Finite element simulation of cutting processes

Simulation Techniques in Manufacturing Technology
Lecture 8

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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Influencing factors on the cutting process

**Workpiece material**
- structure
- texture
- mechanical properties
- hardness
- residual stresses

**Cutting zone**
- chip forming mechanisms
- cooling lubricant
- cutting parameters
- contact conditions
  - e.g.: friction, wear
  - heat transfer

**Tool**
- cutting material
- coating
- geometry
- tool holder

**Machine**
- machine design
- drive system
- clamping device
## Cutting process in comparison to other processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Strain</th>
<th>Strain rate / s(^{-1})</th>
<th>(T_{\text{homolog}})</th>
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<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
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</tbody>
</table>
Requirements to the FE cutting simulation

- Reproduction of the macro/ micro geometry of the tools and kinematic of the cutting process
- Modelling of the thermo mechanical material behavior for the entire temperature and strain rate range
- Implementation of damage approaches, texture microstructure and phase transformation
- Simulation of chip form (remeshing routine, material separation, etc.)
- Consideration of friction, wear and coating
- Modelling of heat generation and transfer (conduction, convection, radiation)
- Consideration of the influence of cooling lubricant
- Utilization of the Lagrangian solving method (instationary cutting processes)
- Generation of a finely structured FE mesh and adaptive remeshing (very high element deformation because of higher gradients of deformation, temperature and tension)
- Appropriate computation time (explicit time integration, parallelization, etc.)
Cutting simulation: Input- und output parameters

**Chip formation**
- Temperature
- Tension
- Deformation
- Rate of deformation
- Chip type
- Chip flow
- Chip crack

**Tool**
- Strain
- Tension
- Temperature
- Cutting forces
- Wear

**Component**
- Strain
- Temperatures
- Deformation
- Burr formation
- Distortion

**Future:**
- Residual stresses
- Surface quality, e.g.: roughness, changes in shape,
- Measurement and position

**Component / tool**
- Geometry
- Material data
- Contact conditions
- Boundary conditions
- Cutting conditions
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5 Damage models for the FE cutting simulation and multiphase simulation
6 Friction and wear models for the FE cutting simulation
7 Criteria for the evaluation of FE software
8 Applications of the FE cutting simulation at the WZL
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Macro- und micro tool geometry

Major clearance angle: \( \alpha = 10^\circ \)

Twist angle: \( \delta = 35^\circ \)

Cutting material: HW-K20

Grain size: \( D_K = 0.5 - 0.7 \ \mu m \)

Construction dimensions DIN 6539

Type: N

Diameter: \( d = 1 \ mm \)

Drill-point angle: \( \sigma = 118^\circ \)
Definition of element type

1D
- bar element

2D
- triangle
- quadrangle

3D
- tetrahedron
- pentahedron
- pyramid
- hexahedron
Creation of tool models close to reality

Drilling tool | Determination of the tool geometry | FEM-model
---|---|---
Real tool | CAD-model |
Macro geometry

Micro geometry
Thermo-mechanical behavior of material

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

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

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

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

- **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
  \[ \sigma = (A + B \varepsilon^n) \cdot (1 + C \ln(\dot{\varepsilon}/\dot{\varepsilon}_0)) \cdot (1 - \left[ \frac{T - T_r}{T_m - T_r} \right]^m) \]

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

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

Source: Diss-Abouridouane
Determination of High speed flow curves

**Split-Hopkinson-Pressure-Bar**

**Split-Hopkinson-Tension-Bar**

**Source:** LFW

**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:** $m = 3.15 \text{ kg}$

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Material law for high strain rate deformation

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

Source: Diss-Brodmann
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Failure mechanisms

Loading type

Shear stress

Shear lokalisation model
(Imperfections theory)

Tensile stress

Pore growth model
(Hancock-Mackenzie)

Source: Diss-Abouridouane

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Damage modelling for the FE cutting simulation (ductile fracture)

- Macro mechanical failure models
  - Equivalent stress/ strain model: \(D_\sigma = \sigma_{v,f} / D_\varepsilon = \varepsilon_{v,f}\)
  - Gosh-Model: \(D_{\text{Gosh}} = (1+\sigma_2/\sigma_1) \sigma_1^2\)
  - Ayada-Model: \(dD = (\sigma_m/\sigma_v) d\varepsilon_v\)

- Micro mechanical failure models (Pore growth models)
  - Hancock-Mackenzie-Modell: \(\varepsilon_f = \varepsilon_n + \alpha \exp\left(-\frac{3 \sigma_m}{2 \sigma_v}\right)\)
  - Gurson-Tveergard-Needleman-Model: \(0 = \left(\frac{\sigma_v}{\sigma_{v,M}}\right)^2 + 2f_q \cosh\left(\frac{3\sigma_m}{2\sigma_{v,M}}\right) - \left[1 + (q_1f)^2\right]\)
  - 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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Failure limit at tensile stress (r: Notch radius)

\[ \varepsilon_f = 0.05 + 2.89 \times 10^{-0.35} \frac{\sigma_m}{\sigma_y} \]

Source: Diss-Abouridouane

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Criteria for chip formation

- **Geometrical separation criterion**
  - Separation when the cutting edge falls below a critical distance $d_{cr}$ to the next workpiece node

- **Physical separation criterion**
  - Separation while exceeding an defined, maximum equivalent stress or at predefined maximum tensions

- **Without a specific separation criterion**
  - Separation through continuous remeshing for ductile material behavior

Distorted grid topology
New networked grid topology
Chip separation - without chip separation criterion by remeshing

Old Mesh
Elements are highly distorted

Chip
Tool

New Mesh
Remeshing leads to better mesh

New Mesh
Microstructure-based 3D modeling for micro cutting AISI 1045
Concept of the Representative Volume Element (RVE)

Capture of all significant microstructural inhomogeneities

Representativeness check of the RVE

Two-phase 3D FE model
(0.1 x 0.1 x 0.1 mm)

Cross section
Longitudinal section

Pearlite
Ferrite

Macrostructure

Microstructure

RVE

Cross section
Longitudinal section

Ferrite
Pearlite

Quasi-static
$T = 20^\circ C$

True stress, MPa

True plastic strain $\varepsilon, \gamma, -$
Microstructure-based 3D FE model: Validation

Two-phase FE model for micro drilling in ferritic-pearlitic carbon steel C45N

![Microstructure](image)

Feed force

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<th>Model</th>
<th>Test</th>
<th>Torque</th>
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<tr>
<td>Isotropic model</td>
<td>22%</td>
<td>12 Nmm</td>
</tr>
<tr>
<td>Mixture model</td>
<td>3%</td>
<td>8 Nmm</td>
</tr>
<tr>
<td>Mixture model</td>
<td>7%</td>
<td>4 Nmm</td>
</tr>
<tr>
<td>Isotropic model</td>
<td>19%</td>
<td>16 Nmm</td>
</tr>
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</table>

d = 1 mm, v_c = 35 m/min, f = 12 µm

Chip form

Workpiece

Drill

Ferrite

Pearlite

Holes
Influence on the formation of residual stresses

- The complete coupling of the various parameters influencing the formation of residual stresses has not been done

Source: Preckel
Input parameters for thermo-mechanical-metallurgical simulation (residual stresses)

- Microstructure, initial state of texture
- Time dependent thermo-mechanical state of stress
- Mathematical approach for the diffusion controlled transformation kinetics: Advanced Johnson-Mehl-Avrami-Kolmogrow-model, 1940
- Mathematical approach for the phase transformation without diffusion Koistenen-Marburger-relation, 1959
- TTT/TTA-diagram for not isotherm conditions (high strain rate)
- Thermal material properties, depending on temperature ($c_p$, $\lambda$, $\rho$, ...)
- Mechanical material properties, depending on temperature ($E$, $v$, $\alpha$, ...)
- Elasto-viscoplastic material law
- Consideration of grain orientation, texture, micro damages, inclusions, etc.
- Description of the damage behavior on high strain rates
- Tool wear model
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Friction model for FE cutting simulation
Thermal load at the workpiece and tool contact zone

Structure in the workpiece

Shear edge

Structure in the chip

Material:
- Material: steel
- Elastic limit: $k_f = 850 \text{ N/mm}^2$
- Cutting material: HW-P20
- Cutting velocity: $v_c = 60 \text{ m/min}$
- Chip thickness: $h = 0.32 \text{ mm}$
- Rake angle: $\gamma_o = 10^\circ$

1. Primary shear zone
2. Secondary shear zone at rake face
3. Jam and separation zone
4. Secondary shear zone at flank face
5. Run-up deformation zone

Cutting edge

Tool flank

Cutting surface

Distribution of temperature in the contact zone
(according to Kronenberg)
Friction model for FE cutting simulation
Deformation at the workpiece and tool contact zone

Structure in the workpiece

- Primary shear zone
- Secondary shear zone at rake face
- Jam and separation zone
- Secondary shear zone at flank face
- Run-up deformation zone

Shear edge

Material:
- C53E

Cutting material:
- HW-P30

Cutting velocity:
- \( v_c = 100 \, \text{m/min} \)

Chip section:
- \( a_p \times f = 2 \times 0.315 \, \text{mm}^2 \)
Friction model for FE cutting simulation

Mechanical stress at the workpiece and tool contact zone

Structure in the workpiece

Shear edge

Structure in the chip

1 Primary shear zone
2 Secondary shear zone at rake face
3 Jam and separation zone
4 Secondary shear zone at the flank face
5 Run-up deformation zone

According to Oxley and Hatton
Friction model for FE cutting simulation

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

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

- Continuous passover from dynamic friction (Coulomb) to static friction (shear):

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

- \( \tau_R \) – shear stress from friction
- \( \sigma_N \) – normal stress
- \( k \) – yield stress in shear according to Mises
- \( k_f \) – yield stress according to Mises
- \( \mu, m \) – friction coefficients
Wear model for FE cutting simulation
Different types of wear at the cutting blade and wear mechanisms

- **Sliding mechanisms**
  - Abrasion
  - Adhesion
  - Delamination

- **Not-gliding mechanisms**
  - Diffusion
  - Electrochemical
  - Oxidation

**Workpiece**
- Crater wear
- Built-up edge
- Flank wear

**Tool**
- Chip
- Cutting-surface
- Flank

**Cutting edge**
- Edge chippage
- Crater wear
- Flank abrasion
- Oxidation notch
Wear model for FE cutting simulation

Tool life equations

Tool life acc. to Taylor: \[ T = v_c^k \cdot C_v \]
Tool life acc. to Hasting: \[ T = \frac{A}{g^B} \]

- \( T \) = tool life
- \( v \) = temperature
- \( k, A, B \) = constant
- \( C_v = T \) für \( v_c = 1 \) m/min

Adhesion / Abrasion

Model acc. to Archard:
\[ \frac{dV}{dt} = K \cdot \frac{F \cdot S}{3H} \]
- \( dV/dt \): wear-volume-rate
- \( H \): hardness
- \( F \): mechanical load
- \( S \): cutting length

Model acc. to Usui:
\[ \frac{dV}{dt} = \sigma_n \cdot v_{ch} \cdot C_1 \cdot e^{-\frac{C_2}{T}} \]
- \( K, C1, C2, G, D \): constant
- \( \sigma_n \): normal stress
- \( V_{ch} \): chip sliding speed
- \( v \): temperature

Model acc. to Takeyama:
\[ \frac{dV}{dt} = G \cdot v_c + D \cdot e^{-\frac{E}{R^9}} \]
- \( E \): constant

Differential wear models

Empirical tool wear models

Physical tool wear models

Adhesion

Abrasion + Diffusion

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Object boundary conditions

Boundary Conditions

Object Conditions
Inter Object Conditions
Environment Object Conditions

2D FEM Cutting Model
Object boundary conditions

Boundary Conditions

Object Conditions

- Friction
- Heat Transfer
- Movement

Inter Object Conditions

Environment Object Conditions

2D FEM Cutting Model
Boundary conditions

Object Conditions
- Friction
- Heat Transfer
- Movement

Boundary Conditions

Self Contact (Chip vs. Workpiece Surface)

Workpiece - Object 2

2D FEM Cutting Model

F: Friction Force
N: Normal Force

F_R: Friction Force
F_N: Normal Force
Object boundary conditions

**Boundary Conditions**

The workpiece is moving in x-direction with the prescribed velocity $v_c$. It is fixed in y-direction.

**Object Conditions**

- **Friction**
- **Heat Transfer**
- **Movement**

**Cutting speed $v_c$ in x-direction**

**Tool** is fixed in x- and y-direction!

**Workpiece**
Object boundary conditions

- Object Conditions
  - Friction
  - Movement
  - Heat Transfer

- Boundary Conditions
  - Heat Transfer

- Tool
- Workpiece
Object boundary conditions

Boundary Conditions

Object Conditions

Inter Object Conditions

Environment Object Conditions

Friction

Heat Transfer

Tool

Heat Transfer

F

F

F

F

F

F

F
Object boundary conditions

Boundary Conditions

Object Conditions

Inter Object Conditions

Environment Object Conditions

Heat Transfer

Heat Convection

Heat Emissivity

Heat Radiation

Heat exchange with environment
FEM software solution for FEM simulation of the cutting process

ABAQUS
Superior Finite Element Analysis

DEFORM™
Design Environment for FORMing

THIRD WAVE SYSTEMS
Modeling Technology for Machining Solutions

MSC.Marc
A Division of MSC.Software
# Criteria for the evaluation of FE software

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<thead>
<tr>
<th>Criteria</th>
<th>Programm</th>
<th>ABAQUS</th>
<th>ANSYS/ LS-DYNA</th>
<th>AdvantEdge</th>
<th>DEFORM</th>
<th>COMSOL</th>
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<td>Creation of geometries</td>
<td>Creation of geometries and import of CAD data</td>
<td>Import of CAD data</td>
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<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>
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</table>

Source: SIMULIA, ANSYS, LSTC, TWS, SFTC, COMSOL
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Applications of the FE cutting simulation at WZL

Research focus at the WZL:
- Process optimization
- Material modelling
Simulation of the high speed cutting process

Cutting speed: \( v_c = 3000 \) m/min
Feed: \( f = 0.25 \) mm
Simulation of the high speed cutting process
Simulation of the high speed cutting process
Simulation of the high speed cutting process
Simulation of the high speed cutting process
Simulation of the high speed cutting process
Simulation of the high speed cutting process
Comparison of different thermal properties of the tools

Orthogonal turning 2D ($v_c = 300$ m/min, $f = 0.1$ mm, C45E)

**Ceramic-Insert**
Thermal conductivity $\lambda = 35$ W/mK

**WC-Insert**
Thermal conductivity $\lambda = 105$ W/mK

$T_{\text{max}} = 650^\circ\text{C}$

$T_{\text{max}} = 550^\circ\text{C}$
Temperature distribution in dependency of the coating and its thickness

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

Heat conductivity:
- HW: 100 W/(mK)
- TiN: 26.7 W/(mK)
- $\text{Al}_2\text{O}_3$: 7.5 W/(mK)

Heat capacity:
- HW: 3.5 J/(cm³K)
- TiN: 3.2 J/(cm³K)
- $\text{Al}_2\text{O}_3$: 3.5 J/(cm³K)

Material: C45E+N
Tensile strength: $R_m = 610$ N/mm²

Cutting Material: HW-K10/20
FE-Based calibration process for tool wear model

Machining experiments

Wear curve

Tool-wear VB

Cutting time t

Regression analysis

dW/dt

Temperature

Normal-tension

Sliding speed

FE-analysis

Determined of the specific material parameters C1 and C2

Regression analysis

Determination of the specific material parameters C1 and C2

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

Regeneration analysis

\[ \lg W / (n VS) = \frac{C_1}{C_2} \cdot \frac{1}{T} \]

Regression analysis

\[ \lg \left( \frac{W}{(n VS)} \right) = \frac{C_1}{C_2} \cdot \frac{1}{T} \]

Regression analysis

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

Regression analysis

\[ \lg W / (n VS) = \frac{C_1}{C_2} \cdot \frac{1}{T} \]

Regression analysis

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

Regression analysis

\[ \lg W / (n VS) = \frac{C_1}{C_2} \cdot \frac{1}{T} \]

Regression analysis

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

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Regression analysis

\[ \lg W / (n VS) = \frac{C_1}{C_2} \cdot \frac{1}{T} \]
2D FE model for tool wear simulation

Phase 1:
Thermo-mechanical FE-simulation of the cutting process till steady state solution is obtained.

Phase 2:
Call of the User subroutine to calculate tool wear wear rate $\frac{dW}{dt} \times \text{time } t$

Tool geometry updating in dependence of wear

Usui's tool wear model:
$\frac{dW}{dt} = \sigma_n \cdot V_s \cdot C_1 \cdot \exp\left(-\frac{C_2}{T}\right)$

Wear

$V_B > V_B^{\text{tool life}}$

Abort
Phase 3: Methodology for moving the nodes at the rake face
Phase 3: Methodology for moving the nodes at the flank face

\[ n_A = n_B = n_C = n_D \]
Verification of the tool wear simulation for the flank wear 
$v_c = 150 \text{ m/min}, f = 0.06 \text{ mm}, a_p = 1 \text{ mm}, \text{ dry}$

$\gamma_{\text{eff}} = -26^\circ \quad a_0 = 7^\circ \quad \text{Time: } 5 \text{ min} \quad \text{Tool} \quad \text{Time: } 15 \text{ min} \quad \text{Time: } 25 \text{ min} \quad \text{Time: } 35 \text{ min}$

$93 \mu\text{m}$
Setup of a 3D FE model
Setup of a 3D FE model - specification of the tool holder

**Tool holder:**

Kennametal  
**ID:** PCLNL252M12 F4 NG27

- **Rake angle** $\gamma_0 = -6^\circ$
- **Relief angle** $\alpha_0 = 6^\circ$
- **Tool inclination angle** $\lambda_s = -6^\circ$
- **Tool cutting edge angle** $\kappa_r = 95^\circ$
Setup of a 3D FE model - Tool position

\[ r_{\text{tool}} = r_{\text{workpiece}} \]
Setup of a 3D FE model - Mesh of the workpiece
3D simulation

Workpiece: AISI 1045
Tool: K10
$v_c = 300 \text{ m/min} \quad f = 0,1 \text{ mm}$
3D FE model - Post processing

Temperature (°C)
For better visualization the tool is hidden

$v=100\,\text{m/min}, \quad a=1\,\text{mm}, \quad f=0.3\,\text{mm}$
Temperature (°C)
For better visualization
the tool is hidden
3D FE model - Post processing

Strain distribution

For better visualization the tool is cut
3D FE model - Post processing

Strain Rate distribution

For better visualization the tool is cut
Models of cutting inserts

Roughing geometry

Finishing geometry

CNMG120408RN

CNMG120408FN
Simulation of the chip flow

**Chip breaker RN**

- **Material:** C45E+N
- **Cutting material:** HC P25
- **Insert:** CNMG120408
- **Insert geometry:**
  \[
  \begin{array}{c|c|c|c|c}
  \alpha_0 & \gamma_0 & \lambda_S & \kappa_r & \varepsilon \\
  6^\circ & -6^\circ & -6^\circ & 95^\circ & 90^\circ \\
  \end{array}
  \]
- **Cutting velocity:**
  \[v_c = 300 \text{ m/min}\]
- **Feed:**
  \[f = 0.1 \text{ mm}\]
- **Depth of cut:**
  \[a_p = 1 \text{ mm}\]
- **Dry cutting**

**Chip breaker FN**
**Simulation of the chip flow**

<table>
<thead>
<tr>
<th>Chip breaker RN</th>
<th>Chip breaker FN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material:</strong></td>
<td><strong>Material:</strong></td>
</tr>
<tr>
<td>C45E+N</td>
<td></td>
</tr>
<tr>
<td><strong>Cutting material:</strong></td>
<td><strong>Cutting material:</strong></td>
</tr>
<tr>
<td>HC P25</td>
<td></td>
</tr>
<tr>
<td><strong>Insert:</strong></td>
<td><strong>Insert:</strong></td>
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<tr>
<td>CNMG120408</td>
<td></td>
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<tr>
<td><strong>Insert geometry:</strong></td>
<td><strong>Insert geometry:</strong></td>
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<td></td>
<td>(\begin{array}{c</td>
</tr>
<tr>
<td><strong>Cutting velocity:</strong></td>
<td><strong>Cutting velocity:</strong></td>
</tr>
<tr>
<td>(v_c = 300) m/min</td>
<td></td>
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<tr>
<td><strong>Feed:</strong></td>
<td><strong>Feed:</strong></td>
</tr>
<tr>
<td>(f = 0.1) mm</td>
<td></td>
</tr>
<tr>
<td><strong>Depth of cut:</strong></td>
<td><strong>Depth of cut:</strong></td>
</tr>
<tr>
<td>(a_p = 1) mm</td>
<td></td>
</tr>
<tr>
<td><strong>Dry cutting</strong></td>
<td><strong>Dry cutting</strong></td>
</tr>
</tbody>
</table>

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Comparison of simulation and real chip flow

CNMG120408
Chip breaker NF
HC-P15
κ_r = 95°
γ_n = -6°
λ_s = -6°
C45E+N
a_p = 1,9 mm
f = 0,25 mm
v_c = 200 m/min
dry

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Fraunhofer IPT
Drilling: Modelling of size effects

Task:

Development of a consistent 3D computation model based on the FE method for scaling the drilling process in consideration of size effects.

- Friction
- Plastic deformation
- Separation of material
- Workpiece
- Drill

Friction

Plastic deformation

Separation of material

Workpiece

Drill

d = 1 mm

d = 10 mm
### Previous results: 3D FE computation model for $d = 1 – 10$ mm

**Material modeling**

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

- Strain hardening
- Plasticity
- Damping mechanism
- Relaxation
- Dynamic strain ageing
- Temperature influence
- Loss of cohesion
- Failure mechanism

**Measuring the drill geometry**

- Tool
- FEM-Model

**FE boundary conditions**

- Cutting parameters
- Tool: rigid / elastic
- Friction law
- Heat transfer
- Element size
- Number of elements
- Remeshing strategy
- Degree of freedom
FE-Simulation of the drilling process with \( d = 1 \text{ mm} \) (DEFORM 3D)

### Machining conditions
- **Workpiece material:** C45E+N
- **Tool material:** HW-K20
- **Cutting speed:** 35 m/min
- **Feed:** 0.012 mm/U
- **Feed velocity:** 133 mm/min
- **Cooling lubricant:** none

### Boundary Conditions
- **Tool:**
  - rigid
  - number of elements: 90 000
- **Workpiece:**
  - visco-plastic (LFW-material law),
  - temperatur fixed at boundary nodes
  - number of elements: 100 000
- **Contact:**
  - coulomb friction \( (\mu = 0.2) \)
  - heat transfer (conduction & convection)

### Computing time and drilling depth:
- 2000 h; 0.18 mm (70\% of the major cutting edge)
Verification of the chip formation

Experimental chip formation

Chip formation in the simulation

Workpiece material: C45E+N
Cutting tool material: HW K20

Cutting speed: $v_c = 35$ m/min
Feed: $f = 0.012$ mm
Model validation: Scaling effect of the chisel edge length

\[ k_{f,max} = \frac{2 \times F_{z,max}}{(d \times f)} \]

Workpiece: C45E+N

Cutting speed: \( v_c = 35 \text{ m/min} \)

Feed: \( f = 0.012 \times d \)

Cutting tool material: HW-K20

Corner radius: \( r_n = 4 \mu \text{m} \)

Cooling: None
Model validation: Temperature at the main cutting edge (center)

Cutting speed: \( v_c = 35 \text{ m/min} \)  
Feed: \( f = 0.012 \times d \)  
Coolant: None  
Workpiece: C45E+N  
Cutting tool material: HW-K20  
Rounding: \( r_n = 4 \mu m \)
Modelling of the face milling process

Materials and cutting parameters:

- **Work material:** Quenched and tempered AISI 1045 (normalized)
- **Tool material:** Coated WC
- **Cutting parameters:**
  - No. of teeth: \( z = 4 \)
  - Diameter: \( D = 32 \text{ mm} \)
  - Engagement angle: \( \phi_A - \phi_E = 180^\circ \)
  - Feed: \( f = 0.5 \text{ mm} \)
  - Feed per tooth: \( f_Z = 0.125 \text{ mm} \)
  - Depth of cut: \( a_p = 0.8 \text{ mm} \)
  - Tool leading angle: \( \kappa_r = 90^\circ \)
  - Tool inclination angle: \( \lambda = -5^\circ \)
  - No. of rev.: \( n = 2250 \text{ min}^{-1} \)
Modelling of the face milling process

Axial and radial rake angle:
- Axial rake angle $\gamma_{\text{axial}} = 9^\circ$
- Radial rake angle $\gamma_{\text{radial}} = 5^\circ$
Modelling of the face milling process

- Depth of cut $a_p$
- Feed $f$
- Workpiece geometry
Finding the best workpiece geometry

1. Simplified workpiece geometry

2. Simplified workpiece geometry

3. Simplified workpiece geometry
Simulation results for the 1. simplified workpiece model

- Rough elements within the work piece
- Simulation of chip formation not accurate enough
Simulation results for the 3. simplified workpiece model

Final workpiece geometry

Left

Right
Results for the face milling operation

Chip formation for the left side of the work piece:

- at the beginning very thin chips are produced
- chip curling starts for higher undeformed chip thickness
Verification of the FE model

Simulation

Full agreement

Experiment
FE based sensitivity analysis

Varied input parameters:
- Heat capacity
- Thermal conductivity
- Flow stress
- Friction coefficient
- Tool micro-geometry

Goal output parameters:
- Cutting force $F_c$
- Passive force $F_p$
- Feed force $F_f$
- Temperature $T$

Legend

<table>
<thead>
<tr>
<th>Influence</th>
<th>Cutting force</th>
<th>Feed force</th>
<th>Passive force</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td><strong>Low</strong></td>
<td><strong>High</strong></td>
<td><strong>Low</strong></td>
<td><strong>Low</strong></td>
</tr>
<tr>
<td>medium</td>
<td><strong>Low</strong></td>
<td><strong>High</strong></td>
<td><strong>Low</strong></td>
<td><strong>Low</strong></td>
</tr>
<tr>
<td>high</td>
<td><strong>Low</strong></td>
<td><strong>High</strong></td>
<td><strong>Low</strong></td>
<td><strong>Low</strong></td>
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</tbody>
</table>
Outline

1. Introduction
2. Requirements of the FE cutting simulation
3. CAD modelling for the FE cutting simulation
4. Constitutive material laws for the FE cutting simulation
5. Damage models for the FE cutting simulation and multiphase simulation
6. Friction and wear models for the FE cutting simulation
7. Criteria for the evaluation of FE software
8. Applications of the FE cutting simulation at the WZL
9. Summary and Outlook
Outlook:
Benchmark-Analysis to choose the best tool geometry

- Fixed input parameter:
  - material parameter, friction coefficients

- Cutting parameter:
  - $v_{c1}, a_p, f_1$
  - $v_{c2}, a_p, f_1$

- Tool:
  - A
  - B
  - C

- Cutting simulation:
  - Determination of the thermomechanical loadspectrum, chip flow, chip form

- Benchmark-Analysis:
  - Flank wear VB
   - Tool A
   - Tool B
   - Tool C

- Cutting parameter:
  - Cutting parameter 1
  - Cutting parameter 2

- Temp, Wear, Stress, Chip flow:
  - Tool A:
    - Temp: +
    - Wear: -
    - Stress: ++
    - Chip flow: -
  - Tool B:
    - Temp: -
    - Wear: --
    - Stress: 0
    - Chip flow: +
  - Tool C:
    - Temp: ++
    - Wear: ++
    - Stress: +
    - Chip flow: +

- Coating:
  - TiN
  - TiAlN
  - AlO$_2$

- Optimised tool- and tool carrier-geometry
Summary

- Machining process: System of complex physically coherent operations

- A holistic and comprehensive simulation of the machining has not been achieved with conventional empirical or analytical approaches

- FEM is a promising method for the holistic simulation of machining
  - High flexibility
  - Implementation of various models that describe the aspects of machining
  - Complete reproduction of the machining process

- The FE cutting Simulation gives good results under the following boundary conditions:
  - Realistic reproduction of the tools macro/ micro geometry
  - Adequate modeling of the thermo mechanical material behavior
  - Exact capturing of the boundary conditions (friction, heat transfer, wear, cooling lubricant, damage, micro structure, etc.)
Questions

- What are the ranges of temperature, strain and strain rate in cutting operations?
- What is the range of strain rate, that can be realized by the Split-Hopkinson-Bar-Test?
- Name two friction models. What are the advantages and the disadvantages of these models?
- How is the strain rate affecting the flow stress curve of a material?
- What are the demands on a temperature measurement setup which allows the evaluation of simulation results?
- Explain the difference between the orthogonal cutting process and the longitudinal cutting process!
- Explain the difference between a plastic and an elastic-plastic flow stress curve!