Advances in modeling of fixed-abrasive processes

by

Peter Krajnik (2), Konrad Wegener (1), Thomas Bergs (2), Albert Shih (1)

Presenting author: P. Krajnik, Chalmers University of Technology, Sweden
Email: peter.krajnik@chalmers.se

CIRP Annals - Manufacturing Technology
Volume 73, Issue 2, 2024
Introduction

• Foundational models such as specific energy and maximum undeformed chip thickness, established 70 years ago, remain integral to grinding research today.

• Grinding knowledge is often expressed in the form of physical and empirical models that cover forces, power, specific energy, wheel/workpiece topography, wear, thermal aspects, cooling, dressing.

• Special attention is given to the geometry, kinematics, and thermo-mechanical modeling.

• Recent advances in process monitoring and big data analytics provide new opportunities to further strengthen the state of the art in modeling through data-driven approaches.

• Examples on how models – implemented in simulation software – can be used to predict and optimize industrial operations.
Basic understanding of terms

- The term “modeling” refers to the derivation of equations and functions that quantify the relationships within the process.
- The resulting “model” describes and quantifies the interrelation of input and output parameters in the process.
- Once developed, the model is used in trials to simulate the process behavior, typically through a computer program.
- “Simulation” with the model provides predictive insights about the process.

P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
Categorization of models

• Models can be broadly categorized as (i) physical or (ii) empirical, as defined in previous CIRP keynote papers, published in 1992 and 2006.
Physical vs. empirical models

- Physical models strictly rely on first principles and physical laws.
- Such underlying laws have general validity and lead to a better understanding of fundamental process mechanics.
- Many analytical problems cannot be solved with general validity, so approximations are obtained through numerical calculations.

- Empirical models are developed through experimentation on the actual grinding system.
- Empirical modeling treats a process as a black box and focuses on data analysis, including fitting models to data and making model inferences based on data.
- Examples of empirical models are numerous, e.g., regression analysis, Bayesian data analysis, artificial neural networks (ANN), etc.
Systemic approach to modeling of fixed-abrasive processes

Section 2: Modeling: geometry and kinematics

Section 3: Modeling: thermomechanical

Section 4: Modeling: data driven

Section 5: Modeling: applications
The first grinding-modeling paper

- Maximum undeformed chip thickness

\[ h_m = \frac{v_w}{v_s \cdot n} \sin(\varphi_s + \varphi_w) \]

\[ h_m = (2/n)\left(\frac{v_w}{v_s}\right)\sqrt{a/d_e} \]

- \(n\) is the number of cutting points per unit length of circumference

Alden, G. (1914). Transactions of the ASME, 36, 451-460

P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
Topography-dependent models

- Maximum undeformed chip thickness

\[ h_m = 2L \left( \frac{v_w}{v_s} \right) \sqrt{a/d_e} \]

- \( L \) is the the cutting-point spacing

Pahlitzsch, G., et.al. (1943). Werkstatttechnik, 11/12, 397-400

P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
The difficulty here is the need to determine the two wheel-topography parameters:

- The number of cutting points per unit area, \( C \)
- The ratio of width-to-thickness of undeformed chip (or chip-shape ratio), \( r \)

\[
h_m = \sqrt{\frac{4}{C \cdot r \left( \frac{v_w}{v_s} \right) \frac{a_e}{d_s}}}
\]


P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
Dimensionless parameters

\[
\tan \varepsilon = \left( \frac{v_w}{v_s} \right) \sqrt{\frac{a}{d_e}}
\]

\[
\tan \varepsilon_{max} = 2 \left( \frac{v_w}{v_s} \right) \sqrt[2]{\frac{a}{d_e}}
\]


P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
The theory of aggressiveness

- Aggressiveness quantifies an abrasive interaction at a contact point via the kinematical process parameters and the contact geometry.
- The fundamental parameter, the point-aggressiveness, $Aggr^*$, is defined as the ratio of the normal component, $v_n$, and the tangential component, $v_t$, of the relative-velocity vector.
- The simplified quantity needed for optimization of grinding operations is the aggressiveness number, which is the average $Aggr^*$ in an abrasive contact.
- Works for grinding, dressing and other processes.

\[
Aggr^* = \frac{v_n}{v_t} = \frac{\vec{v} \cdot \vec{n}}{\sqrt{\vec{v} \cdot \vec{v} - (\vec{v} \cdot \vec{n})^2}} = \frac{\tau}{u}
\]

\[
Aggr = \left(\frac{v_w}{v_s}\right) \sqrt{\frac{a}{d_e}}
\]


P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
\[ h_{eq} = \left( \frac{v_W}{v_s} \right) a \]

\[ Aggr = \left( \frac{v_W}{v_s} \right) \sqrt{\frac{a}{d_e}} \]

**The Significance of Chip Thickness in Grinding**


**Abstract**

In this contribution a survey is made of recent work related to geometrical basic grinding parameters.

Special attention is paid to the experimental relationship with practical grinding results.

A comprehensive representation of grinding data using the "equivalent grinding thickness" is presented.

Some practical applications of this "grinding chart" are highlighted.

1. Introduction

In grinding research, quite a number of authors did investigate the possibility of characterizing the working conditions by means of the undeformed chip thickness.

Contrary to turning and milling, the undeformed chip thickness in grinding is a rather complex function of the kinematical grinding conditions and the wheel surface geometry.

As a result, many different equations have been proposed by various authors to calculate this parameter (1, 2, 3, 4, 5, 6, 7, 8).

The practical application of those mathematical formulae was difficult basically because the distance between two preceding cutting tips was included in the formulation. This last parameter


---

**h_{eq}, equivalent chip thickness**

---

Evolution of geometrical & kinematical models

\[ h_m = \frac{2}{n} \cdot \frac{v_w}{v_s} \cdot \sqrt{\frac{a}{d_e}} \]

\[ h_m = \sqrt{\frac{4}{C \cdot r\left(\frac{v_w}{v_s}\right)}} \cdot \sqrt{\frac{a_e}{d_e}} \]

\[ h_m = 2L \cdot \frac{v_w}{v_s} \cdot \sqrt{\frac{a}{d_e}} \]

\[ Aggr = \frac{v_w}{v_s} \cdot \sqrt{\frac{a_e}{d_e}} \]
Wheel truing, dressing, and topography

Topography of dresser

Topography of grinding wheel

Topography of workpiece

Interaction dresser - grinding wheel

Interaction WP - grinding wheel
# Thermo-mechanical modeling framework

<table>
<thead>
<tr>
<th>Material removal</th>
<th>Force model</th>
<th>Wear model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boolean</td>
<td>Friction wheel</td>
<td>Generalized</td>
</tr>
<tr>
<td>Brittle</td>
<td>Friction grain</td>
<td>Attritious (Usui)</td>
</tr>
<tr>
<td>Ductile</td>
<td>Modified Kienzle</td>
<td>Chipping</td>
</tr>
<tr>
<td></td>
<td>Kienzle</td>
<td>Macro fracture</td>
</tr>
<tr>
<td></td>
<td>3-D geometric</td>
<td>Pullout</td>
</tr>
<tr>
<td></td>
<td>3-D-plastic</td>
<td>Loading</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coolant flow</th>
<th>Heat release</th>
<th>Process signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>«useful flow»</td>
<td>Partition coeff.</td>
<td>Internal stress</td>
</tr>
<tr>
<td>CFD 2D</td>
<td>Heat layer</td>
<td>Temperature</td>
</tr>
<tr>
<td>CFD 3D</td>
<td>Grain heat conduction</td>
<td>Hardening</td>
</tr>
<tr>
<td>CFD+Heat transfer</td>
<td></td>
<td>Microstructure</td>
</tr>
</tbody>
</table>

P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
Grinding mechanics by field equations and numerical solutions

- Simulation of chip formation using Smoothed-Particle Hydrodynamics (SPH)
- Johnson-Cook (J-C) material model
- Friction model and local heat release included

- Temperature distribution in chip formation simulated with SPH at different penetration depths and grit orientations
Synthetization of grinding wheels from single grits
Synthetization of grinding wheels from single grits

P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
Wear phenomena in grinding wheels

- Attritious wear (flattening, dulling) – arises from high mechanical-thermal loading and chemical interactions between the abrasive grit and workpiece.
- Grit fracture wear entails the loss of abrasive material as fragments break from the grit, either on a micro scale or a macro scale.
Alteration of grit geometry with progressing wear

- Usui’s model can predict the wear rate due to normal stress, sliding speed, and temperature:

\[
\frac{dW}{dt} = A_1 \sigma_n v_t \exp \left( - \frac{A_2}{T} \right)
\]

- Archard’s law

\[
W = A_3 \sigma_n LH^{-1}
\]

- Barwell’s model

\[
W(t) = W_0 \tau_w \left[ 1 - \exp \left( - \frac{t}{\tau_w} \right) \right] + W_c t
\]
Modeling of fluid flow in grinding

- A typical modeling approach includes computational fluid dynamics (CFD), which enables the development of multivariable and multiphase models.
- Flow rates, hydrodynamic pressure, heat transfer and temperatures in the contact zone are predicted with 2D-CFD and 3D-CFD simulations.
- Recent CFD applications have used the Shear Stress Transport (SST) k-ω model, a useful turbulence model capable of handling various turbulence scales.
Data-driven modeling

- In contrast to physical models, less fundamental process understanding is required to make decisions based on measured process results.
- Some advantages over FE and MD models are the lower computational efforts.

- A data-driven model is developed in five steps:
  1. Acquisition of raw signals from sensors and machine control
  2. Pre-processing of the raw signals;
  3. Feature extraction
  4. Feature selection
  5. Model construction
Data-driven wheel-wear prediction

Grinding conditions:
Wheel: 38A60K9V
\( v_s = 40 \, \text{m/s} \)
\( Q'_w = 2 \, \text{mm}^3/\text{mms} \)

First principal component
Second principal component

- 2  -1  0  1  2

-0.4 -0.2  0  0.2  0.4

-2  -1  0  1  2

-2  -1  0  1  2

\( v_w = 0.16 \, \text{m/s} \)
\( v_w = 0.46 \, \text{m/s} \)

Sharp
Worn
No burn
Burn

Sharp
Worn
No burn
Burn

P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
Data-driven detection of grinding burn

• Approaches for detecting grinding burn without the use of ML models were already developed as early as the 1980s and 1990s. It was established that the AE signal is effective for grinding burn identification.

• Data-driven identification of grinding burn offers the potential for indirect inspection of workpieces for grinding burn.

• In particular, the AE signal emitted during grinding can be used to detect damage at an early stage.

• The AE signals from a spindle-integrated sensor and tailstock-mounted sensor were examined. The spindle current was also recorded (Irms).

• For the Support Vector Machine (SVM) model, statistical features from the time domain as well as from various time-frequency transforms (PSD, STFT, WPT, EEMD, and VMD) were utilized.

Data acquisition, signal processing and feature engineering

Scores in training and test

P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
Applications of modeling

- The **calibration** employs experimental measurements, such as power and quality inspections from grinding calibration tests, to find model constants depending on the wheel, work material, and process parameters.

- The **simulation** acts as a virtual grinder, taking inputs of the grinding wheel; the workpiece; the process parameters; and a database.

- The **optimization** is built upon the simulation module and considers aspects such as machine-axes limits and requirements for the final product.

- The GRINDsim® software developed by the late Stephen Malkin has been used to design, validate and optimize grinding processes in production by companies such as: General Motors (GM); Timken; and RTX /Pratt & Whitney.
# Gear-grinding simulations

<table>
<thead>
<tr>
<th>Input data</th>
<th>Workpiece</th>
<th>Tool</th>
<th>Kinematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Workpiece Image]</td>
<td>![Tool Image]</td>
<td>![Kinematics Image]</td>
<td></td>
</tr>
</tbody>
</table>

## GearGRIND3D

Simulation Wälzschleifen | Generating Gear Grinding

<table>
<thead>
<tr>
<th>Output data</th>
<th>Gear</th>
<th>Contact conditions</th>
<th>Characteristic values</th>
<th>Penetration geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Gear Image]</td>
<td>![Contact Conditions Image]</td>
<td>![Characteristic Values Image]</td>
<td>![Penetration Geometry Image]</td>
<td></td>
</tr>
</tbody>
</table>

P. Krajnik, K. Wegener, T. Berge, A. Shih (2024 STC-G Keynote)
Grinding force model for continuous generating gear grinding

Chip geometry

Mean chip thickness

Chip volume

Material removal rate

Grinding force

P. Krajnik, K. Wegener, T. Bergs, A. Shih (2024 STC-G Keynote)
Summary and outlook

- The integration of process kinematics into various simulation tools has become more manageable thanks to advances in computer speed and ease of use, enabling the development of dedicated simulation software.

- Developing physical models necessitates field equations for all these models, involving partial differential equations. The discretization methods utilized include FEM, SPH, MD, CFD, FV, and dexels.

- Wear modeling remains insufficiently developed as no existing model takes into account the full effect chain of wear and loading.

- Further research is needed to understand the interaction between grinding fluid and the grinding wheel as well as the heat-transfer mechanisms within the wheel-workpiece contact zone.

- Most data-driven models use supervised machine learning (ML), which is highly process-dependent and sensitive to variations in process parameters, limiting their transferability. Acceleration and acoustic emission (AE) sensors are primarily used. Support Vector Machine (SVM) approaches often outperform Artificial Neural Networks (ANN).