khalili*, for helping and supporting me, listening to my problems and all the long talks we had. We should visit each other more often.

Thank you, my amazing boy-band and lunch friends *Robert Auenhammer*, *Michele Maglio*, *Henrik Vilhelmson*, *Ata Jafarzadeh*, *Carl Larsson*, for creating the best lunch table with the funniest, the most enjoyable and the most taboo breaking conversations. Thank you, my friends from Türkiye *Osman Aydemir*, *Ezgi Gülmez*, *Gülen Günalp* for believing in me, supporting me and putting a smile on my face every time we talk.

Finally, I would like to thank all my friends, my colleagues and Chalmers University of Technology for all the help, support, fikas and creating such a nice environment for work and research.

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A	A. S. Ertürk, A. Malakizadi, and R. Larsson. A thermomechanically motivated approach for identification of flow stress properties in metal cutting. *International Journal of Advanced Manufacturing Technology* **111** (2020), 1055–1068. DOI: 10.1007/s00170-020-06121-z
Paper B	R. Larsson and A. S. Ertürk. Gradient-enhanced damage growth modeling of ductile fracture. *International Journal for Numerical Methods in Engineering* **122** (2021), 5676–5691. DOI: 10.1002/nme.6768
Paper C	A. S. Ertürk, A. Malakizadi, and R. Larsson. Evaluation of different flow stress models for machining simulations. *Journal of Manufacturing Science and Engineering (revised - to be submitted)* (2023)
Paper D	A. S. Ertürk, A. Malakizadi, and R. Larsson. An ML-based approach for inverse identification of heat flux in machining. *Procedia CIRP* **115** (2022), 208–213. DOI: 10.1016/j.procir.2022.10.075
Paper E	A. S. Ertürk, A. Malakizadi, and R. Larsson. Towards an accurate estimation of heat flux distribution in metal cutting by machine learning. *Procedia CIRP* **117** (2023), 359–364. DOI: 10.1016/j.procir.2023.03.061
Paper F	A. S. Ertürk and R. Larsson. Subscale modeling of material flow in the primary shear zone in orthogonal metal cutting. *(manuscript - to be submitted)* (2023)

The author's contribution to the appended papers:

- Paper A: Formulating the paper, development of the methodology, implementation of the model, performing the simulation, writing the initial draft and managing the review process.
- Paper B: Implementation of the model, performing the simulation and writing the initial draft.
- Paper C: Formulating the paper, development of the methodology, implementation of the model, performing the simulation, performing the experiment, writing the initial draft and managing the review process.
- Paper D: Formulating the paper, development of the methodology, implementation of the model, performing the simulation, performing the experiment, writing the initial draft and managing the review process.
- Paper E: Formulating the paper, development of the methodology, implementation of the model, performing the simulation, performing the experiment, writing the initial draft and managing the review process.

- Paper F: Formulating the paper, implementation of the model, performing the simulation and writing the initial draft.

Contents

Abstract **i**

Preface **v**

Acknowledgements **v**

Thesis **vii**

Contents **ix**

I Extended Summary **1**

1 Introduction **1**

2 Simulations Strategies **3**
- 2.1 FE chip forming simulation . . . 3
- 2.2 FE heat transfer simulation . . . 5
- 2.3 FE material flow simulation . . . 6

3 Material Modeling **8**
- 3.1 Elastic . . . 8
- 3.2 Plastic . . . 9
  - 3.2.1 Effect of strain . . . 9
  - 3.2.2 Effect of strain rate . . . 9
  - 3.2.3 Effect of temperature . . . 10
- 3.3 Damage . . . 12

4 Calibration Methods **14**
- 4.1 Empirical . . . 14
- 4.2 Analytical . . . 15
- 4.3 Numerical . . . 15

5 Verification Cases **17**
- 5.1 Cutting forces . . . 17
- 5.2 Chip morphology . . . 17
- 5.3 Temperature . . . 19

6 Conclusion **20**

References **22**

Part I

Extended Summary

1 Introduction

Turning, milling, drilling, broaching and many more are categorized as metal cutting processes. All these processes require suitable workpiece-tool combinations and cutting conditions which means selecting a proper tool material, tool geometry and cutting conditions so that the tool does not wear out quickly and the quality of the cut surface is acceptable. Due to many different combinations of tools and cutting conditions, finding the optimum conditions for the cutting processes by trial and error method can be time-consuming and costly which also causes waste of materials and energy. That is why it is a good alternative to use virtual methods such as analytical and numerical models for the decision-making about the process setup and conditions. However, these models are established based on assumptions and simplifications, and they include many parameters and properties which should be determined. Thus, analytical and numerical models can not completely replace the experiments, but they can help tremendously to reduce the number of experiments and trials that need to be performed.

Compared to numerical models, analytical models are a robust and efficient way of obtaining information for the cutting processes [1]. Especially with the widening use of machine learning methods, they have the potential to be more robust and accurate [2]. However, it is important to keep in mind that the robustness of the analytical models is a result of many simplifications and assumptions included in the model, and machine learning models require a large amount of data to be accurate. On the other hand, numerical models provide more in-depth and detailed information about the cutting processes in exchange for computational time. The detailed information about the shear zones, chip formation and distributions of stress and temperature is very valuable to understand the metal cutting process and to select suitable conditions [3, 4]. To obtain realistic results from numerical simulations, realistic data should be provided in the simulation setup such as material properties, friction behavior, contact behavior and heat transfer properties. Obtaining these properties and related parameters requires in-depth investigation and detailed assessment of the cutting processes.

FE simulation of metal cutting processes is studied by many researchers but still needs improvement due to the complex nature of the cutting process [5, 6, 7, 8, 9]. The complexity of the process comes from the extreme conditions and many mechanisms involved such as high deformation levels, extreme speed, dynamic effects, high temperatures, fracture and wear effects. While realistically simulating the process, all of these effects should be taken into consideration. However, including all the effects would make simulations computationally extremely costly. That's why the simulations need to rely on realistic assumptions and simplifications to be efficient in terms of both time and accuracy.

In this thesis, the aspects mentioned above are discussed in more detail including different types of finite element simulations and their setup, material modeling and calibration methods, required experiments and verification cases. As for the metal cutting process, the focus is placed on the turning process of carbon steels; however, the simulation of the other cutting processes and metals goes along the same path as the turning process. Therefore, this thesis can also be a guide for simulating other metal cutting processes. The aim with this thesis is to give a road map for the finite element simulations of the turning process in detail and explain the steps required for an efficient simulation while mentioning the challenges and giving some recommendations to overcome them.

The outline of the extended summary consists of:

- **Simulations Strategies** – shows different finite element simulations such as chip forming, heat transfer and material flow simulations and explains their setups.
- **Material Modeling** – includes information about the material models and the properties that need to be considered in the model.
- **Calibration Methods** – discusses different methods to calibrate the parameters of the material models.
- **Verification Cases** – states the suitable experiments and data required to verify the simulation results.
- **Conclusion** – summarizes the thesis with concluding remarks and future work suggestions.

2 Simulations Strategies

There are different ways of simulating the turning process by using the finite element method. Depending on the aim of the simulation and the effects that need to be considered, a suitable one should be selected. In this section three simulation strategies are presented such as chip forming, heat transfer and material flow simulations.

2.1 FE chip forming simulation

FE chip forming simulation is commonly used for representing the turning process and estimation of forces, temperatures, stresses and chip formation. The coupled effect of mechanical and thermal aspects makes chip forming simulation a realistic tool for the optimization and determination of cutting parameters. Moreover, the remeshing algorithms implemented in the simulations prevent the non-convergence caused by highly distorted elements and assist in the forming of the chip [10]. For representing orthogonal cutting experiments, where the cutting edge of the tool is perpendicular to the direction of the cut (see Fig. 2.1), 2D chip forming simulations are more suitable and robust compared to 3D simulations since the passive force and effects in the depth of cut direction (i.e., out of plane direction) are close to zero. However, 3D simulations are necessary for the oblique cutting conditions, where the cutting edge of the tool is not perpendicular to the direction of the cut, effects in the depth of cut direction can not be ignored, and passive force is nonzero.

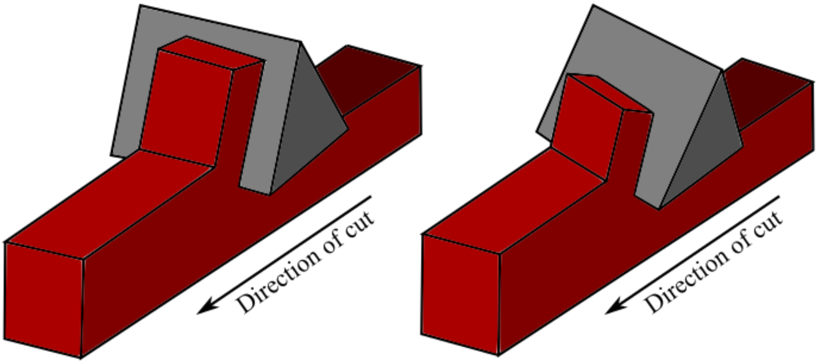

Figure 2.1: Orthogonal (left) and oblique (right) cutting.

The setup for 2D and 3D FE chip forming simulations are given in Fig. 2.2. In the simulations, the tool (in grey color) is assumed stationary while the workpiece (in red color) is moving towards the tool with the velocity of cutting speed of the metal cutting process. The relative location of the tool with respect to the workpiece is determined based on the depth of cut and feed of the cutting process. For 2D simulations, the width of cut is assumed to be the unit length which means the forces obtained from the simulations should be considered as force per unit length. The heat transfer to the environment and between tool-workpiece are also considered in the simulations including the contact behavior in the tool-chip-workpiece interface. The mechanical aspect of the contact behavior is represented with a friction model which should include the effects of pressure and velocity on the contact interface since the friction behavior is highly affected by both of them. In the chip forming simulations, the tool is assumed to be rigid since the stiffness of the tool material is very high compared to the workpiece material [6]. For the workpiece material, elastic, plastic and damage properties can be defined. If the mechanical and thermal properties of the materials are significantly sensitive to temperature change, temperature-dependent material properties should be implemented to improve the accuracy of the simulations.

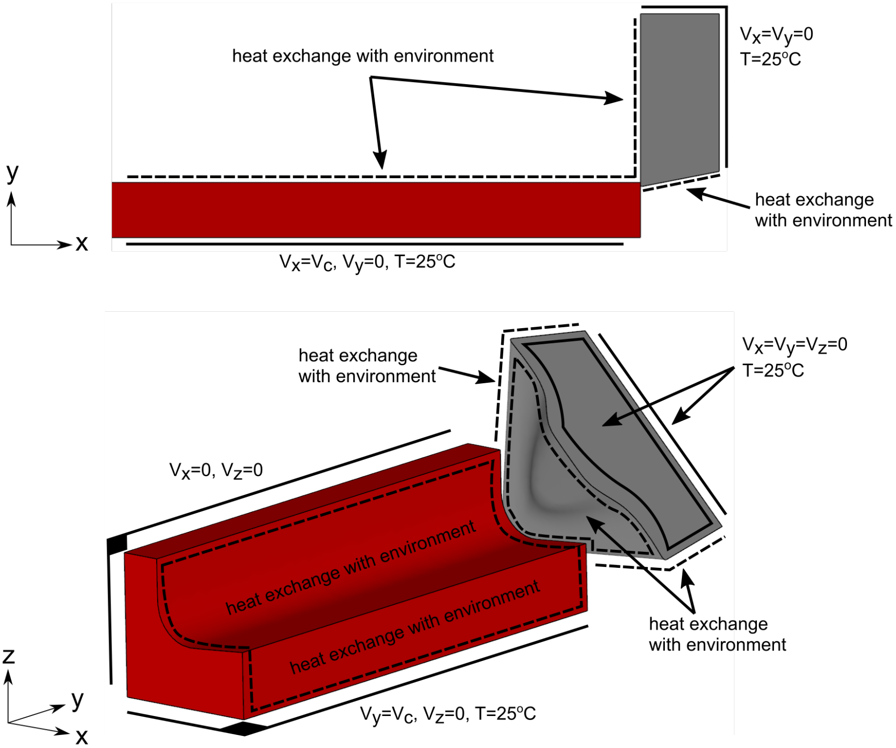

Figure 2.2: FE chip forming simulation setup for 2D (top) and 3D (bottom).

The convergence and accuracy of FE simulations are dependent on the mesh size, remeshing, time-stepping and total time of the simulations. Selecting a suitable mesh size and time step ensures convergence and provides accurate results. However, selecting a very small mesh size and time step increases the computational cost of the simulations. Moreover, very small mesh size may cause stress concentration in the deformed material which may be misleading when interpreting the results. Similar to time-stepping, remeshing frequently may lead to more accurate results and more realistic chip formation in exchange for computational time. On the other hand, the total time of the simulation determines whether the thermo-mechanical steady-state condition is reached or not during the chip forming simulation. If the validation and the estimations are performed for the steady-state metal cutting process, the total time should be selected accordingly to ensure steady conditions. Since there are many effects and settings that can be included and changed in an FE simulation, the simulation itself is an optimization problem for researchers and engineers to solve where the objective is to reduce the computational cost while keeping the accuracy at acceptable levels.

2.2 FE heat transfer simulation

FE heat transfer simulations are performed to validate/predict the temperature measurements and the heat fluxes on the tool. In these simulations, the workpiece can be ignored since the mechanical effects are not considered which reduces the computational time significantly since there is no chip formation and remeshing. Instead, the assembly may include the parts such as the tool, shim, tool holder and thermocouples (see Fig. 2.3) to make the simulation as realistic as possible. The setup of the heat transfer simulations is arranged according to the turning process as shown in Fig. 2.3. The room temperature is applied to the far edge of the tool holder, while the heat flux, which is due to material deformation and friction in turning process, is applied to the contact area on the rake face of the tool. The contact area represents the area where the chip is interacting with the tool, which can be obtained by visual inspection of the tool after the turning process. In Fig. 2.3, this area is simplified into a rectangle-like area; however, it has a more complex shape, in reality [11]. Similarly, the heat flux applied to this area may be assumed as a constant value; however, due to different heat sources such as the plastic deformation of the workpiece material and the friction between the chip and the tool, the heat flux is not uniformly distributed on the area [12, 13]. Additionally, the interaction between the tool and chip/workpiece takes place also on the flank face of the tool and creates a heat source [14] which is not included in the setup shown in Fig. 2.3 to simplify the model.

Heat transfer to the environment is also implemented in the model for all outer surfaces while the contact between the assembly components is assumed to be perfect for simplification. For additional accuracy of the results, the contact properties between the components can be modelled in more detail, and temperature-dependent material properties can be considered for the components. As mentioned for FE chip forming simulations, meshing and time-stepping are also important for heat transfer simulations. Meshing is especially important in the connections between the components of the assembly since the energy is transferred from one surface to another including nodal and elemental values. Additionally, a sufficiently fine mesh should be selected in the tool-chip contact area (i.e., applied heat flux area in Fig. 2.3) to provide enough resolution for the non-uniform heat flux distribution.

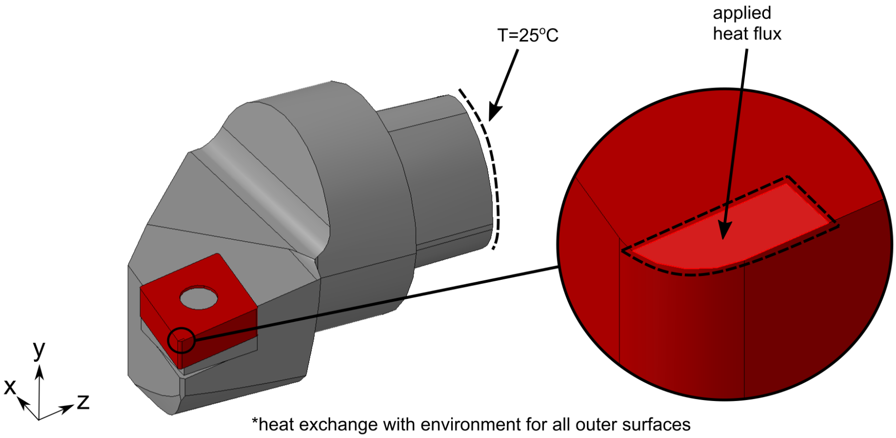

Figure 2.3: FE heat transfer simulation setup.

2.3 FE material flow simulation

FE material flow simulation is another method for the simulations in the metal cutting literature [15, 16]. It requires prior knowledge about the considered region to model the cutting process (i.e., Eulerian approach). This is challenging due to forming of the chip and changing boundaries; however, it is also advantageous due to preventing the problems associated with separation of the chip compared to Lagrangian approach [17]. In FE material flow simulation, the workpiece material is considered as a fluid with very high viscosity instead of a solid. Since the primary shear zone (see Fig. 2.4) is dominated by the shear deformation of the workpiece material, this zone is suitable to represent the deformation behavior in terms of material flow combining Navier-Stokes relations with the cutting process kinematics.

The FE material flow simulation is a coupled thermo-mechanical simulation where the focus is the primary shear zone in the setup shown in Fig. 2.4. In the setup, the cutting speed is applied to the edge where the material flows into the primary shear zone. On the contact edge between the tool and chip, the velocity is zero due to the assumed sticking condition [18]. A friction model can be implemented on this edge as well as a heat transfer to the tool, and the simulation region can be expanded to include also the secondary and tertiary shear zones. This may increase the computational time; however, it will surely increase the accuracy of the force and temperature estimations significantly. FE material flow simulations are more time-efficient compared to FE chip forming simulations. However, the assumptions and simplifications in the simulation region may reduce the accuracy of the results. Lastly, as mentioned before in previous sections, mesh size and time step should be selected carefully for convergence, accuracy and computational cost.

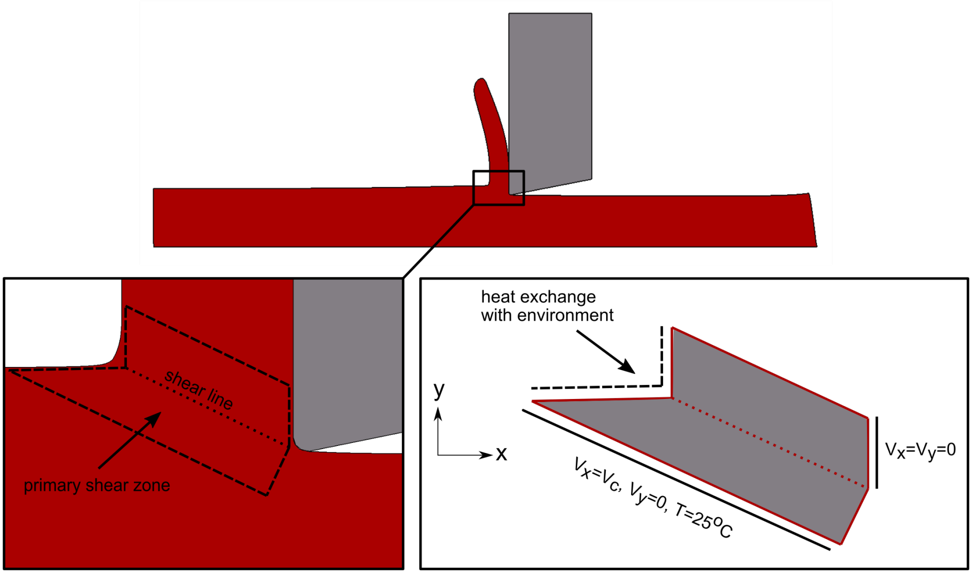

Figure 2.4: FE material flow simulation setup.

3 Material Modeling

As mentioned in the previous chapter, there are different finite element simulations to represent the turning process. The accuracy of these simulations is dependent on how well the setup of the simulation represents the real process and how the material properties are defined. Since carbon steels have a complex mechanical response, it is quite challenging to represent their mechanical behavior accurately with material models, especially under high deformation rates and temperatures as observed in turning processes. Thus, this section includes the mechanical response and modeling of carbon steels and the effects which should be considered and included in the simulations such as elastic, plastic and damage properties. These properties are only discussed for workpiece material since the tool is often assumed to be rigid in the simulations.

3.1 Elastic

Considering the high deformation levels (i.e., high strains) reached during the cutting process, the elastic region occupies only a small portion of the deformation region for carbon steels. Thus, the dominant behavior is the plastic deformation in metal cutting which is why the elastic behavior of the workpiece material is commonly ignored in the material modeling for cutting simulations. However, ignoring the elastic behavior has its downsides since the machined workpiece material behind the tool expands elastically (i.e., springback effect), and this creates a contact region between the machined surface and the tool as shown in Fig. 3.1. Thus, this leads to changes in the surface roughness, tool flank wear and cutting forces [19]. It is worth mentioning that the contact between the machined surface and the tool can also be caused by the ploughing effect and the elastic property of the workpiece material contributes to this effect [20]. Aside from the springback and ploughing effect, it is observed that the elastic energy density affects the frequency and degree of segmentations in segmented chips [10] which would not be represented correctly if the elastic property of the workpiece material is not included in the simulations.

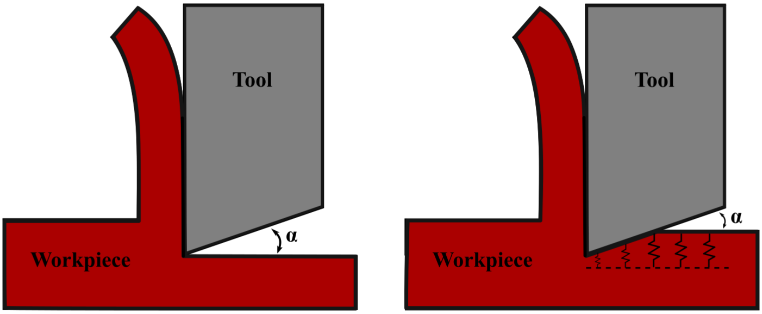

Figure 3.1: Effect of including elastic property of the material; without elasticity (left), with elasticity (right).

3.2 Plastic

As mentioned previously, the dominant deformation mechanism in metal cutting is plastic deformation. Thus, it is crucial to represent the plastic behavior of workpiece material in the simulations realistically. The plastic behavior of carbon steels is very complex to represent due to the effects of strain, strain rate and temperature. Thus, a suitable plastic model (e.g., perfectly plastic, viscoplastic and thermo-viscoplastic, etc.) should be selected by observing the significance of these effects.

3.2.1 Effect of strain

The effect of strain on the mechanical response of carbon steels can be observed from data available in the literature. As examples, the true stress-strain curves of different steels are given in Fig. 3.2. As can be seen in the figure, the stress increases with increasing strain in a trend of a power law which should be represented with the selected material model. Commonly used material models such as Johnson-Cook [21] and Zerilli-Armstrong [22] represent this behavior in their constitutive relations.

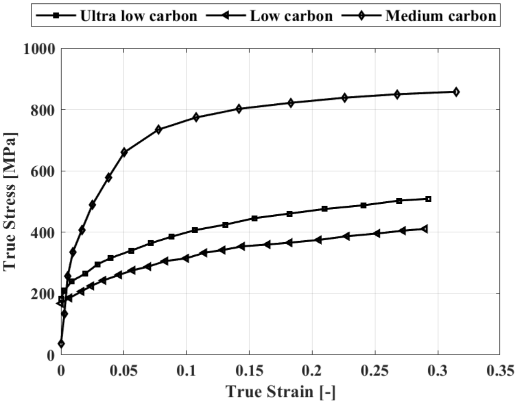

Figure 3.2: Stress-strain response of ultra low carbon [23], low carbon [23] and medium carbon [24] steels under quasi static loading at room temperature.

3.2.2 Effect of strain rate

The effect of strain rate is related to the loading rate during the experiments. In the case of quasi-static (i.e., very low-speed) loading, the material has enough time to reach the equilibrium state. When the loading is faster, the material cannot reach the minimum energy state, and the resistance of the material against deformation increases. As an example, the stress response of medium carbon steel is given in Fig. 3.3 for different strain rates. It can be seen that both yield stress and the maximum stress response increase with increasing strain rate while the failure strain decreases. The material models used in the literature [21, 22, 25, 26] includes this as a multiplicative effect to the effect of strain.

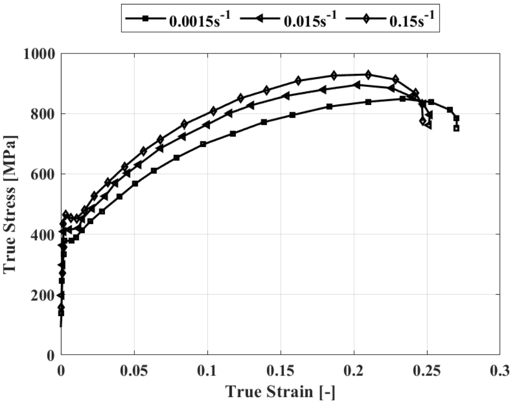

Figure 3.3: Stress-strain response of medium carbon steel [27] under different strain rates at room temperature.

3.2.3 Effect of temperature

An increase in temperature lowers the energy required to deform the material, and the material softens (see Fig 3.4). This is the common temperature dependent behavior that is represented in the material models [21, 22].

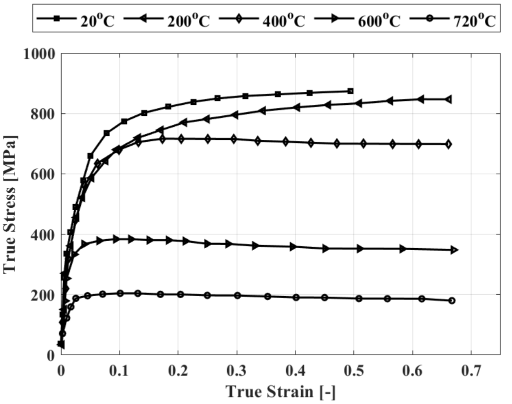

Figure 3.4: Stress-strain response of medium carbon steel [24] under quasi static loading at different temperatures.

Some steels also go through dynamic strain aging under certain strain rates and temperatures which causes hardening in the material. Dynamic strain aging happens due to the alloy atoms diffusing into the dislocations and preventing their movement. The temperature and strain rate range, in which this phenomenon occurs, depends on the material and alloy composition. An example of this phenomenon can be seen in Fig. 3.5 for different steels. This effect is considered in some of the material models in the literature [28, 29].

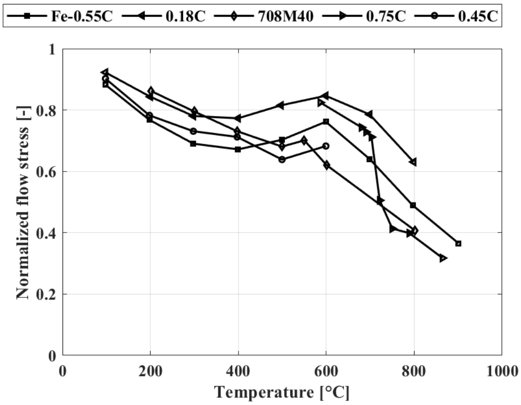

Figure 3.5: Normalized flow stress-temperature response of different steels [28].

Dynamic recovery and recrystallization mechanisms can be also triggered depending on the temperature and strain rate which causes softening in the material [31]. Since a small portion of the energy is stored in the defects and dislocations during the deformation, the material tries to reach the lower energy state through microstructural changes. These changes (i.e., microstructural and submicroscopic) happen to relieve some of the

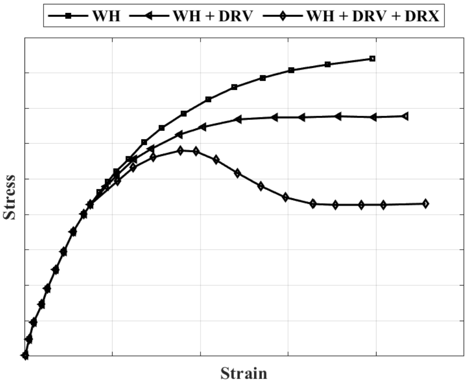

Figure 3.6: Illustration of stress-strain response including the effects of work hardening (WH), dynamic recovery (DRV) and dynamic recrystallization (DRX) [30].

accumulated strain in the material during recovery [32]. The material undergoes further changes at high temperatures, and the old/deformed grains are replaced with new strain-free/defect-free grains through recrystallization [32]. The effects of these mechanisms on the stress-strain response are illustrated in Fig. 3.6.

Carbon steels also undergo microstructural changes (i.e., phase transformation) due to temperature. The transformation shows differences regarding the carbon content of the steel (see Fig. 3.7 [33]). The effect of the microstructural changes on the mechanical response of the material should be also taken into account in the metal cutting process since the workpiece material can reach very high temperatures due to friction and plastic deformation [34].

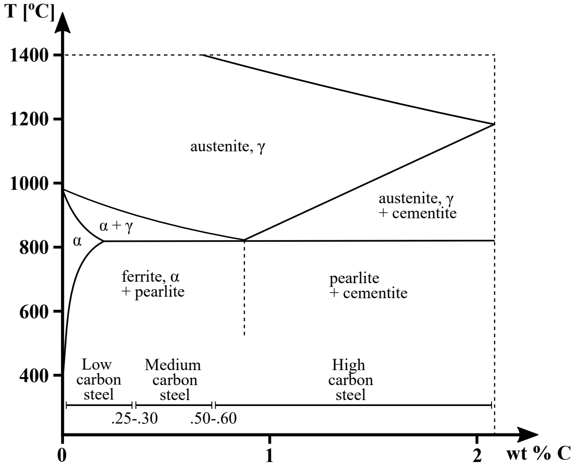

Figure 3.7: Iron carbon (Fe-C) phase diagram.

3.3 Damage

Depending on the type of simulation and the setup, the damage/fracture property of the workpiece material can be included in the simulations. For metal cutting simulations, this is decided based on the chip formation. For instance, the serrated chips indicate high shear deformation and damage on the free surface of the chips. Thus, damage should be included in material modeling for the cases with serrated chips; otherwise, the forces would be overestimated in the simulation results since the mechanical resistance of the material is assumed to be increasing without damage (see Fig. 3.8). There are different options for damage modeling depending on the material behavior such as brittle fracture [35], ductile fracture [36], local damage [37] and nonlocal damage [38] models. A common damage model used in FE simulations is the Johnson-Cook cumulative-damage fracture model [39]. A progressive-damage model can be also implemented for representing the behavior of the workpiece material after failure as in [40]. Aside from the material behavior, the computational cost of the simulations should be also considered while selecting the suitable damage model.

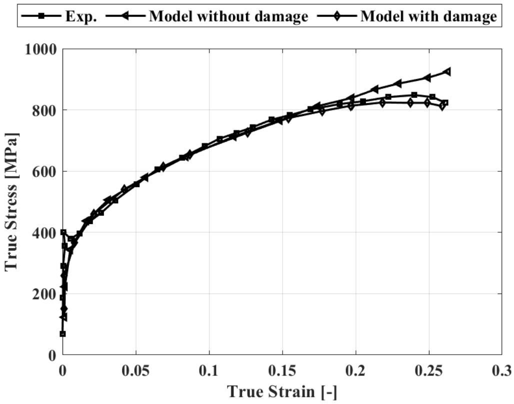

Figure 3.8: Stress-strain response of a medium carbon steel under $0.15\mathrm{s}^{-1}$ strain rate at room temperature compared to the models with and without damage [27].

4 Calibration Methods

Material models can represent the behavior of workpiece material during metal cutting with high accuracy if suitable parameters are selected. To identify/calibrate these parameters, a proper technique such as empirical, analytical and numerical methods should be employed while considering the cost, accuracy, time consumption and experimental effort. Additionally, it is important to mention that the higher number of parameters in the material model may improve the accuracy of the model; however, it increases the computational cost and experimental effort of the calibration process which should be taken into account while selecting the material model.

4.1 Empirical

Calibration of the material models by using conventional tensile and compression tests is not suitable for metal cutting since these tests do not represent the extreme conditions observed in cutting processes where the strain rate and temperature may reach up to 10^6s^{-1} and 1000°C [41, 42]. Often the tests such as Taylor's impact, Split Hopkinson Pressure Bar and high-speed compression tests are used to calibrate the material models for metal cutting simulations [43, 44, 45, 46, 47]. However, these tests are expensive, difficult to perform and require a large amount of experimental effort to generate enough data to cover the wide range of strain, strain rate and temperature to calibrate the material models. Moreover, the strain and strain rate values observed in these experiments are still below the ones seen in metal cutting [42]. Thus, the material models calibrated by using these tests may not fully represent the behavior of the workpiece material during the cutting process.

The empirical approach for the calibration of material models follows the steps shown in Fig. 4.1. Firstly, the experiments are carefully designed to cover different ranges of strain, strain rate and temperature considering the required amount of data and experimental effort. Following the design of experiments, the tests are performed, and the data are collected. Then, the material model is calibrated based on the collected data by using a suitable method which may vary from a simple linear fitting model to a complex machine learning model.

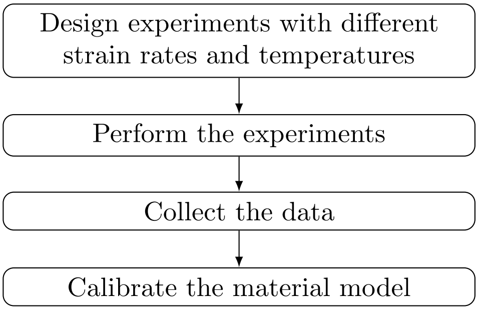

Figure 4.1: Example progress of an empirical calibration process.

4.2 Analytical

Another method to calibrate the material models is to use analytical models that represent the kinematic relations in metal cutting processes such as in [1, 48]. The calibration process by using analytical methods is very fast, but the accuracy suffers from the assumptions and simplifications that are made. To increase the accuracy of the analytical models, data from metal cutting experiments (i.e., measured forces, chip thickness, etc.) can be included and embedded in the kinematics of metal cutting process (i.e., semi-analytical models) such as in [49, 50, 51]. Semi-analytical methods rely on both the kinematics and experimental data which makes the relation between the material model parameters and the workpiece material more realistic. These models have higher accuracy than pure analytical methods and still manage to be robust [52]. Additionally, they require some experimental effort but not as much as pure empirical calibration. The process of the calibration is given in Fig. 4.2. The calibration relies on getting well-representative variables such as strain, strain rate, temperature, etc. by using material properties and experimental data.

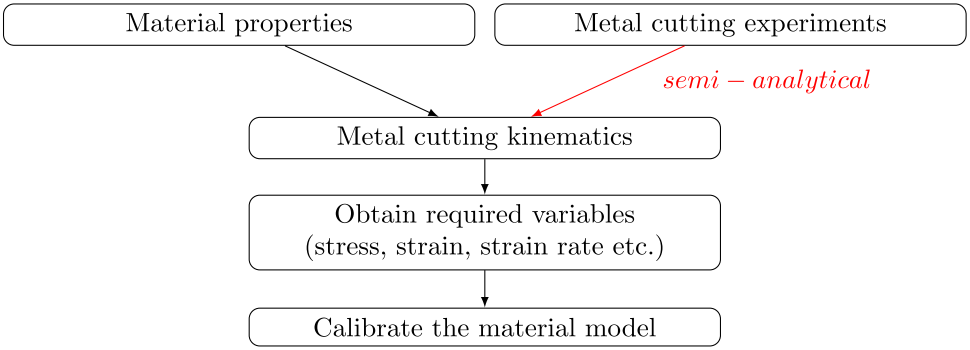

Figure 4.2: Example progress of an analytical/semi-analytical calibration process.

4.3 Numerical

Metal cutting simulations themselves can also be used for calibration of material model parameters such as in [53, 54]. To achieve this, different sets of material model parameters are created, and the simulations are performed for each set as shown in Fig. 4.3. By comparing the simulation results with experimental data, the error of the simulations is calculated. The parameter set with minimum error indicates the most suitable material model parameters. Additionally, minimization can be performed on the parameter sets and the error values to find the optimum parameter set. Since the calibration process is based on the simulations, the accuracy of them is directly related to the calibrated material model. However, many simulations are required for this type of calibration process which makes it computationally costly. It should be taken into account that error sources unrelated to the material model such as friction, contact and thermal properties will be compensated by the material model parameters during the calibration process.

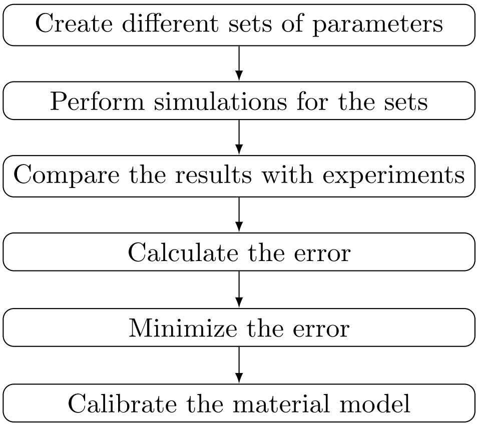

Figure 4.3: Example progress of a numerical calibration process.

5 Verification Cases

The results obtained from the metal cutting simulations should be verified with experiments to observe the performance of the FE models. Depending on the simulation, the verification can be performed based on the measured cutting forces, observed chip thickness/morphology and measured temperature.

5.1 Cutting forces

Surface quality, power/energy consumption, vibration and tool life in metal cutting can be traced back to the cutting forces which makes them the most crucial factor in the cutting process [55, 56]. Thus, realistic estimation of the cutting forces has significant importance for optimizing the cutting process parameters and tool design. This also makes the verification of the estimated forces the most common way to evaluate the overall performance of the metal cutting simulations. For the verification of the simulations, suitable test cases should be selected depending on the setup of the simulations. For example, the orthogonal cutting (OC) experiments are more suitable to be represented with 2D simulations, while 3D simulations can be used for representing the face turning (FT) tests. Moreover, the simulation results should be verified for different cutting conditions to show the overall reliability of the simulations. In Table 5.1, some example verification cases are shown which are taken from [57]. As seen in the table, the forces may change significantly depending on the cutting condition.

Table 5.1: Cutting Conditions of Turning Experiments for Force Prediction

Test	Cutting Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Cutting Force (N/mm)	Feed Force (N/mm)	Passive Force (N/mm)
OC1	240	0.050	2	168	164	—
OC2	240	0.075	2	235	216	—
OC3	240	0.100	2	283	230	—
FT1	150	0.100	1	332	245	57
FT2	200	0.150	1	433	267	73
FT3	250	0.200	1	578	323	99

5.2 Chip morphology

Chip morphology, which is a product of the interaction between the workpiece and the tool, is another important aspect of the verification of metal cutting simulations. The shape and thickness of the chips, which are dependent on the cutting conditions and the workpiece material, indicate different mechanisms of deformation happening in the material [58, 59]. For example, serrated chips mean that there is a high shear deformation and damage happening in the chip causing a serrated structure on the free surface of the chip [59]. This suggests that the damage model and fracture mechanics should be included in the simulations for the tests where these kinds of chips are observed. The chips collected from the orthogonal cutting tests given in Table 5.1 are shown in Fig. 5.1. The thickness and shape of these chips can be compared to the chips in 2D simulations. However, for oblique cutting tests (i.e. face turning in Table 5.1), it is quite difficult, almost impossible, to measure the chip thickness due to the curling of the chips in all three dimensions as shown in Fig. 5.2. Instead, the shape of the chips can be used for verification of the 3D simulations.

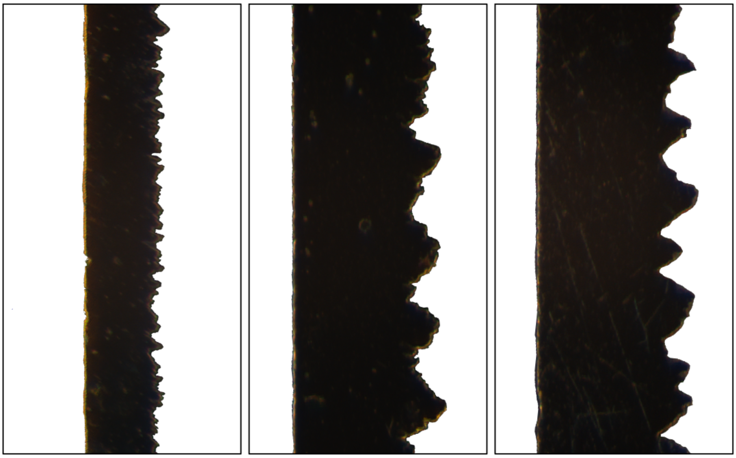

Figure 5.1: Chips from Orthogonal Cutting 1 (left), 2 (middle), 3 (right).

Figure 5.2: Chips from Face Turning 1 (left), 2 (middle), 3 (right).

5.3 Temperature

Due to the coupled thermo-mechanical nature of the metal cutting process, a significant amount of heat is generated by the deformation of the workpiece material, chip formation and friction. The high temperature due to heat generation changes the behavior of the workpiece material [60] and also affects the tool life [61]. Thus, it is crucial to represent the thermal aspect of the cutting process realistically in the simulations which require verification of temperature. For the verification process, temperature measurements are required which may be the maximum temperature [62] or temperature measurements from different locations on the tool-tool holder assembly [63]. The example temperature measurements given in Fig. 5.3 [64] are from three different locations inside the tool. Moreover, as mentioned in the previous sections, temperature measurement tests should be performed for different cutting conditions (see Table 5.2) to evaluate the reliability of the simulations. By doing so, the performance of the material model, friction model and thermal properties of the material can also be evaluated.

Table 5.2: Cutting Conditions of Turning Experiments for Temperature

Experiment	Cutting Speed (V_c)	Feed (f)	Depth of Cut (a_p)
Face Turning 1	150 m/min	0.050 mm/rev	0.8 mm
Face Turning 2	150 m/min	0.100 mm/rev	0.8 mm
Face Turning 3	150 m/min	0.150 mm/rev	0.8 mm

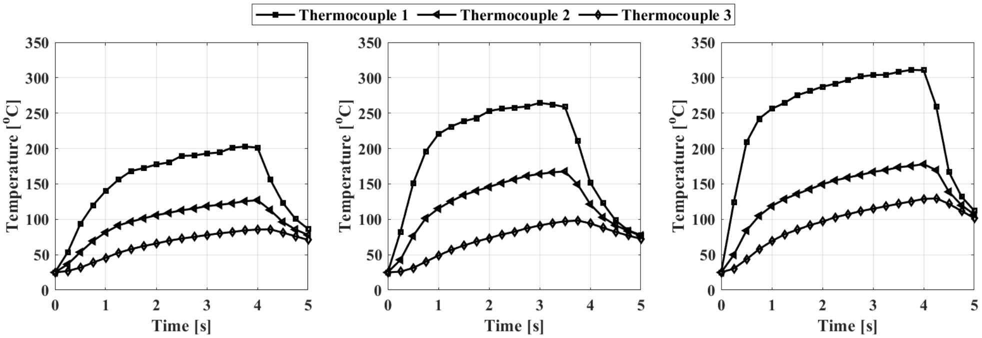

Figure 5.3: Temperature from Face Turning 1 (left), 2 (middle), 3 (right).

6 Conclusion

There are many challenges and complexities that are needed to be considered in FE simulations of cutting processes. These start with selecting the type of simulations to be performed and ends with selecting the type of experiments to be performed. Moreover, there are many effects that need to be implemented and many parameters that need to be identified which makes FE simulations computationally costly compared to analytical and semi-analytical models. That is why finding the optimum point between the accuracy and time consumption for metal cutting simulations is of interest to many researchers and engineers. To accomplish this, in **Papers A-F**, we investigated the different aspects of machining with simulations.

In **Paper A**, we focused on establishing a robust and efficient identification method for material model parameters used in metal cutting simulations. The identification process performed with only experiments requires the experiments to be performed under varying loading rates at varying temperatures while only a simulation-based identification process needs many simulations to be performed with different cutting conditions. Both of these approaches take a lot of time and effort. This challenge is overcome by using a combination of metal cutting experiments and cutting kinematics (i.e., a semi-analytical method) to identify the material model parameters. 2D chip forming simulations are performed for this study and the results are verified by comparison of cutting forces and chip thickness with experimental measurements of orthogonal cutting.

In **Paper B**, an enhanced damage growth model was developed for ductile fracture to investigate the effects of nonlocal evolution of damage and global damage threshold. Since, there are many damage models available in the literature for ductile failure, selecting a suitable model for the simulations is crucial to obtain realistic results. The results obtained in this study showed that implementing a global damage threshold improved the mesh dependency of the results. However, results from the nonlocal damage model do not show significant differences compared to local damage models even under high loading rates (i.e., split-Hopkinson pressure bar simulations).

In **Paper C**, our aim was to investigate different material models for the flow stress property of the workpiece material and evaluate their performance in metal cutting simulations. As mentioned in the Material Modeling section, there are many effects that can be included in the plastic property of the material, and the material model should represent the effects such as strain hardening/softening, strain rate hardening, thermal softening, etc., properly. To observe the overall performance of the models, the evaluation is done for two different setups; orthogonal cutting and face turning. Thus, both 2D and 3D chip forming simulations are performed. The evaluation is concluded by selecting the best-suited model for the chip forming simulations of the medium carbon steel used in the study. It should be mentioned that the calibration of the material models in this work is performed with the approach presented in **Paper A**.

In **Paper D**, our focus was shifted from cutting forces and chip formation to temperature and heat flux in metal cutting. To obtain realistic temperature distribution on the tool in the simulations, the applied heat flux needs to have a realistic distribution. However, estimating the heat flux distribution on the tool is quite complex due to different heat sources related to plastic deformation and friction on different sides of the tool.

To tackle with this complex case, we used a machine learning approach combined with heat transfer simulations. The results showed that machine learning has the potential to estimate the complex heat flux distribution. It should be stated that this study also provided some information and answered some of our questions related to the temperature levels that are observed and may trigger thermal softening/hardening mechanisms that are discussed in **Paper C**.

In **Paper E**, we improved our heat transfer model in **Paper D** further by adding the time-dependency of the heat flux, the chip flow direction and the effect of the tool nose. Additionally, we observed the effect of imposing a maximum temperature constraint on the machine learning model. Even though the results are improved compared to the previous work, the identification of the heat flux is very dependent on the reliability of the provided experimental data. Thus, challenges still remain regarding temperature experiments and obtaining reliable measurements from different points on or inside the tool.

In **Paper F**, our goal was to obtain detailed information about the primary shear zone and estimate the cutting forces and temperature while reducing the computational cost of the simulations by using material flow simulations instead of chip forming simulations. Since the computational cost is a big disadvantage of the FE chip forming simulations, the material flow simulations can also be used for the inverse identification process of some parameters more efficiently. The model consists of a semi-analytical model to provide the velocity distribution in the primary shear zone and the Navier-Stokes equations for the full solution in the region. Based on the obtained results, the material flow model has a significant potential for the estimation of forces and temperature.

Even though some challenges are overcome in **Papers A-F**, there are still many challenges to tackle with and improvements to be made. Some suggestions for future work and improvements would be; the semi-analytical model used in **Paper A** for the identification method can be improved to include the non-equal primary shear zone, the nonlocal damage model established in **Paper B** can be implemented for metal cutting simulations, a more detailed material model including damage or a machine learning-based material model can be used in chip forming simulations (especially for the cases with high feed) in **Paper C**, the measured temperatures in **Papers D** and **E** can be obtained by using a different test method and heat sources on the flank side of the tool can be included in the heat transfer simulations, and lastly, the secondary and tertiary shear zones can be included in the material flow simulations in **Papers F**.

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