Superior Surface Integrity by Knowledge-based Manufacturing – Recent Advances
2017 GAFOE Symposium, Evendale, Ohio, 31.03.17-02.04.17
Outline
Recent frontiers of machining

The Loch Ness Monster „Nessie“
• Below the surface
• Not well described
• Famous (thus kind of important)

A Chameleon
• Changes color
• Complex mechanism
• Interacts with its environment using „code“

Pictures: thegreenhead.com, nationalgeographic.com
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Highly relevant to interdisciplinary challenges in manufacturing

Pictures: thegreenhead.com, nationalgeographic.com
Manufacturing Technologies
What exactly are we doing?

Processes

Pictures: IWT Bremen
Manufacturing Technologies
What exactly are we doing?

Processes

Components

Pictures: IWT Bremen, FAG, xylon.de
Manufacturing Technologies
What exactly are we doing?
Manufacturing Technologies
and their accuracy around 1900

Pictures: huettenmuseum-thale.de
Manufacturing Technologies
their accuracy and tasks today

Geometrical accuracy

- Conventional machining (turning, milling, grinding, …)
  - accuracy of ca. 1 µm
  - Ø of a human hair ≈ 70 µm

- Ultraprecision machining (diamond machining, polishing, …)
  - accuracy on a nm scale
  - mirrors for telescopes: shape deviation of < 8 µm over 1 m
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Consideration of the surface integrity

- Surface roughness
- Hardness
- Residual stresses
- Cracks and microcracks

Pictures: GE, ALMA, IWT Bremen
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Surface Integrity

The Loch Ness Monster „Nessie“
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Subsurface Properties and Surface Integrity
- Below the surface
- Not well understood
- Highly relevant to industry and science

Pictures: thegreenhead.com, IWT Bremen
Surface Integrity

Relevance

Liberty ships

Pictures: ETH Zürich, Wikipedia
Surface Integrity
still a frontier of engineering

acc. to Field & Koster, Annals of the CIRP 27/1, 1971

fatigue strength

max residual stress

residual stresses σ_{II} at surface

sets

varied: grinding processes

max/min

target

Milling
Turning
Grinding
EDM
Fine Grinding

max residual stress

MPa

MPa

MPa

MPa
Different processes - identical results

thermal/thermomechanical

Induction hardening
Grind hardening

mechanical

Deep rolling
Grind strengthening

Different processes lead to identical surface properties
The new approach of „Process Signatures“
for the prediction of the effects of manufacturing processes

\[ \text{SV}_{\text{initial}} \]
\[ \text{initial state} \]
\[ \text{energy input} \]
\[ \text{external load} \]
\[ \text{e.g. mechanical, thermal, chemical} \]
\[ \text{conversion and dissipation of energy} \]
\[ \text{internal material load} \]
\[ \text{material modification} \]
\[ \text{final state} \]
\[ \text{SV}_{\text{final}} \]

\[ \text{SV: state variables e.g. residual stress, hardness} \]

\[ \text{tool} \]
\[ \uparrow v_f \]

\[ \text{P}_1 \]
\[ \text{P}_2 \]

\[ \text{tool} \]
\[ \uparrow v_c \]

\[ \text{grind hardening} \]

\[ \text{cryogenic deep rolling} \]
The new approach of „Process Signatures“ for the prediction of the effects of manufacturing processes

internal material load

"TELL ME YOUR INNERMOST FEELINGS!"

strain/stresses

temperatures

spatial gradients (µm) over time (µs)
The new approach of „Process Signatures“ for the prediction of the effects of manufacturing processes

- material modification
- phase transformation
- residual stresses
- hardness
- roughness
- grain size

Which are the decisive properties?
The new approach of „Process Signatures“ for the prediction of the effects of manufacturing processes.

**internal material load** → **material modification**

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**Graph:**
- **Y-axis:** Max. residual stress $\sigma_{r,\text{max}}$ MPa
- **X-axis:** Max. equivalent stress $\sigma_{\text{eq,\text{max}}}$ MPa

- **Data Points:**
  - $d_b = 6 \text{ mm}$
  - $d_b = 13 \text{ mm}$

- **Standard Deviation** indicated by error bars.

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Meyer and Kämmler, Procedia CIRP, 2016
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Outline
Recent frontiers of machining

Surface Chemistry
- Changes with temperature
- Complex mechanism
- Interacts with its environment in machining

A Chameleon
- Changes color
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Pictures: nationalgeographic.com
Thermal load in manufacturing processes

Require application of metalworking fluids

Surface

Subsurface

Increasing thermal load

Pictures: IWT Bremen
Metalworking Fluids in manufacturing processes

Tasks and supply

Main Tasks

- Lubrication
- Cooling
- Chip removal

Pictures: IWT Bremen, metalfluids.com, mwfmag.com
Metalworking Fluids in manufacturing processes

Composition

- Oil-based
- Water-based

Additives
- Extreme pressure (EP)
- Anti-wear (AW)
- Friction-modifier
- Emulsifiers
- Biocides
- Corrosion-inhibitors
- Anti-foam
- Anti-fogging
- ...

Main Questions
- Where?
- Why?
- How?

[DIN 51385]
Metalworking Fluids in manufacturing processes

Target site: Contact zone between tool and workpiece

[Davies et al., 2005]
Metalworking Fluids in manufacturing processes
Target site: Contact zone between tool and workpiece

Target site depends on the type of process

Marangoni effect

[Davies et al., 2005]
Metalworking Fluids in manufacturing processes

Efficiency and relevance

Depth of cut $a_e$

$\mu m$

0

600

Tool path $l$

mm

0

200

Thermische Schädigung Rissbildung

$\text{Schleiflänge } l$

$\text{Depth of cut } a_e$

$\text{mm}$

$\text{µm}$
Metalworking Fluids in manufacturing processes
Efficiency and relevance

Thermal Damage
Crack Formation

Depth of cut $a_e$

0
μm

Tool path l

0
200
mm

Thermische Schädigung
Rissbildung

Schleiflänge l

Draufsicht
Zustellung ae600
0
µm
Schleifweg l0 200mm

Depth of cut $a_e$

600

0

mm

200

IWT
Stiftung Institut für Werkstofftechnik Bremen

ECO Centrum

LFM
Labor für Mikrozerspanung

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Metalworking Fluids in manufacturing processes
Efficiency and relevance

![Diagram showing depth of cut vs. tool path with labels for thermal damage, crack formation, and grinding burn limit.](image)

- Thermal Damage
- Crack Formation
- Grinding burn limit ($Q_{w,crit}^'$)
Metalworking Fluids in manufacturing processes
Efficiency and relevance

Crit. specific material removal rate $Q'_{w,crit}$

standard deviation

$+$100%
Metalworking Fluids in manufacturing processes
Efficiency and relevance

Considerable effect
Antagonism?
Metalworking Fluids in manufacturing processes
interactions with metal surfaces

100Cr6 (AISI 52100) Surface
Metalworking Fluids in manufacturing processes
interactions with metal surfaces

100Cr6 (AISI 52100) Surface
Metalworking Fluids in manufacturing processes
interactions with metal surfaces

Polysulfide 40 (PS)

van der Waals forces, hydrogen bonds

Overbased sodium sulfonate (OBS)

ionic interactions

100Cr6 (AISI 52100) Surface
Metalworking Fluids in manufacturing processes
interactions with metal surfaces

Polysulfide 40 (PS)

Overbased sodium sulfonate (OBS)

van der Waals forces, hydrogen bonds

Ester (E)

ionic interactions

Type and strength of interaction depending on various factors
Surface Integrity
- Identification of working mechanisms
- Multifactorial effects during the process
- Interdisciplinary challenge
  - Manufacturing Technologies
  - Materials Science
  - Computer Science
  - Physics
- First steps taken based on new understanding

Surface Chemistry
- Confirmation of working mechanisms
- Multifactorial effects during process
- Interdisciplinary challenge
  - Manufacturing Technologies
  - Materials Science
  - Chemistry
  - Microbiology
- First steps taken based on new understanding

We are on our way to paradigm-shift by knowledge-based manufacturing
Thank you for your kind attention!

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