Cutting with geometrically undefined cutting edges I

Simulation Techniques in Manufacturing Technology
Lecture 9

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
# Outline

1. **Fundamentals**

2. **Motivation of Simulation**

3. **Classification of Process Models**

4. **Application Areas for Simulation**

5. **Conclusion**
Surface grinding process
System „grinding“

Input Parameters

- Machine
- Workpiece
- Tool
- Preparation
- Coolant
- Process parameters
- Boundary condition

What happens here…?
From milling to grinding

- number of cutting edges
- chip thickness
Characteristics of grinding

- cutting edges possess different geometries
- mainly highly negative chip angle
- varying distance of the cutting edges and thus different chip thicknesses
- varying distance of the cutting edges from the rotation axes
- tool consists of three components (grain, bonding, pore)
- tool can be dressed in the machine
**Definition of grinding**

- Grain is fixed in the tool and moves on a kinematic curve

- The workpiece surface mostly shows almost parallel scratch-tracks

- Surface characteristics and deformation in the rim zone depend on the grinding direction

Machining with geometrically undefined cutting edges

- Cutting edge
- Chip
- Workpiece

<table>
<thead>
<tr>
<th>force-bound</th>
<th>track-bound</th>
<th>room-bound</th>
<th>energy-bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Diagram of force-bound machining]</td>
<td>![Diagram of track-bound machining]</td>
<td>![Diagram of room-bound machining]</td>
<td>![Diagram of energy-bound machining]</td>
</tr>
</tbody>
</table>
Phases of chip formation – ductile material

- initial penetration leads to elastic deformation of the workpiece (I)

- phase of elastic deformation is followed by a phase of elastic and plastic deformation (II)

- the chip formation begins, when the cutting depth reaches $T_\mu$ (III)

source: König
Phases of chip formation – brittle material

- Plastical deformation occurs, when surface pressure > compressive strength
- Micro cracks lead to material shattering → break-out of material particles
- Lateral cracks cause material flaking/chipping
- Axial cracks damage work piece surface layer

Diagram:
- Primary particles
- Secondary particles
- Grit path
- Bonding
- Grit (cutting edge)
- Workpiece
- Grinding wheel
- Elastic deformation
- Pressure softening
- Scratching

Equations:
- $F_{t,S}$
- $F_{n,S}$
Theoretical chip thickness at a single grain

- $h_{cu,max}$ max. undeformed chip thickness
- $v_s$ cutting speed, wheel speed
- $d_{eq}$ equivalent diameter of the grinding wheel
- $v_w$ workpiece speed
- $f_{as}$ feed per grain
- $a_e$ depth of cut

**Maximum chip thickness at the single grain**

$$h_{cu,max,SG} \approx 2 \cdot \pi \cdot d_{eq} \left( \frac{v_w}{v_c} \right) \cdot \sqrt{\frac{a_e}{d_{eq}}}$$

$$F_c, \frac{1}{Rz}, \Delta r_S = f (h_{cu})$$
Theoretical chip thickness in a grinding process

- $h_{cu,max}$: max. undeformed chip thickness
- $v_s$: cutting speed, wheel speed
- $d_{eq}$: equivalent diameter of the grinding wheel
- $v_w$: workpiece speed
- $f_{as}$: feed per grain
- $a_e$: depth of cut
- $C_{stat}$: static cutting edge density
- $k$: constant (material dependent)
- $\alpha, \beta, \gamma$: coefficients (depending on the grinding wheel specification and the material characteristics of the workpiece)
  - e.g. $\alpha = \beta = 1/3$; $\gamma = 1/6$

Maximum undeformed chip thickness

$$h_{cu,max} \approx k \cdot \left( \frac{1}{C_{stat}} \right)^\alpha \cdot \left( \frac{v_w}{v_s} \right)^\beta \cdot \left( \frac{a_e}{d_{eq}} \right)^\gamma$$

$F_c$, $1/R_z$, $\Delta r_S = f (h_{cu})$
The grinding system

<table>
<thead>
<tr>
<th>Input</th>
<th>set-values</th>
<th>Process</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>system</td>
<td></td>
<td>char. values</td>
<td>technology</td>
</tr>
<tr>
<td>machine</td>
<td>depth of cut</td>
<td>cutting mechanisms</td>
<td>workpiece</td>
</tr>
<tr>
<td>type</td>
<td>feed rate</td>
<td>thermal</td>
<td>form-/ shape-accuracy</td>
</tr>
<tr>
<td>characteristics</td>
<td>workpiece speed</td>
<td>mechanical</td>
<td>surface roughness</td>
</tr>
<tr>
<td>workpiece</td>
<td>cutting speed</td>
<td>wear mechanisms</td>
<td>influence on the rim zone</td>
</tr>
<tr>
<td>geometry</td>
<td>dressing conditions</td>
<td>mechanical</td>
<td>grinding wheel</td>
</tr>
<tr>
<td>material</td>
<td>pressure</td>
<td>thermal</td>
<td>wear</td>
</tr>
<tr>
<td>grinding wheel</td>
<td>flow rate</td>
<td>tribo-chemical</td>
<td>clogging</td>
</tr>
<tr>
<td>profile</td>
<td></td>
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</tr>
<tr>
<td>specification</td>
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<tr>
<td>dressing tool</td>
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<tr>
<td>type</td>
<td></td>
<td></td>
<td>output</td>
</tr>
<tr>
<td>specification</td>
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<td>unit costs</td>
</tr>
<tr>
<td>cooling system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>system</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: König, Klocke
Grinding techniques according to DIN 8589 (selection)

- Workpiece geometry (cylinder/cuboid)
- Machined workpiece area (external/- internal-, surface/- rotary-grinding)
- Active grinding wheel area (circumferential/- face-grinding)
- Main feed direction (lengthwise/- crosswise-grinding)

<table>
<thead>
<tr>
<th></th>
<th>Cylindrical Grinding</th>
<th>Surface Grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>External-</td>
<td>Internal-</td>
</tr>
<tr>
<td>Crosswise</td>
<td><img src="crosswise.png" alt="Diagram" /></td>
<td><img src="surface.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Traverse</td>
<td><img src="traverse.png" alt="Diagram" /></td>
<td><img src="surface.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Face</td>
<td><img src="face.png" alt="Diagram" /></td>
<td><img src="surface.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Circumferential</td>
<td><img src="circumferential.png" alt="Diagram" /></td>
<td><img src="surface.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- Percentage breakdown:
  - Surface: 18%
  - Internal: 7%
  - Others: 3%
  - External: 72%
Grinding wheel topography

- Real grinding wheel sections can be described, e.g. via computer tomography and surface measurement methods.
- Grain-, pore- and bond fractions can be thus described.
Cutting edge allocation

- Grains are irregularly distributed on the periphery of the grinding wheel.
- The grain protrusion differs from grain to grain.
- Grains engage to different degrees and are thus strained in differing amounts.

\[ L_{S, \text{kin}} \approx \text{Factor} \times L_{S, \text{stat}} \]

- The kinematic cutting edge distance arises from the grinding parameters.
- The static cutting edge distance can be measured.

Source: K. Steffens
### Abrasives

<table>
<thead>
<tr>
<th>symbol</th>
<th>abrasive</th>
<th>Knoop - hardness [N/mm²]</th>
<th>thermal stability [°C]</th>
<th>thermal conductivity [W/(m°C)]</th>
<th>fields of application</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>corundum</td>
<td>1950 to 2200</td>
<td>2000</td>
<td>6</td>
<td>• medium-tough to hard materials below 60 HRC (Rₘ&lt; 500 N/mm²) such as:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• malleable cast iron</td>
</tr>
<tr>
<td>C</td>
<td>silicon carbide</td>
<td>3000</td>
<td>1300</td>
<td>55</td>
<td>• surface grinding of cemented carbides, cast-iron, ceramics, non-ferrous metals</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• dressing</td>
</tr>
<tr>
<td>B</td>
<td>cubic boron nitride (CBN)</td>
<td>4700</td>
<td>1370</td>
<td>200-700</td>
<td>• hardened steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• low alloy steel</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• HSS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• precision grinding</td>
</tr>
<tr>
<td>D</td>
<td>diamond</td>
<td>8000</td>
<td>900</td>
<td>600 - 2100</td>
<td>• carbon saturated steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• glas, stone, ceramics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• tungsten carbide, cermets</td>
</tr>
</tbody>
</table>

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## Bond types

<table>
<thead>
<tr>
<th>symbol</th>
<th>bond type</th>
<th>characteristics</th>
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<tbody>
<tr>
<td>V</td>
<td>vitrified bond</td>
<td>• brittle and thus sensitive to impact load</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• high modulus of elasticity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• high thermal stability, low resistance to thermal shock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• chemical resistance against oil and water</td>
</tr>
<tr>
<td>D</td>
<td>resin bond</td>
<td>• high impact and shock resistance as well as resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>to side pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• application in cut-off and roughing wheels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• high elasticity in fine-grinding wheels enables high</td>
</tr>
<tr>
<td></td>
<td></td>
<td>surface qualities</td>
</tr>
<tr>
<td>M G</td>
<td>metal bond galvanic bond</td>
<td>• high wear resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• difficult to dress</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• high thermal conductivity</td>
</tr>
</tbody>
</table>
Outline

1 Fundamentals

2 Motivation of Simulation

3 Classification of Process Models

4 Application Areas for Simulation

5 Conclusion
Continuously increasing demands of the market lead to increasing requirements for manufacturing processes.
Motivation

The grinding process
- Finishing manufacturing process to achieve a high product quality and precision
- High dimension and form accuracy
- High surface quality
- High performance process with high stock removal rate

For controlling and improving the grinding process a high degree of technological knowledge is required.

A high potential to increase the process knowledge and the process optimization is based on modeling and simulation the grinding process.
Modeling and Simulation: aims and requirements

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

Today without process simulation

76 weeks

Goals
- Specification sheet product
- Concept design and choice of material
- Lay-out
- Manufacturing aspects
- Design
- Manufacturing planning
- Manufacturing
- Work piece-test

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

FEM-Calculation

Manufacturing tests
Modeling and Simulation: aims and requirements

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

Future with process simulation

54 weeks

Reduction of the cycle time by 30%

Goals

- Specification sheet product
- Concept design and choice of material
- Lay-out
- Design
- Manufacturing planning
- Manufacturing
- Work piece-test

FEM simulation

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Modeling and Simulation: aims and requirements

Goals
- increase of the process comprehension
- increase of the process knowledge
- prediction of the process stability
- prediction of the component characteristics
- Reduction of planning- and development steps
- Cost reduction

Requirements
- High result quality
- Realistic prediction of the process results
- High process reliability
- adaption of technological innovations
Citations of modeling and simulation in grinding

Number of articles

<table>
<thead>
<tr>
<th></th>
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</tr>
</tbody>
</table>
Outline

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Modeling – a human property

Experience

Perception

Model vision
Modeling – a human property

Reality / Perception → Sensorium → Mind

IT-based converting
Basic of reasons

Inductive reasoning
Modeling based on experience

The particular
Reality

Deductive reasoning
Derivation of reason from theoretical derived models

The general
Model section
## Definitions

<table>
<thead>
<tr>
<th><strong>Model</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>It delivers general information about elements, structure and behavior of a part of the reality.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Simulation</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A simulation is a replication of a dynamic process in a model.</td>
<td></td>
</tr>
</tbody>
</table>
Modeling and simulation of grinding processes

- Heuristic and empirical models are limited and difficult to transfer from one process to another.
- Finite Element models are complex to apply and the necessary material properties are often not known.
- Molecular dynamics are very fundamental.
- Fundamental models can be regression models with physical background.
- Kinematics models can be used for applicable simulations.

Molecular Dynamics (MD)
Finite Element analysis (FEA)
Fundamental
Regression
Artificial neural nets
Rule based

Source: CIRP Keynote Paper 2006, Brinksmeier et al.
Partitioning of different model types from literature review

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

Source: Heinzel 2009
## Comparison of model types

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Starting Effort</th>
<th>CPU Needed</th>
<th>Knowledge Needed</th>
<th>Maintenance + Development</th>
<th>Amount of Data</th>
<th>Effort for Experiments</th>
<th>Effort for Data Analysis</th>
<th>Transferability to Other Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Dynamics (MD)</td>
<td>●</td>
<td>●</td>
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<td>○</td>
<td>○</td>
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<td>kinematics</td>
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</tr>
<tr>
<td>fundamental</td>
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<tr>
<td>artificial neural nets</td>
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<td>○</td>
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<td>○</td>
<td>●</td>
<td>●</td>
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<td>○</td>
</tr>
<tr>
<td>rule based</td>
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<td>○</td>
<td>●</td>
<td>●</td>
<td>○</td>
<td>●</td>
<td>○</td>
<td>●</td>
</tr>
</tbody>
</table>

Source: CIRP Keynote Paper 2006, Brinksmeier et al.
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5 Conclusion
Molecular Dynamics (MD) provides a sufficiently detailed and consistent description of the micro mechanical and thermal state of the modeled material to allow for the investigation of the grit/workpiece contact dynamics. Materials in MD allows to go beyond ideal, single crystalline structures or homogeneous material properties and to describe poly-crystals, defect structures, pre-machined or otherwise constraint workpiece models and non-smooth surfaces.

**Advantage**
- Large 3D atomistic modeling and simulation
- Good combination with other model types

**Disadvantage**
- Enormous CPU-power and long calculation time needed
- Unknown suitable material potential functions and parameters
- Less further development
Molecular Dynamics (MD)

A, B: original crystal C: new crystal

Crystal orientation and deformation during grain boundary crossing in 2D can be observed.

Limitation:
Long calculation time
Unknown suitable material specific potential functions

Source: CIRP Keynote paper 2006, Brinksmeier et al

Groove scratching with 2 grits
(side/top view - 360 000 time steps, 144 ps)
Kinematics

Based on the grinding wheel and workpiece geometry and the process kinematics, significantly different kinematic models following varied approaches have been developed.

**There are two basic kinematic approaches, and another two grinding models, kinematic-geometrical models and kinematic-empirical models.**

**Advantage**
- Low starting effort
- High convergence of modeling results to real grinding processes

**Disadvantage**
- High knowledge needed
- Long calculation time
- Only trends not absolute values of results
Types of models

- **Octree-model**
  - Steric partitioned model
  - Segmentation of the space into eight smaller subspaces
  - Homogeneous areas can be described by big spaces with less memory
  - From a certain depth of the tree of the octree the memory requirements will be very big

- **Dexel-model**
  - Illustration of the model with pins
  - By combination of several blocks in different axes it is possible to display complex bodies
  - Reduction of the memory requirements, accuracy and velocity compared to the octree-model

Quelle:
Generation of the dexel-model

A DEXEL

Direction of view

Pixel
dexel matrix
Display Screen

modelfaults
Model concept of the process kinematics and the penetration calculation

Assumptions:
1. workpiece is fixed
2. grinding wheel moves around the workpiece
Model concept of the process kinematics and the penetration calculation

- $K_s, K_w$: coordinate system
- $P$: point
- $\vec{r}_s, \vec{r}_w$: position vector to point $P$
- $a, b, g$: rotation around $x, y, z$-axis
- $D$: rotation matrix
- $\Delta x, \Delta y, \Delta z$: offset rate
- $\vec{V}$: offset vector

\[
\vec{r}_w = T_{s,w} \cdot \vec{r}_s
\]

transformation matrix

\[
T_{s,w} = \begin{bmatrix}
D & \vec{V} \\
0^T & 1
\end{bmatrix} = \begin{bmatrix}
\cos b \cos g & \sin a \sin b \cos g & \cos a \sin b \cos g & \Delta x \\
- \sin b & \sin a \cos b & \cos a \cos b & \Delta y \\
0 & 0 & 0 & 1
\end{bmatrix}
\]
**Diffusion calculation by the use of Boolean operation**

<table>
<thead>
<tr>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  nothing or just workpiece</td>
</tr>
<tr>
<td>2  workpiece behind grinding wheel</td>
</tr>
<tr>
<td>3  modify front part of the dexel</td>
</tr>
<tr>
<td>4  delete dexel</td>
</tr>
<tr>
<td>5  create dexel</td>
</tr>
<tr>
<td>6  modify back part of the dexel</td>
</tr>
<tr>
<td>7  Grinding wheel behind workpiece</td>
</tr>
<tr>
<td>8  just grinding wheel</td>
</tr>
</tbody>
</table>
Developed simulation environment
Overview

- Definition of objects
- Visualization of the process
- Definition of the dynamic of the machine
- Definition of object properties
- Definition of coordinate transformation
- Definition of force-model
- Movements of axis
- Documentation of parameters $F$, $dx$, $Q'w$, ...
- Visualization of parameters $F$, $dx$, $Q'w$, ...
Process simulation – Diffusion calculation

- Transmission of the actual positions of diffusion calculation
- Diffusion calculation results in interference-ratios of the grinding wheel and workpiece
- Calculate forces from geometry and process-, workpiece- and tool properties
- Reback the forces on the mechanical model to shift calculation

Source: WZL, DFG ICD B-2.2
Finite Element Analysis (FEA) is the simulation of a total physical process. It consists of a computer model of a material or design that is stressed and analyzed for specific results. There are generally two types of analysis that are used in industry: 2-D modeling, and 3-D modeling.

**Advantage**
- Little experience needed
- High transferability to other processes

**Disadvantage**
- High computational effort and high CPU-power needed
- Limited by current measuring techniques within the process
- High effort for experiments and data analysis
From the real process to a Finite Element Model

**Boundaries**

- Two-dimensional model
- Linear moving heat source
- Temperature-independent thermal material properties
- The surface of the solid is adiabatic
- Bottom surface is set to 20°C
- Maximum temperature of the coolant lubricant is \( t_B = 120°C \) due to the boiling point of emulsion

In this approach of a Finite Element Model only a thermal load is considered.
Simulation results for the creep grinding process

Material
100Cr6 (HRC 62)
Grinding wheel
B181 LHV 160
Grinding parameters
\[ v_w = 12 \text{ m/min} \]
\[ Q'_w = 40 \text{ mm}^3/\text{mms} \]
\[ v_s = 160 \text{ m/s} \]
Coolant lubricant
Emulsion (5%)

Austenizing temperature was not reached during the simulation of different grinding processes.
Therefore, it is assumed that no phase transformation will take place.
Scratch groove for a single-grain engagement

topography-measurement of a scratch groove by means of a white-light interferometer

modelling of a scratch groove by means of finite element simulation
Fundamental analytical approaches (FA) develop predictive models that are deductively derived from basic physical interrelationships. Based on the knowledge of a process and the selection of appropriate physical quantities, physical models can be developed using mathematical formulations. FA can provide a good way to illustrate insights of the grinding process.

<table>
<thead>
<tr>
<th><strong>Advantage</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Low computer power needed</td>
</tr>
<tr>
<td>- A good way to illustrate insights of the grinding process</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Disadvantage</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Limited to the ranges of the different parameters</td>
</tr>
<tr>
<td>- Depending on the accuracy of input parameters</td>
</tr>
<tr>
<td>- High effort for experiments and data analysis</td>
</tr>
</tbody>
</table>
Regression

Regression analysis (RA) is the generic term for any mathematical statistical method that aims to find a functional interrelation between dependent random variables (output parameters and the machining results) and one or more independent random variables (input parameters).

Advantage
- Low computer power needed
- Vast field of possible application
- Big potentials

Disadvantage
- Depending on the effort and number of experiments
- Limit application for a developed model
- Extensive coefficient calculations
Force model based on regression

\[ F' = c_{wp} \cdot c_{gw} \cdot \left( \frac{1}{q} \right)^{e_1} \cdot a_e^{e_2} \cdot d_{eq}^{e_3} \]

- Compare the coefficients and exponents of the different models.

- The mathematical part of modeling is enhanced by using new and more complex polynomials obtaining a higher quality of simulation.

- Empirical models were compared to newly developed modeling techniques such as artificial neural networks and fuzzy set theory.

<table>
<thead>
<tr>
<th>gr. wheel</th>
<th>set. parameters</th>
<th>model coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f_c</td>
<td>a_d</td>
</tr>
<tr>
<td>mm</td>
<td>µm</td>
<td>µm</td>
</tr>
<tr>
<td>EK60L7VX</td>
<td>60</td>
<td>50-250</td>
</tr>
<tr>
<td>CK45</td>
<td>0.2</td>
<td>3*20</td>
</tr>
<tr>
<td></td>
<td>60-220</td>
<td>15-105</td>
</tr>
<tr>
<td></td>
<td>3*50</td>
<td></td>
</tr>
<tr>
<td>B126V180</td>
<td>20-90</td>
<td>6-100</td>
</tr>
<tr>
<td>100Cr6</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

1) König/Werner 2) Peters/Decneut 3) Saljé/Bock

Source: Paul
## Common empirical models

<table>
<thead>
<tr>
<th>Fundamental Topography</th>
<th>$N_{kin} = \left( \frac{1}{q} \right)^{e_1} a_e \frac{e_1}{2} \left( \frac{1}{d_{eq}} \right)^{e_1} \frac{e_1}{2} \ N_{St} = n \cdot z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip Thickness</td>
<td>$h = \left( \frac{1}{q} \right)^{e_1} a_e \frac{e_1}{2} \left( \frac{1}{d_{eq}} \right)^{e_1} \frac{e_1}{2}$</td>
</tr>
<tr>
<td>Cutting Force</td>
<td>$F' = c_{gw} \cdot c_{wp} \left( \frac{1}{q} \right)^{e_1} a_e e_2 \left( \frac{1}{d_{eq}} \right)^{e_3}$</td>
</tr>
<tr>
<td>Temperature</td>
<td>$\theta_{z \text{ max}} = A_1 \cdot \frac{\alpha^{e_1}}{\lambda} \cdot a_e e_2 \cdot v_w e_3 \cdot v_c e_4 \cdot d_{eq} e_5 \cdot \frac{A \cdot a_e e_6 \cdot v_w e_7 \cdot d_{eq} e_8 \cdot z}{A}$</td>
</tr>
<tr>
<td>Roughness</td>
<td>$R_t = \left( \frac{1}{q} \right)^{e_1} a_e e_2 \left( \frac{1}{d_{eq}} \right)^{e_3}$</td>
</tr>
<tr>
<td></td>
<td>$R_z = A + c_{gw} \cdot c_{wp} \left( \frac{1}{q} \right)^{e_2} a_e e_1 \frac{v_c e_3}{V_w e_4}$</td>
</tr>
</tbody>
</table>
Wear model by regression analysis

- regression model on basis of test results
- for external + internal cylindrical grinding and surface grinding
- wear increases with increasing specific material removal $V'_w$ + decreases with higher overlap rate $U_d$

\[
\Delta r_s = 0.74 + 0.76 \cdot \xi'_w \cdot I_k^{-0.07} \cdot l_k^{0.74} \cdot (V'_w + 19.3)^{0.31} \cdot U_d^{-0.24} + 0.01 \cdot \xi'_w \cdot l_k^{0.66} \cdot (V'_w + 1.8)^{0.69} \cdot U_d^{-1.25}
\]

Source: Osterhaus

About 1100 tests

$\xi'_w = 0.1 \text{ mm}^3/\text{mm}$

$I_k = 1 \text{ mm}$

with

machining value $\xi'_w = Q'_w / n_s$

kinematical contact length $l_k = l_g \cdot |1 - 1/q|$
Artificial Neural Nets (ANN) models are distinguished by several properties which make them suitable for modeling of complex, nonstationary processes that depend on many input variables. ANNs have been applied to both cylindrical and surface/creep feed grinding in applications that can be classified into three broad classes: Prediction of output parameters of grinding; Prediction of optimal input parameters of grinding; Monitoring of grinding.

**Advantage**
- Be able to handle so-called soft input parameters without a numerical value
- Easily adaptable to different problems
- Be able to handle slightly incomplete data bases

**Disadvantage**
- Relies heavily on the quality and number of data sets for testing
- Amount of data
Artificial Neural Nets (ANN)

ANN’s have been applied to both cylindrical and surface/creep feed grinding in applications that can be classified into three broad classes:

- **Prediction of output parameters of grinding, such as surface roughness, grinding forces, etc..**
- **Prediction of optimal input parameters of grinding at which the desired output parameters are achieved.**
- **Monitoring of grinding to detect or predict unfavorable phenomena, such as grinding burn and chatter.**

![Diagram of ANN model inputs, model outputs, and ANN model]

**Figure 20:** General scheme for prediction of output parameters by ANN.

Source: CIRP Keynote paper 2006, Brinksmeier et al.
**Rule Based (RB)**

The **Rule-Based-(RB)**-approach can help modeling the human reasoning process, especially when it comes to ill-defined or difficult problems. Within the field of grinding processes a variety of approaches are employed of the many possible classifications of artificial intelligence methodologies. Often used approaches are knowledge based systems and fuzzy logic systems.

<table>
<thead>
<tr>
<th>Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Takes the knowledge into account which is based on human experience</td>
</tr>
<tr>
<td>▪ High simulation quality</td>
</tr>
<tr>
<td>▪ Easy to combine with other model approaches</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Sophisticated knowledge base needed</td>
</tr>
<tr>
<td>▪ Difficult to transfer to other grinding processes as the rule sets are unique for every grinding process</td>
</tr>
</tbody>
</table>
**Rule Based (RB)**

- **Knowledge based systems** refers to a system for extending and/or querying a knowledge base and performing a function which would normally require human intelligence and expertise.

- **Fuzzy logic systems** is normally used to refer to a highly domain-specific type of knowledge based system which gives advice and is used for a specialized purpose.

Source: CIRP Keynote paper 2006, Brinksmeier et al
Outline

1 Fundamentals

2 Motivation of Simulation

3 Classification of Process Models

4 Application Areas for Simulation

5 Conclusion
Conclusion

In grinding several types of models are used:
- physical (kinematics, MD, fundamental, FEA)
- empirical (regression, ANN)
- heuristic (rule based)

They describe important process parameters (wheel topography, workpiece roughness, forces, temperatures, etc.).

Every model has advantages and disadvantage when simulating the grinding process.

A model can not take into account both the macroscopic and the microscopic view.
Conclusion - Difficulties in grinding process simulation

Cutting speeds:
\[ v_c \approx 15 - 200 \text{ m/s} \]

Temperatures:
peaks above 1200°C

Temperature gradients:
\[ 10^6 \text{ °C/s} / 10^3 \text{ °C/mm} \]

Forming speeds:
\[ \dot{\phi} \approx \text{up to } 10^7 \text{ 1/s} \]

Many material properties are not known within these ranges
## Conclusion - classification of process models

<table>
<thead>
<tr>
<th>Process models</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Empiric process models</strong></td>
</tr>
<tr>
<td>Based on experimental investigations</td>
</tr>
<tr>
<td>Good description of special problems</td>
</tr>
<tr>
<td>little development input necessary for easy problems</td>
</tr>
<tr>
<td>limited transferability to other manufacturing conditions</td>
</tr>
<tr>
<td><strong>Physical process models</strong></td>
</tr>
<tr>
<td>Derived from physical constitutional laws</td>
</tr>
<tr>
<td>Manufacturing independent</td>
</tr>
<tr>
<td>Describes inner contexts</td>
</tr>
<tr>
<td>Exact formulation of the context often impossible</td>
</tr>
<tr>
<td>high development input necessary</td>
</tr>
</tbody>
</table>
Backup

Quelle:
Finite Element Analysis (FEA)

- Applications of the process simulation
  - Temperature distribution
  - Thermal deformation
  - Residual stresses
  - Single grain scratching

- Software
  - Abaqus
  - Ansys
  - Deform

Source: CIRP Keynote paper 2006, Brinksmeier et al
**Kinematics**

**Two Basic kinematic approaches** describe surface grinding and/or cylindrical grinding processes using two-dimensional model grains, by calculating the roughness, or the topological cross section, of a workpiece and the chip thickness.

**Kinematic-geometrical grinding models** focus on the geometric penetration of workpiece and grinding wheel.

**kinematic-empirical models** has similar output parameters to above models, but different way of calculating the process characteristics and results.

**Applications in grinding**:
- Modeling of the grinding wheel topography
- Modeling of the surface profile and the surface roughness of workpiece

Source: CIRP Keynote paper 2006, Brinksmeier et al
Coordinate transformation

\[ \mathbf{r}_w = T_{s,w} \cdot \mathbf{r}_s \]

Transformationsmatrix

\[ T_{s,w} = \begin{bmatrix} D & \mathbf{V} \\ \mathbf{0} & 1 \end{bmatrix} = \begin{bmatrix} \cos \beta \cos \gamma & \sin \alpha \sin \beta \cos \gamma & \cos \alpha \sin \beta \cos \gamma & \Delta x \\ \sin \alpha \cos \beta \cos \gamma & -\cos \alpha \sin \gamma & \cos \alpha \sin \beta \sin \gamma & \Delta y \\ -\sin \beta & \sin \alpha \cos \beta & \cos \alpha \cos \beta & \Delta z \\ 0 & 0 & 0 & 1 \end{bmatrix} \]
Multistage grinding

- High material removal rates and good surface finish are exclusive.

- Multi-step machining with different set-values.

- The dressing strategy must be adapted.

- Different grinding wheel specifications can be used for roughing and finishing.

<table>
<thead>
<tr>
<th></th>
<th>Q_w</th>
<th>R_a,z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td>Finishing</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>Spark-out</td>
<td></td>
<td>= 0</td>
</tr>
</tbody>
</table>

V_w: 70% 30% 0%

V_c: 15% 60% 25%