Simulation Techniques in Manufacturing Technology

Introduction

Laboratory for Machine Tools and Production Engineering
Chair of Manufacturing Technology

Prof. Dr.-Ing. Dr.-Ing. E.h. Dr. h.c. Dr. h.c. F. Klocke
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# STMT-Lecture: Time schedule

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<th>Room No.</th>
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<td>53C/101</td>
<td>Abouridouane</td>
<td>Introduction to STMT 53B, R312b</td>
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<td>28. Okt</td>
<td>L</td>
<td>53C/101</td>
<td>Ozhoga-Maslovskaja</td>
<td>Forming technology basics 54A, R411</td>
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<td>04. Nov</td>
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<td>53C/101</td>
<td>Ozhoga-Maslovskaja</td>
<td>Actual simulation techniques in forming process 54A, R411</td>
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<td>11. Nov</td>
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<td>Ozhoga-Maslovskaja</td>
<td>Bulk metal forming 54A, R411</td>
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<td>18. Nov</td>
<td>L</td>
<td>53C/101</td>
<td>Ozhoga-Maslovskaja</td>
<td>Sheet metal forming and separation 54A, R411</td>
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<td>Principles of Cutting 53B, R312b</td>
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<tr>
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<td>Abouridouane</td>
<td>Overview of the various cutting processes 53B, R312b</td>
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<td>FE-Simulation of cutting processes 53B, R312b</td>
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<td>16. Dez</td>
<td>W</td>
<td>53B/101a</td>
<td>Abouridouane</td>
<td>FEM-Workshop (Abaqus and Deform)</td>
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<tr>
<td>16. Dez</td>
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<td>L</td>
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<td>Barth</td>
<td>Cutting with geometrically undefined cutting edge I 54A, R403</td>
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<tr>
<td>20. Jan</td>
<td>L</td>
<td>53B/101a</td>
<td>Barth</td>
<td>Cutting with geometrically undefined cutting edge II 54A, R403</td>
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<td>20. Jan</td>
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<td>53B/101a</td>
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<tr>
<td>27. Jan</td>
<td>L</td>
<td>53B/101a</td>
<td>Abouridouane</td>
<td>Methods of validation and optimization techniques 53B, R312b</td>
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<td>27. Jan</td>
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<td>03. Feb</td>
<td>L</td>
<td>53C/101</td>
<td>Abouridouane</td>
<td>Revision of contents 53B, R312b</td>
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<tr>
<td>03. Feb</td>
<td>E</td>
<td>53C/101</td>
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## Time:
- Lecture (L):  Fr, 10.00-11.30h
- Exercise (E): Fr, 11.45-12.30h

## Location:
- WZL, RWTH Aachen
  - Herwart-Opitz-Haus
  - Steinbachstr. 53
  - 52074 Aachen

## Room:
- 53C, 101

## Contact:
- Dr.-Ing. M. Abouridouane
  - Tel. (0241) 80-28176
STMT-Lecture: Exam, computer exercise, literature

- Examination
  - Type of examination: Oral
  - Date of the examination: February, the xxth 2017
  - Room, time, and distribution of groups will be given!
  - Duration: 60 minutes for each group

- Computer exercise
  - Date for the FEM-Workshop: December, the 16th 2016
  - Room: 53B/101a (WZL, Herwart-Opitz-Haus)
  - Time: 10:00 to 18:00

- Literature about metal machining (Emails list!)
  - Manufacturing processes 1 - Cutting of Klocke
  - Metal Machining (Theory and Applications) of Childs
  - Machining Dynamics of Kai Cheng

- Any other discussion points, comments or questions?
  - Please contact Mr. Abouridouane (Tel.: +49 241 80-28176)
STMT-Lecture: Supervisors

- Cutting process
  Dr.-Ing. Mustapha Abouridouane
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  Fax: +49 241 80-22293
  m.abouridouane@wzl.rwth-aachen.de

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  Herwart-Opitz-Haus 54A 411
  Tel.: +49 241 80-27428
  Fax: +49 241 80-22293
  o.ozhoga-maslovskaja@wzl.rwth-aachen.de

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  Herwart-Opitz-Haus 54A 403
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  Fax: +49 241 80-22293
  s.barth@wzl.rwth-aachen.de
RWTH Aachen and Fraunhofer-Gesellschaft

Fraunhofer-Gesellschaft
- More than 65 institutes and facilities at 40 locations in Germany
- >23,000 employees
- approx. €2.0 billion research funds per year, €1.7 billion through research contracts
- 3 institutes in Aachen

Fraunhofer

RWTH Aachen University
- Founded in 1870
- 40,375 students

Faculty of Mechanical Engineering
- 11,700 students (incl. 2,700 first year students)
- 53 professors
- 2,600 employees
- 170 graduates per year
Production Technology in Aachen

Laboratory for Machine Tools and Production Engineering (WZL)
- RWTH Aachen University institute
- Founded in 1906
- 839 employees
- 16,000 m² offices and laboratories

Fraunhofer Institute for Production Technology IPT
- Fraunhofer-Gesellschaft institute
- Founded in 1980
- 450 employees
- 6300 m² offices and laboratories
- Certified to DIN EN ISO 9001:2008
Budget 2013: WZL, Fraunhofer IPT, WZLforum, WZL Aachen GmbH

Budget: 53.61 Mio €

- Industrial projects: 41.70%
- Public funding*: 33.57%
- Basic funding by Fraunhofer-Gesellschaft and RWTH Aachen University: 24.73%

* EU, AiF, BMBF, DFG
Two Institutes – One Philosophy

- Process Technology
- Production Machines
- Mechatronic Systems Design
- Production Quality and Metrology
- Technology Management

- Manufacturing Technology
- Gearing Technology
- Machine Tools
- Metrology and Quality Management
- Production Engineering and Production Management
Our Focus

Process Technology
- Machining and material removal processes
- Laser materials processing
- Forming processes
- CAx, Virtual Reality

Production and Machine Tools
- Design of production machines and components
- Control technology and automation
- Component and production machines testing

Metrology
- Tactile metrology
- Optical metrology

Gearing Technology
- Gear manufacturing
- Gear calculation and investigation

Management
- Business Engineering
- Technology management
- Innovation management
- Production management
- Quality management

Education
- Professional training
- Executive MBA for Technology Managers
- Conferences, congresses, seminars

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# Process and Manufacturing Technology

**Prof. Dr.-Ing. Dr.-Ing. E.h. Dr. h.c. Dr. h.c. Fritz Klocke**

<table>
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<th>Cutting technology</th>
<th>Grinding and forming</th>
<th>Laser machining</th>
<th>CAx technologies</th>
<th>Process and product monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning, milling, drilling, broaching</td>
<td>Grinding, lapping, polishing, honing</td>
<td>Joining, cutting, forming</td>
<td>Laser surface treatment</td>
<td>CAD/CAM technologies</td>
</tr>
<tr>
<td></td>
<td>Solid forming, sheet metal forming, hard smooth rolling, tribology</td>
<td>Rapid Manufacturing</td>
<td></td>
<td>Process monitoring systems and strategies</td>
</tr>
<tr>
<td>Tool and die making</td>
<td>Laser surface treatment</td>
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<td>Material removal processes</td>
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<tr>
<td>Precision and micro technology</td>
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<td>Optics and optical systems</td>
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<tr>
<td>Plant engineering and construction</td>
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<tr>
<td>Automotive, aerospace, turbine construction</td>
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</table>
Process and Manufacturing Technology

- Manufacturing fundamentals
- Machining with a geometrically defined cutting edge
- Machining with a geometrically undefined cutting edge
- Material removal processes
- Forming processes
- Laser machining
- Gearwheel manufacture
- Precision and ultra-precision processes
- Process and product monitoring
- Process simulations, methods and tools for technology planning and production design, virtual reality
# Manufacturing Technology:
## Group: Fundamentals of Cutting & Modeling and Evaluation

<table>
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<th>Fundamentals of Cutting</th>
<th>Modeling and Evaluation</th>
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<td>Technology planning</td>
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<td>Analysis of wear</td>
<td>Modelling and model development</td>
</tr>
<tr>
<td>Process Design</td>
<td>Simulation of tool wear</td>
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<tr>
<td>Tool development</td>
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<tr>
<td>Concept for cooling lubricants</td>
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<td>Energy-saving production</td>
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<tr>
<th>Space- and aircraft-industry, turbine construction (machining of turbine disks and blades, structural components..)</th>
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<tr>
<td>Automotive industry (processing of crankcase, cylinder head, cylinder, camshaft, axle parts...)</td>
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<tr>
<td>Tool technology (wear analysis, tool layout, macro, micro geometry...)</td>
</tr>
<tr>
<td>Materials manufacturer (machinability, lead substitute ...)</td>
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<tr>
<td>Resource efficiency (material, energy, auxiliaries...)</td>
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Chair of Manufacturing Technology
Group Fundamentals of Cutting

- Analysis of the machinability
- Material analysis of tools and components, analysis of tool wear
- Process development and process optimisation in turning, milling, drilling, broaching, tapping
- Development of machining strategies, HSC and HPC machining, circular processes
- Development and optimisation of lubricooling strategies: dry, MQL, conventional wet, high-pressure and cryogenic
- Tool development: substrate, macro and micro geometry, cutting edge preparation, coating, chip form geometry
- Development of environmentally friendly and resource efficient machining processes
Chair of Manufacturing Technology –
Modelling and Evaluation of Cutting Processes

Modelling of cutting processes

- Development of process models for cutting technologies
- Simulation of the thermo-mechanical load spectrum during machining
- Cutting tool design and optimization of process parameters using FEM-simulations

Evaluation of cutting processes

- Acquiring and assessing of energy and material consumptions of single processes (indicators)
- Evaluation and design of processes and technology chains in respect to energy and resource efficiency
- Ecological life cycle management and Life cycle assessment (LCA)
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Lecture objectives

- Fundamentals and basic knowledge in manufacturing technology for a better understanding of the mechanisms during metal machining
- Modelling approaches for simulation
- Simulation techniques
- Application of simulation in manufacturing technology
- Challenges of simulation and future developments
| 1 | Lecture organisation  |
| 2 | Presentation of WZL  |
| 3 | Lecture objectives   |
| 4 | Modelling and simulation: Definition, motivation and integration |
| 5 | Lecture topics and fundamental knowledge |
| 6 | FE modelling for the forming process |
| 7 | FE modelling for the cutting process |
| 8 | FE model validation |
| 9 | Optimization integration in the FEM |
Modelling – a human property

Experience

Perception

Model vision
Modelling – a human property

Reality / Perception

Sensorium

Modeling

Mind

IT-based converting
Basic of reasons

Inductive reasoning
Modeling based on experience

Deductive reasoning
Modeling based on theoretical derived models

The particular Reality

The general Model section
# Definitions

## Model

A model is an abstract system that corresponds to a real system and is used for expensive and/or impossible

- investigations,
- calculations and
- explanations or demonstration purposes.

It delivers general information about

- elements,
- structure and
- behavior

of a part of the reality.

## Simulation

A simulation is a replication of a dynamic process based on a model.
Continuously increasing demands of the market lead to increasing requirements for manufacturing processes.
Why process modelling?

- Manufacture complex parts
- Increase quality
- Increase reliability of production
- Apply new materials (Al, Mg, …)
- Use material more efficiently
- Reduction of time required for training
- Reduction of lead time
- Reduction of time
- Reduction of lead time
- Reduction of time required for training
- Reduction of pre-production trials
- Reduction of tool cost

Source: BMW
Integration of process modelling into the process chain

Process chain:
- Design of car exterior
- Part design
- Means of production
  - Planning
  - Tool design
- Tool manufacturing and testing
- Part production

Application:
- Sheet metal forming simulation
  - Part evaluation
  - Process optimisation

Software solution:
- Methods applied:
  - 2D modelling
  - one-step modelling
  - modelling with membrane elements
  - Short computation time with sufficient precision

Methods applied:
- Simulation with membrane elements
- Simulation with shell elements
- High Precision within acceptable computation times

Source: BMW
Modelling and Simulation: aims and requirements

Goals

- Increase of the process knowledge & comprehension
- Prediction of the process stability
- Prediction of the component characteristics
- Reduction of planning and development steps
- Cost reduction

Today without process simulation

- 4
- 12
- 16
- 8
- 24
- 12

76 Weeks

specification sheet product
concept design and choice of material
lay-out
manufacturing aspects
design
manufacturing planning
manufacturing
workpiece test

Goals

- Increase of the process knowledge & comprehension
- Prediction of the process stability
- Prediction of the component characteristics
- Reduction of planning and development steps
- Cost reduction
Modelling and Simulation: aims and requirements

Goals

- Increase of the process knowledge & comprehension
- Prediction of the process stability
- Prediction of the component characteristics
- Reduction of planning and development steps
- Cost reduction

Future with process simulation

<table>
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<th>Task</th>
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<td>Concept design and choice of material</td>
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<td>12</td>
<td>Lay-out</td>
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<tr>
<td>14</td>
<td>Design</td>
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<tr>
<td>12</td>
<td>Manufacturing planning</td>
</tr>
<tr>
<td>12</td>
<td>Manufacturing</td>
</tr>
<tr>
<td>12</td>
<td>Workpiece test</td>
</tr>
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54 Weeks

Reduction of the cycle time by 30%

specification sheet product

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Modelling and Simulation: aims and requirements

**Goals**
- Increase of the process knowledge & comprehension
- Prediction of the process stability
- Prediction of the component characteristics
- Reduction of planning and development steps
- Cost reduction

**Requirements**
- High result quality
- High process reliability
- Adaption of technological innovations
- Realistic prediction of the process results
Partitioning of different model types from literature review

- **Basic & regression models**: 20%
- **ANN models**: 4%
- **Rule & knowledge models**: 6%
- **Overview article**: 2%
- **MD - models**: 1%
- **FEA - models**: 19%
- **Kinematic geometrical models**: 10%
- **Analytical models**: 38%

Source: Heinzel 2009
The history of the development of cutting process models

### The use*

- **Analytical models:** 38%
- **Basic and regression models:** 20%
- **FEA models:** 19%
- **Kinematic geometrical models:** 10%
- **Rule and knowledge models:** 6%
- **ANN models:** 4%
- **Overview article:** 2%
- **MD models:** 1%

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Source: Ivester, 50th CIRP General Assembly, Sidney 2000; *Heinzel 2009

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Sheet Metal Forming Techniques

- Deep drawing
- Stretch forming
- Spinning
- Ironing
- Bending
- Hydroforming

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Forming process: Extruding a transmission shaft
Face milling
Grinding process
Grinding process
Lattice Types of an Unit Cell

<table>
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<th>Lattice Type</th>
<th>Examples</th>
<th>Sliding Planes</th>
<th>Sliding Directions</th>
<th>Sliding Systems</th>
<th>Formability</th>
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<tbody>
<tr>
<td>face-centred cubic (fcc)</td>
<td>γ-Fe, Al, Cu</td>
<td>4</td>
<td>3</td>
<td>12</td>
<td>very good</td>
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<tr>
<td>body-centred cubic (bcc)</td>
<td>α-Fe, Cr, Mo</td>
<td>6</td>
<td>2</td>
<td>12</td>
<td>good</td>
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<tr>
<td>hexagonal (hex)</td>
<td>Mg, Zn, Be</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>poor</td>
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</table>
Stress Determination Depending on Load

tensile test

\[ \sigma = \frac{F}{A_0} \]

tensile stress

compression test

\[ \sigma = \frac{-F}{A_0} \]

compression stress

shear test

\[ \tau = \frac{F}{A_0} \]

shear stress
Strain Determination of an Idealized Upsetting Process

true strain (plastic)

\[ d\phi = \frac{dl}{l} \quad \Rightarrow \quad \phi = \int_{l_0}^{l} \frac{dl}{l} = \ln \frac{l}{l_0} \]

\[ \Rightarrow \quad \varphi_x = \ln \frac{l_1}{l_0} ; \quad \varphi_y = \ln \frac{b_1}{b_0} ; \quad \varphi_z = \ln \frac{h_1}{h_0} \]

including of volume constancy

\[ l_0 \cdot h_0 \cdot b_0 = l_1 \cdot h_1 \cdot b_1 = \text{const.} \]

\[ \Rightarrow \quad \varphi_x + \varphi_y + \varphi_z = 0 \]

engineering strain (elastic)

\[ d\varepsilon_x = \frac{dl}{l_0} \quad \Rightarrow \quad \varepsilon_x = \int_{l_0}^{l} \frac{dl}{l_0} = \ln \frac{l}{l_0} = \frac{\Delta l}{l_0} \]

\[ \varphi_x = \ln \left( \frac{l_1}{l_0} \right) = \ln \left( \frac{l_0 + u_x}{l_0} \right) = \ln \left( \frac{l_0 + \Delta l}{l_0} \right) = \ln \left( \frac{\Delta l}{l_0} + \frac{l_0}{l_0} \right) = \ln (\varepsilon_x + 1) \]
Stress-Strain Curve up to the Uniform Elongation

true tensile stress:
(related to real section)

engineering stress:
(related to starting section)
Flow curve

- Required stress to overcome strain hardening
- Minimal required stress for initial plastic deformation

Flow stress $k_f$

True strain $\phi$
Stress conditions with corresponding Mohr’s stress circles

**Uniaxial**

**Biaxial**

**Triaxial**
Yield criteria

- Shear stress hypothesis by Tresca

\[ \sigma_2 = \sigma_3 = 0 \]

\[ \sigma_1 = \frac{F}{A} = k_f = 2k \Rightarrow k = \frac{k_f}{2} \]

with \( \tau_{max} \Rightarrow \sigma_1 - \sigma_3 = k_f \)

\[ k_f = \frac{1}{2} \max(|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1|) \]

- Form change – Energy hypothesis by von Mises

\[ k_f = \sqrt{\frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \]
### Levy-Mises flow rule

**Elastic**

Hooke's law:
Mathematical dependence between stress and strain.
\[ \varepsilon = \frac{1}{E} \cdot \sigma \]

**Plastic**

Levy-Mises flow rule:
Mathematical dependence between yield stress and strain rate.

The strain rate tensor and the deviatoric stress tensor are proportional to each other (\( \lambda \) = proportionality factor).

Flow rule:
\[
\begin{align*}
\dot{\varphi}_1 &= d\lambda (\sigma_1 - \sigma_m) \\
\dot{\varphi}_2 &= d\lambda (\sigma_2 - \sigma_m) \\
\dot{\varphi}_3 &= d\lambda (\sigma_3 - \sigma_m)
\end{align*}
\]

Alternative form (division by dt):
\[
\begin{align*}
\dot{\varphi}_1 &= \dot{\lambda} (\sigma_1 - \sigma_m) \\
\dot{\varphi}_2 &= \dot{\lambda} (\sigma_2 - \sigma_m) \\
\dot{\varphi}_3 &= \dot{\lambda} (\sigma_3 - \sigma_m)
\end{align*}
\]

Proportionality factor \( \lambda \) (not constant):
\[ \dot{\lambda} = f(k_f, \dot{\varphi}) \]

Out of flow rule and v. Mises yield criterion follows:
\[ \dot{\lambda} = \frac{1}{k_f} \cdot \sqrt{\frac{3}{2} \left( \dot{\varphi}_1^2 + \dot{\varphi}_2^2 + \dot{\varphi}_3^2 \right)} \]
**Yield stress and yield criterion**

Assumption for plastic flow (v. Mises)

\[ \sigma_v = k_f = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \]

Equivalent stress

Real process (multiaxial)

Determination of flow curves (uniaxial)

Yield criterion

\[ \sigma_v = k_f \]
Forming Property: Measuring Grid Technique

- Deformation of the measuring grid because of tensile and compression stresses inside the sheet metal while forming

- The effective strain can be derived from the grid deformation = maximum deformation (forming limit)

\[ \varphi_b = \ln \frac{b_1}{d_0} \quad \varphi_l = \ln \frac{l_1}{d_0} \]
Forming Property: Forming Limit Curve

Variable strip thickness to vary $\varphi_2$ (one test corresponds with one value of $\varphi_2$)

Definition: $\varphi_1 > \varphi_2$

Test conditions: deep drawing test with hemispherical stamp and straight strip

Material: RR St 1403
Sheet thickness: 1 mm

Determination of forming limit curve to predict failure by using FEM
<table>
<thead>
<tr>
<th></th>
<th>Outline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lecture organisation</td>
</tr>
<tr>
<td>2</td>
<td>Presentation of WZL</td>
</tr>
<tr>
<td>3</td>
<td>Lecture objectives</td>
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<td>4</td>
<td>Modelling and simulation: Definition, motivation and integration</td>
</tr>
<tr>
<td>5</td>
<td>Lecture topics and fundamental knowledge</td>
</tr>
<tr>
<td>6</td>
<td>FE modelling for the forming process</td>
</tr>
<tr>
<td>7</td>
<td>FE modelling for the cutting process</td>
</tr>
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<td>8</td>
<td>FE model validation</td>
</tr>
<tr>
<td>9</td>
<td>Optimization integration in the FEM</td>
</tr>
</tbody>
</table>
**Considerations prior to a FE simulation study (Forming process)**

<table>
<thead>
<tr>
<th>Definition of the simulation problem</th>
<th>Constituents of a model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective of the simulation study</td>
<td>Geometry</td>
</tr>
<tr>
<td>Relevant physical mechanisms:</td>
<td>– Accurate form reproduction</td>
</tr>
<tr>
<td>– Mechanical, thermal, electro-magnetic…</td>
<td>– Stock or special FE mesh generator</td>
</tr>
<tr>
<td>Type of the problem:</td>
<td>– Critical areas, complex shapes</td>
</tr>
<tr>
<td>– Linear</td>
<td>Material</td>
</tr>
<tr>
<td>– Non-linear</td>
<td>– Material model formulation</td>
</tr>
<tr>
<td>Time dependency:</td>
<td>– Elasticity and Poisson’s ratio</td>
</tr>
<tr>
<td>– Static</td>
<td>– Density, hardening</td>
</tr>
<tr>
<td>– Dynamic</td>
<td>– Thermal properties</td>
</tr>
<tr>
<td>Simulation software &amp; hardware:</td>
<td>Boundary conditions</td>
</tr>
<tr>
<td>– Solvers for the intended objectives</td>
<td>– Process parameters</td>
</tr>
<tr>
<td>– Element types</td>
<td>– Process kinematics</td>
</tr>
<tr>
<td>– Specific numerical technologies</td>
<td>– Process steps</td>
</tr>
</tbody>
</table>
Procedure of FE-Analysis

Pre-processor

1. CAD-model
2. Idealization
3. Discretization
4. Boundary conditions

Solver

5. FE-Analysis

Post-processor

6. Interpretation of the results

\[
\begin{bmatrix}
\sigma_{11} & G_{12} & 0 & 0 & 0 \\
G_{12} & \sigma_{22} & 0 & 0 & 0 \\
0 & 0 & G_{33} & 0 & 0 \\
0 & 0 & 0 & G_{23} & 0 \\
0 & 0 & 0 & 0 & G_{13}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\gamma_{12} \\
\gamma_{13} \\
\gamma_{23}
\end{bmatrix}
\]
FE Study process

- **CAD model**
  - Geometry of a workpiece and a tool.
  - Often available as CAD Data.
  - Universal formats for 3D data (STEP, STP, STL…)

- **Idealization**
  - Simplification of the real geometry for a more structured mesh

- **Discretization**
  - Meshing of an object into discrete domains

- **Boundary conditions**
  - Numerical reproduction of mechanic, kinematic, contact, electro-magnetic, thermal conditions of a real process

- **Material modeling**
  - Numerical formulation of relevant material properties (elasticity, plasticity, shear etc.)

- **FE-Analyses**
  - Calculation of elementary matrices, definition of the system matrix and a vector of outer forces, solution of linear equation systems for every integration point

- **Evaluation**
  - Analysis of the results and answering the objective of the study
Simulation of bulk metal forming processes

Chronology of FEM-Simulation: Material modelling

- Description of material behavior using mathematical material models
- Use of ideal-plastic material model is sufficient for bulk metal forming processes
- Use of elastoplastic material models for simulation of sheet metal forming processes

![Material modelling flowchart]

- CAD model
- Idealization
- Discretization
- Boundary conditions
- Material modelling
- FE-Analyses
- Evaluation

![Material models]

- Elastic
- Ideal plastic
- Plastic with hardening
- Elasto-plastic with hardening

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Simulation of bulk metal forming processes

Chronology of FEM-Simulation: FE-Analysis

- Implicit solution method:
  - Small number of time steps (respectively long time increments)
  - Higher effort for iterations compared to explicit solution method
  - Often less computation time then with explicit solution method
  - Applicable especially for static and quasi-static problems

- Explicit solution method:
  - Length of increment depends on the speed of sound c, Young's modulus E and material density ρ; this requires a high number of increments
  - Longer computation time compared to implicit solution method
  - Applicable especially for highly dynamic problems (e.g. crash-simulations)
Simulation of bulk metal forming processes

Movie: FEM-Simulation cross joint

- Typical evaluation variables are stress-strain-profiles or characteristic values such as the degree of damage.
## Lecture organisation

## Presentation of WZL

## Lecture objectives

## Modelling and simulation: Definition, motivation and integration

## Lecture topics and fundamental knowledge

## FE modelling for the forming process

## FE modelling for the cutting process

## FE model validation

## Optimization integration in the FEM
## The great challenges of the cutting process

<table>
<thead>
<tr>
<th>Process</th>
<th>Strain</th>
<th>Strain rate / s(^{-1})</th>
<th>(T_{\text{homolog}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion</td>
<td>2 – 5</td>
<td>(10^{-1} – 10^{-2})</td>
<td>0.16 – 0.7</td>
</tr>
<tr>
<td>Forging / Rolling</td>
<td>0.1 – 0.5</td>
<td>(10 – 10^{+3})</td>
<td>0.16 – 0.7</td>
</tr>
<tr>
<td>Sheet metal forming</td>
<td>0.1 – 0.5</td>
<td>(10 – 10^{+2})</td>
<td>0.16 – 0.7</td>
</tr>
<tr>
<td>Cutting</td>
<td>1 – 5</td>
<td>(10^{+3} – 10^{+6})</td>
<td>0.16 – 0.9</td>
</tr>
</tbody>
</table>

→ Extreme conditions in the cutting process

Source: Jaspers
Influence factors on the cutting process

<table>
<thead>
<tr>
<th>Workpiece</th>
<th>Cutting condition</th>
<th>Tool</th>
<th>Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ-structure</td>
<td>Chip formation mechanisms</td>
<td>Cutting material</td>
<td>Machine design</td>
</tr>
<tr>
<td>Texture</td>
<td></td>
<td>Cooling lubricant</td>
<td>Drive unit</td>
</tr>
<tr>
<td>Material properties</td>
<td></td>
<td>Cutting parameters</td>
<td>Clamping device</td>
</tr>
<tr>
<td>Hardness</td>
<td></td>
<td>Contact conditions</td>
<td></td>
</tr>
<tr>
<td>Residual stress</td>
<td></td>
<td>e.g.: Friction, heat transfer, wear, etc.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Input and output parameters of the cutting simulation

**Chip Formation**
- temperatures
- stresses
- deformations
- strain rate
- kind of chip
- chip flow
- chip breakage

**Workpiece / Tool**
- geometries
- material data
- contact conditions
- boundary conditions
- cutting conditions
- Tool
  - strain
  - stresses
  - temperatures
  - process forces
  - wear

**Workpiece**
- strain
- temperatures
- deformation
- burr formation
- distortion
- prospective: residual stresses, surface qualities, like: roughness, dimensional- and formdeviation
Tool geometry modelling for a realistic tool CAD model

<table>
<thead>
<tr>
<th>Drilling tool</th>
<th>Acquisition of tool geometry</th>
<th>FE-CAD-Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real tool</td>
<td>CAD-Model</td>
<td></td>
</tr>
<tr>
<td>Macro-geometry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Micro-geometry</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Drilling tool**
  - Acquired geometry for realistic tool CAD model

- **Acquisition of tool geometry**
  - Macro-geometry: 4 mm
  - Micro-geometry: 6 µm

- **FE-CAD-Model**
Definition of element type

**1D**
- bar element

**2D**
- triangle
- quadrangle

**3D**
- tetrahedron
- pentahedron
- pyramid
- hexahedron
Material law to calculate stresses

\[ M \ddot{u} + C \dot{u} + Ku = F \]

\[ \varepsilon = \sum B_i \cdot u_i \]

\[ \sigma = \sigma (\varepsilon, \dot{\varepsilon}, T) \]
Thermo-mechanical behavior of material

\[ \sigma = \sigma(\phi, \dot{\phi}, T) \]

- **Strain Hardening**
- **Strain Rate Hardening**
- **Thermal Softening**

Source: Diss- Abouridouane
Constitutive material modelling for the FE cutting simulation

- **Empirical models:** e.g. Johnson-Cook-Modell
  \[ \sigma = (A + B \varepsilon^n) \cdot (1 + C \ln(\dot{\varepsilon}/\dot{\varepsilon}_0)) \cdot (1 - \left[ \frac{T - T_r}{T_m - T_r} \right]^m) \]

  - Strain hardening
  - Strain rate sensitivity

- **Micro mechanical models:** e.g. enhanced Macherauch-Vöhringer-Kocks-model
  \[ \sigma \approx \sigma_a + \sigma_0^* \left( 1 - \frac{kT}{\Delta G_0} \cdot \ln \left( \frac{\dot{\varepsilon}_0}{\dot{\varepsilon}} \right) \right)^{1/q} + \eta \dot{\varepsilon} \]

  - Athermal processes
  - Thermal activated processes
  - Damping process

- **Semi-empirical models:** e.g. Zerilli-Armstrong-model for bcc-materials
  \[ \sigma = \Delta \sigma_G' + C_1 \exp \left[ -C_2 T + C_3 T \ln(\dot{\varepsilon}) \right] + C_4 \varepsilon^n + C_5 L^{-1/2} \]

  - Initial density of dislocations
  - Influence of temperature and strain rate
  - Dislocation jam
  - Influence of grain size

**Source:** Diss-Abouridouane
Determination of High speed flow curves

Split-Hopkinson-Pressure-Bar

Split-Hopkinson-Tension-Bar

Strain rate: $500 \text{ s}^{-1} - 10000 \text{ s}^{-1}$
Temperature range: $93 \text{ K} - 1273 \text{ K}$
Projectile speed: $2.5 \text{ m/s} - 50 \text{ m/s}$
Projectile mass: $m = 3.15 \text{ kg}$

Source: LFW
Material law for high strain rate deformation

\[
k_{f\text{ ad}} = \frac{K(B + \varphi)^n + \eta \dot{\varphi}}{1 + a \int [K(B + \varphi)^n + \eta \dot{\varphi}] \dot{\varphi} \, dt}
\]

Source: Diss- Brodmann
## Material damage mechanisms

<table>
<thead>
<tr>
<th>Type of load</th>
<th>Shear loading</th>
<th>Tensile loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear localisation model</td>
<td>(Imperfection theory)</td>
<td>Void growth model</td>
</tr>
</tbody>
</table>

**Quelle:** Diss-Abouridouane

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Damage modelling for the FE cutting simulation (ductile failure)

- **Macromechanical damage models**
  - Effective stress / effective strain model: \( D_\sigma = \sigma_{v,f} \quad / \quad D_\varepsilon = \varepsilon_{v,f} \)
  - Gosh-Model: \( D_{\text{Gosh}} = (1+\sigma_2/\sigma_1) \sigma_1^2 \)
  - Ayada-Model: \( \text{d}D = (\sigma_m/\sigma_v) \text{d}\varepsilon_v \)

- **Micromechanical damage models (Void expansion models)**
  - Hancock-Mackenzie-Model \( \varepsilon_f = \varepsilon_n + \alpha \exp\left( -\frac{3 \sigma_m}{2 \sigma_v} \right) \)
  - Gurson-Tveergard-Needleman-Model \( 0 = \left( \frac{\sigma_v}{\sigma_{v,M}} \right)^2 + 2fq_1 \cosh\left( \frac{3\sigma_m}{2\sigma_{v,M}} \right) - \left[ 1 + (q_1f)^2 \right] \)
  - Johnson-Cook-Model \( \varepsilon_f = \left[ D_1 + D_2 \exp\left( -D_3 \frac{\sigma_m}{\sigma_v} \right) \right]\left[ 1 + D_4 \ln\left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right]\left[ 1 + D_5 \frac{T}{T_m} \right] \)

Source: Diss-Abouridouane

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Friction modelling for the FE cutting simulation

Thermal load on the tool-workpiece interface

Temperature distribution on the contact zone
(by Kronenberg)

Workpiece material:
Yield strength: k_f = 850 N/mm²
Cutting material: HW-P20
Cutting speed: v_c = 60 m/min
Uncut chip thickness: h = 0,32 mm
Rake angle: γ_o = 10°
Friction modelling for the FE cutting simulation

Deformation on the tool-workpiece interface

1. primary shearing zone
2. secondary shearing zone of the face
3. separative zone (stagnation point)
4. secondary shearing zone of the flank
5. preliminary deformation zone

workpiece material: C53E
cutting edge material: HW-P30
cutting speed: \( v_c = 100 \text{ m/min} \)
cross-section area of cut: \( a_p \times f = 2 \times 0.315 \text{ mm}^2 \)
Friction modelling for the FE cutting simulation

Mechanical load on the tool-workpiece interface

1. primary shearing zone
2. secondary shearing zone of the face
3. separative zone (stagnation point)
4. secondary shearing zone of the flank
5. preliminary deformation zone

Workpiece structure

Cut surface

Turning tool

Flank

Rake face

Shearing plane

Chip structure

Normal stress: $\sigma_n$

Shear stress: $\tau$

Contact zone

Tool

by Oxley und Hatton

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Friction modelling for the FE cutting simulation

- **Coulomb friction model:**
  \[ |\tau_R| = \mu \cdot \sigma_N \]

- **Shear friction model:**
  \[ \tau_R = m \cdot k \quad \text{with} \quad k = \frac{k_f}{\sqrt{3}} \]

- **Transition from sliding friction (Coulomb) to sticking friction (Shear):**

  Z.B.: Usui-Model
  \[ \tau_R = k \left\{ 1 - \exp\left(-\mu \frac{\sigma_N}{k}\right) \right\} \]

- \( \tau_R \) – Friction shear stress
- \( \sigma_N \) – Normal stress
- \( k \) – Von Mises flow shear stress
- \( k_f \) – Von Mises flow stress
- \( \mu, m \) – Friction coefficients
Wear modelling for the FE cutting simulation
Wear types on the tool cutting edge and wear mechanisms

- Sliding mechanisms:
  - Abrasion
  - Adhesion
  - Delamination

- No sliding mechanisms:
  - Diffusion
  - Electrochemical
  - Oxidation

- Tool cutting edge
- Crater wear
- Flank wear
- Cutting edge breakouts
- Chip
- Rake face
- Tool
- Built-Up-Edge
- Flank face
- Workpiece
- Oxidation
- Rake face
- Flank face
- Built-Up-Edge
## Tool wear modelling

### Tool life equations

**Tool life by Taylor:**
\[ T = v^k_C \cdot C_v \]

**Tool life by Hasting:**
\[ T = \frac{A}{g^B} \]

- \( T \) = tool life
- \( v \) = temperature
- \( k, A, B \) = constants
- \( C_v = T \) for \( v_c = 1 \text{ m/min} \)

### Tool wear rate models

**Empirical tool wear model**

**Physical tool wear model**

- **Adhesion**
- **Abrasion + Diffusion**

### Adhesion / Abrasion

**Model by Archard:**
\[ \frac{dV}{dt} = K \frac{F \cdot S}{3H} \]

- d\( V/\)dt = wear volume per time
- H = hardness
- F = mechanical load
- S = cutting path

**Model by Usui:**
\[ \frac{dV}{dt} = \sigma_n \cdot v_{ch} \cdot C_1 \cdot e^{(-\frac{C_2}{T})} \]

- K, C1, C2, G, D = constants
- \( \sigma_n \) = normal pressure
- \( v_{ch} \) = sliding velocity
- \( v \) = temperature

**Model by Takeyama:**
\[ \frac{dV}{dt} = G \cdot v_c + D \cdot e^{-\frac{E}{R \cdot g}} \]

- K, C1, C2, G, D = constants
- \( v_c \) = sliding velocity
- \( v \) = temperature
FEM Software Solution for FEM simulation of the Cutting Process
### Criteria for the evaluation of FE software

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Program</th>
<th>ABAQUS</th>
<th>ANSYS/ LS-DYNA</th>
<th>AdvantEdge</th>
<th>DEFORM</th>
<th>COMSOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creation of geometries</td>
<td>Creation of geometries and import of CAD data</td>
<td>Import of CAD data</td>
<td>Creation of simple geometries and import of CAD data</td>
<td>Creation of simple geometries and import of CAD data</td>
<td>Creation of simple geometries and import of CAD data</td>
<td></td>
</tr>
<tr>
<td>Material catalogue</td>
<td>No, has to be defined</td>
<td>Yes, expandable</td>
<td>Yes, wide</td>
<td>Yes, new catalogue importable</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Element type</td>
<td>Every type</td>
<td>Every type</td>
<td>tetrahedron, rectangle</td>
<td>tetrahedron, rectangle</td>
<td>Every type</td>
<td></td>
</tr>
<tr>
<td>Time integration</td>
<td>Implicit / Explicit</td>
<td>Implicit / Explicit</td>
<td>Explicit</td>
<td>Implicit</td>
<td>Implicit</td>
<td></td>
</tr>
<tr>
<td>Remeshing routine</td>
<td>none</td>
<td>none</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>use</td>
<td>general</td>
<td>general</td>
<td>Cutting process</td>
<td>Deforming process</td>
<td>general</td>
<td></td>
</tr>
<tr>
<td>Influence on simulation computation</td>
<td>High, by Python</td>
<td>Possible, by Fortran</td>
<td>no</td>
<td>High, by Fortran</td>
<td>High, by Matlab</td>
<td></td>
</tr>
<tr>
<td>parallelization</td>
<td>possible</td>
<td>possible</td>
<td>possible</td>
<td>possible</td>
<td>possible</td>
<td></td>
</tr>
<tr>
<td>Usage at the WZL</td>
<td>Eigenfrequency analysis, elast. Tool behavior, elasto-plastic component behavior</td>
<td>no</td>
<td>no</td>
<td>Cutting simulation</td>
<td>Thermo-elastic deformation</td>
<td></td>
</tr>
</tbody>
</table>

Source: SIMULIA, ANSYS, LSTC, TWS, SFTC, COMSOL

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Cutting process simulation

Calculation of the thermo-mechanical tool-load-collective for an ideal dimensioning of the tools' micro- and macrogeometry.
Simulation of the chip flow (turning)

**Chip breaker RN**

- **Material:** C45E+N
- **Cutting material:** HC P25
- **Insert:** CNMG120408
- **Insert geometry:**
  
  \[
  \begin{array}{c|c|c|c|c}
  \alpha_0 & \gamma_0 & \lambda_S & \kappa_r & \varepsilon \\
  \hline
  6^\circ & -6^\circ & -6^\circ & 95^\circ & 90^\circ \\
  \end{array}
  \]
- **Cutting velocity:** \(v_c = 300\) m/min
- **Feed:** \(f = 0,1\) mm
- **Depth of cut:** \(a_p = 1\) mm
- **Dry cutting**

**Chip breaker FN**
Segmented Chip Simulation reveals periodic sticking zone

- First Contact
- Start of Shearing
- Crack Initiation
- Gliding
- End of Gliding
- New Segmentation
- Start of Shearing
- Crack initiation
Verification of the mechanical load

Cutting tool material: HC-P25
Workpiece material: C45E+N
CL: dry
Process: turning

Process forces F/N

<table>
<thead>
<tr>
<th>Process forces F/N</th>
<th>constant: f = 0.1 mm; ap = 3 mm</th>
<th>constant: v_c = 350 m/min; ap = 3 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>v_c = 250 m/min</td>
<td></td>
<td>v_c = 350 m/min</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>a_p = 1 mm</td>
<td></td>
<td>f = 0.1 mm</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>a_p = 3 mm</td>
<td></td>
<td>f = 0.2 mm</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>v_c = 350 m/min</td>
<td></td>
<td>f = 0.1 mm</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>a_p = 1 mm</td>
<td></td>
<td>f = 0.2 mm</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>F_p</td>
<td>F_f experiment simulation</td>
<td>F_f simulation</td>
</tr>
<tr>
<td>a_p = 3 mm</td>
<td></td>
<td>f = 0.2 mm</td>
</tr>
</tbody>
</table>

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FE simulation of turning considering coating

3 µm  
TiN  
6 µm  

570
560
550
540
530
520
510
0

Calculated temperature at the chip bottom side $T_{sp}$ / °C

coating thickness

TiN  3 µm  
TiN  6 µm  
HW  
TiN  6 µm  
Al$_2$O$_3$  6 µm

heat conductivity:

- HW: 100 W/(mK)
- TiN: 26.7 W/(mK)
- Al$_2$O$_3$: 7.5 W/(mK)

heat capacity:

- HW: 3.5 J/(cm$^3$K)
- TiN: 3.2 J/(cm$^3$K)
- Al$_2$O$_3$: 3.5 J/(cm$^3$K)

material: C45E+N

tensile strength: $R_m = 610$ N/mm$^2$

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FE-Based Calibration process for the tool wear model

Machining experiments

Wear curve

Modeling

t = 10 min
t = 6 min
t = 4 min
t = 1 min

Regression analysis

Temperature
Normal-tension
Sliding speed

FE-analysis

Regression analysis

\[
\frac{dW}{dt} = \sigma_n \cdot V_{ch} \cdot C_1 \cdot e^{\left(-\frac{C_2}{T}\right)}
\]

Determination of the specific material parameters C1 and C2

Modeling
<table>
<thead>
<tr>
<th>1</th>
<th>Lecture organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Presentation of WZL</td>
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<tr>
<td>3</td>
<td>Lecture objectives</td>
</tr>
<tr>
<td>4</td>
<td>Modelling and simulation: Definition, motivation and integration</td>
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<tr>
<td>5</td>
<td>Lecture topics and fundamental knowledge</td>
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<tr>
<td>6</td>
<td>FE modelling for the forming process</td>
</tr>
<tr>
<td>7</td>
<td>FE modelling for the cutting process</td>
</tr>
<tr>
<td>8</td>
<td>FE model validation</td>
</tr>
<tr>
<td>9</td>
<td>Optimization integration in the FEM</td>
</tr>
</tbody>
</table>
Technical Sensors in Metal Cutting

Acoustic emission
Heat radiation
Cutting force
Acceleration

Source: Kistler Instrumente AG
Temperature Sensor

- Thermo-element
  ![Thermo-element diagram](image1)

- Resistance thermometers
  ![Resistance thermometers](image2)

- Two color pyrometer
  ![Two color pyrometer](image3)

- Infrared camera
  ![Infrared camera](image4)
3D Coordinate Measuring
Features and Technical Data of the Test Bench

- Shaft holder max. 32x32
- Grooving / Parting Tool holders for orthogonal cutting (Inclination angle = 0°, tool edge angle = 0°)
- Phantom v7.3 High speed video camera, LED Illumination

![Test Bench Features and Technical Data](image-url)
Advanced Experimental Setup: Orthogonal Cut on Broaching Machine

- High speed external broaching machine:
  - Type: Forst RASX 8x2200x600 M/CNC
  - Max. force: 80 kN
  - Power: 40 kW
  - Max. cutting speed: 150 m/min
  - Tool fixed and workpiece moved
  - Optimal filming of the cutting zone

- High speed camera:
  - Type: Vision Research Phantom v7.3
  - Frame rate: 6.688 fps by 800 x 600 pixel
  - 500.000 fps by 32 x 16 pixel

- High speed IR camera:
  - Type: FLIR SC7600
  - Frame rate: 100 fps by 640 x 512 pixel
  - 800 fps by 160 x 128 pixel
  - Measurement range: -20°C - 3000 °C (±1°C)
## Turning: Comparison of Simulation and Real Chip Flow

<table>
<thead>
<tr>
<th>Tool Details</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNMG120408</td>
<td></td>
</tr>
<tr>
<td>Chip breaker NF</td>
<td></td>
</tr>
<tr>
<td>HC-P15</td>
<td></td>
</tr>
<tr>
<td>$\kappa_r = 95^\circ$</td>
<td></td>
</tr>
<tr>
<td>$\gamma_n = -6^\circ$</td>
<td></td>
</tr>
<tr>
<td>$\lambda_s = -6^\circ$</td>
<td></td>
</tr>
<tr>
<td>C45E+N</td>
<td></td>
</tr>
<tr>
<td>$a_p = 1.9 \text{ mm}$</td>
<td></td>
</tr>
<tr>
<td>$f = 0.25 \text{ mm}$</td>
<td></td>
</tr>
<tr>
<td>$v_c = 200 \text{ m/min}$</td>
<td></td>
</tr>
<tr>
<td>dry</td>
<td></td>
</tr>
</tbody>
</table>

![Image of turning tool and chip flow](image.png)
FE simulation of face milling operation

Simulation

Experiment

Full agreement
FE computation of mechanical tool load and chip form in drilling

Cutting speed: \( v_c = 35 \text{ m/min} \)
Feed: \( f = 0.18 \text{ mm} \)
Drill diameter: \( d = 8 \text{ mm} \)

Workpiece: C45E+N
Cutting tool material: HW-K20
Cutting edge radius: \( r_\beta = 60 \mu\text{m} \)
FE computation of the cutting temperature in drilling

Cutting speed: $v_c = 35$ m/min
Feed: $f = 0.012 \times d$
Coolant: none

Workpiece: C45E+N
Cutting tool material: HW-K20
Cutting edge radius: $r_n = 4$ µm

Temperature at the major cutting edge $T$ [°C]

<table>
<thead>
<tr>
<th>diameter $d$ [mm]</th>
<th>Experiment</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
High Speed Thermography During Chip Formation ($v_C = 150$ m/min)

**h = 0.10 mm**

- **Workpiece:**
  - AISI 1045 normalized
  - 3.5 x 50 x 200 mm

- **Tool:**
  - Carbide, uncoated
  - Sharp ($r_B \leq 5$ µm)

**h = 0.50 mm**
Material and Friction Laws Validation: Chip Formation (Orthogonal Cut, $v_c = 150$ m/min, AISI 1045)

<table>
<thead>
<tr>
<th>$h$</th>
<th>FE simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 mm</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>0.4 mm</td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>0.3 mm</td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>0.2 mm</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
</tr>
<tr>
<td>0.04 mm</td>
<td><img src="image9" alt="Image" /></td>
<td><img src="image10" alt="Image" /></td>
</tr>
<tr>
<td>0.02 mm</td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
</tbody>
</table>
Material and Friction Laws Validation: FE Cutting Simulation ($v_C = 150$ m/min, $h = 0.50$ mm, DEFORM)
Development of 3D FE computation model for macro twist drilling: 
- \( d = 8 \text{ mm} \), homogeneous microstructure, Deform 3D

**Boundary conditions adjustment**
- Twist drill: Rigid with mesh 
  \( d = 8 \text{ mm} \) and \( r_\beta = 30 \mu\text{m} \)
- Workpiece: Visco-plastic 
  \( D \times H = 12 \times 4 \text{ mm} \) 
  with heat dissipation 
  100,000 3D-Tetrahedron
- Contact: Coulomb friction law (\( \mu = 0.30 \)), heat transfer 
  (Conduction & Convection)

**Cutting parameters definition**
- Workpiece material: 27R, 45R, 60R
- Tool material: HW
- Cutting speed: 120 m/min
- Feed rate: 0.25 mm/rev

**Constitutive material law (WZL)**

\[
\sigma = \left( A + B \varepsilon^n \right) \left( 1 + C \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \left[ 1 - \left( \frac{T - T_r}{T_m - T_r} \right)^m \right]
\]
FE model results: Chip formation, temperature, computation time: 1 day 45R, $v_c = 120$ m/min, $f = 0.25$ mm, $d = 8$ mm, dry
FE-Simulation of the drill entrance: Computation time: 5 days
45R, $v_c = 120$ m/min, $f = 0.25$ mm, $d = 8$ mm, dry
Check of the optimized FE model: Feed force and torque
45R, $v_c = 120$ m/min, $f = 0.25$ mm, $d = 8$ mm, dry

![Graph showing feed force and torque over drilling time]

- Feed force $F_z$ / N
- Torque $M_z$ / Nm
- Drilling time $t$ / ms

With entrance vs. without entrance
FE model validation: Feed force and torque (deviation less than 15%) $v_c = 120 \text{ m/min}$, $f = 0.25 \text{ mm}$, $d = 8 \text{ mm}$, dry
Outline

1. Lecture organisation
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9. Optimization integration in the FEM
What is the Optimization Problem?

Minimize (or maximize) an objective "performance" function:

\[ F(x_1, x_2, \ldots, x_n) \]

taking into account the constraints:

- \((x_1, x_2, \ldots, x_n)\) are the \(n\) system variables
- \(G_i(x_1, x_2, \ldots, x_n)\) are the \(p\) equality constraints
- \(H_j(x_1, x_2, \ldots, x_n) < 0, \quad j=1,2,\ldots,q\)

Source: Papalambros
System Example: Cantilever Beam

Mathematical model:

\[
U = \frac{FL^3}{3EI} = \frac{FL^3}{3E\left(\frac{bh^3}{12}\right)} = \frac{4FL^3}{Eb h^3}
\]

- System variables: \( F(t), U(t), M_b(t), V(t) \)
- System parameters: \( h, b, L \)
- System constants: \( E, \rho \)
Integration of the Optimization in the FEM

Physical problem
Mathematical model
Numerical model

Change physical problem
Improve mathematical model

Does answer make sense?
Yes!

Refine analysis
Process improvement and optimization

FEM
Optimization
Thank you for your attention