Sustainable Production, Life Cycle Engineering and Management
Series Editors: Christoph Herrmann, Sami Kara

Marius Winter

Eco-efficiency of Grinding Processes and Systems

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Sustainable Production, Life Cycle Engineering and Management

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Modern production enables a high standard of living worldwide through products and services. Global responsibility requires a comprehensive integration of sustainable development fostered by new paradigms, innovative technologies, methods and tools as well as business models. Minimizing material and energy usage, adapting material and energy flows to better fit natural process capacities, and changing consumption behaviour are important aspects of future production. A life cycle perspective and an integrated economic, ecological and social evaluation are essential requirements in management and engineering. This series will focus on the issues and latest developments towards sustainability in production based on life cycle thinking.

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Foreword

Grinding is a machining process featuring the application of a tool with undefined cutting edges for the processing of hard materials, to create complex profiles and to achieve a superior surface finish. Almost every technological product is directly or indirectly connected with the grinding process during its production. However, grinding is also a time, energy and resource demanding process, resulting in high economic and environmental impacts per removed amount of material. In comparison with machining processes with defined cutting edge, these demands result in a lower eco-efficiency of grinding processes and systems. To maintain the technological, economic and environmental competiveness of grinding processes and systems, an approach is needed which helps to identify and evaluate potentials to increase the eco-efficiency.

In this book, Marius Winter defines an integrated assessment approach to describe, model, evaluate and improve the eco-efficiency of existing and new grinding processes and systems. The foundation and novelty of the proposed concept is the combined empirical and physical modelling of technological, economic and environmental impact indicators based on the relevant energy and resource flows of the grinding process and system. The concept includes a single and integrated evaluation and improvement of different grinding process and system scenarios. Furthermore, an application cycle is provided to transparently determine, evaluate and improve existing and new grinding processes and systems. The developed approach promotes a holistic view on the grinding process and system and is designed to support the designer and operator of such processes and systems to identify decisions which meet the internal and external requirements. The developed approach also shows the potential to be transferred to other manufacturing processes.

With this published work as well as with his active role, Marius Winter has strongly contributed to foster the further development of the topic "cutting fluids" and "mineral oil-free production" in Braunschweig and to foster the development of the Joint German-Australian Research Group "Sustainable Manufacturing and Life Cycle Engineering".

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During my time as a research engineer I had the pleasure to be part of a highly motivated and supportive team, which allowed me to gather knowledge of multiple research topics. I want to express my sincere thanks to all these colleagues of the whole institute for creating a supportive, collaborative and positive atmosphere, allowing also the discussion of non-research-related topics. In particular, I want to thank Dr.-Ing. Ralf Bock and Dr.-Ing. Sebastian Thiede for their constant support, motivation and fruitful discussions. I am grateful (as well) to M.A. Anne-Marie Schlake for her adjuvant proofread of my manuscript and for providing the opportunity to unravel the daily mysteries of the IWF. Furthermore, I want to thank M.Sc. Nadine Madanchi and Dr. Wen Li for the common interest in research topics about cutting fluids, machining processes, sustainable manufacturing, etc. It was a pleasure to discuss with you new ideas for experiments, projects and publications. A special thank goes also to my officemates Dipl.-Ing. (FH) Stefan Andrew for our quibbling and contradicting discussions and to Dipl.-Wirtsch.-Ing. & Ingénieur diplômé Patricia Egede for our pleasant and fruitful conversation about our research work and work-related topics. Representative for the students that I have supervised in their theses works or assistant jobs I would like to thank Björn Berning, Tim Sieker, Janna Wilke, Alexander Leiden, Joachim Schütte and Christian Sowa for their exceptional work and great support. Many thanks also go to all project partners from industry and research for their trustful collaboration and exchange of experiences.

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Symbols and Abbreviations

Upper Case Symbols

A	Physical model (–)
A_{cf}	Surface area of evaporating cutting fluid (mm^2)
$A_{cu,max}$	Maximal uncut chip area (mm^2)
A_{fm}	Used filtration material surface area (m^2)
$A_{fm,total}$	Total used filtration material surface area (m^2)
A_g	Sectional area cutting groove (mm^2)
A_p	Sectional area piled-up material (mm^2)
A_w	Workpiece surface area (mm^2)
B	Empirical model (–)
C	Proportionality constant ($1/\sqrt{mm}$)
C'	Constraint factor (–)
C_i	Constant (–)
C_{cf}	Cutting fluid costs (€)
C_e	Energy costs (€)
C_{fm}	Filtration material costs (€)
C_{gw}	Grinding wheel costs (€)
C_m	Material costs (€)
C_s	System costs (€)
C_{total}	Total costs (€)
C_w	Waste costs (€)
$CO_{2,p,cf}$	Equivalent CO_2 impact to produced cutting fluid (kg CO_2eq./kg)
$CO_{2,p,e}$	Equivalent CO_2 impact to produced electrical energy (kg CO_2eq./kWh)
$CO_{2,p,fm}$	Equivalent CO_2 impact to produced filtration material (kg CO_2eq./piece)
$CO_{2,p,gw}$	Equivalent CO_2 impact to produced grinding wheel (kg CO_2eq./piece)
$CO_{2,w,cf}$	Equivalent CO_2 impact to disposed cutting fluid (kg CO_2eq./kg)

$CO_{2,\mathrm{w,fm}}$	Equivalent CO_2 impact to disposed filtration material (kg CO_2eq./m^2)
$CO_{2,\mathrm{w,gw}}$	Equivalent CO_2 impact to disposed grinding wheel residues (kg CO_2eq./kg)
$CO_{2,\mathrm{w,s}}$	Equivalent CO_2 impact to disposed grinding swarf (kg CO_2eq./kg)
D	Diffusion coefficient of the cutting fluid (m^2/s)
E	Relative absolute error (–)
E_i	Exponent i (–)
Env_{cf}	Cutting fluid-related equivalent CO_2 impact (kg CO_2eq.)
Env_{e}	Energy-related equivalent CO_2 impact (kg CO_2eq.)
Env_{fm}	Filtration material-related equivalent CO_2 impact (kg CO_2eq.)
Env_{gw}	Grinding wheel-related equivalent CO_2 impact (kg CO_2eq.)
Env_{w}	Waste-related equivalent CO_2 impact (kg CO_2eq.)
Env_{total}	Overall equivalent CO_2 impact (kg CO_2eq.)
F_0	Bond strength (N)
F_{n}	Normal forces (N)
F'_{n}	Specific normal forces (N/mm)
F_{t}	Tangential force (N)
F'_{t}	Specific tangential force (N/mm)
G	Reference point (–)
H	Material hardness (MPa)
$H_{\mathrm{b,g}}$	Hardness of the bulk material of the grain (MPa)
$H_{\mathrm{b,w}}$	Hardness of the bulk material of the workpiece (MPa)
$H_{\mathrm{s,g}}$	Hardness of the grain surface (MPa)
$H_{\mathrm{s,w}}$	Hardness of the workpiece surface (MPa)
I	Statistical factor (–)
K	Wear coefficient (1/Pa)
K_l	Constant (–)
K_{g}	Grain concentration (%)
K_{c}	Abrasive wear coefficient (1/Pa)
$K_{\mathrm{c,g}}$	Abrasive wear coefficient of the grain (1/Pa)
$K_{\mathrm{c,max}}$	Maximal abrasive wear coefficient (1/Pa)
L	Sampling length (mm)
M_i	Torque of spindle i (Nm)
N_{g}	Number of grains (1/mm^2)
$N_{\mathrm{g,d}}$	Number of grains created by conditioning (1/mm^2)
P	Normal load (N)
P_0	Machine tool idle power (W)
P_{au}	Power demand of the auxiliary units (W)
P_{c}	Cutting power (W)
P'_{c}	Specific cutting power (W/mm)
P_{ca}	Compressor power demand for the compressed air generation (W)

P'_{ca}	Specific compressor power demand for the compressed air generation (W/(Nm^3/min))
$P_{CFF,cl}$	Cutting fluid filter power demand cooling unit (W)
$P_{CFF,f}$	Cutting fluid filter power demand filtration pump (W)
$P_{CFF,i}$	Cutting fluid filter power demand of pump i (W)
$P_{CFF,idle}$	Cutting fluid filter power demand idle state (W)
$P_{CFF,l}$	Cutting fluid filter power demand lifting pump (W)
$P_{CFF,proc}$	Cutting fluid filter power demand processing state (decentralised) (W)
$P_{CFF,proc,total}$	Cutting fluid filter power demand processing state (central) (W)
$P_{CFF,s}$	Cutting fluid filter power demand supply pump (W)
P_{cu}	Power demand of the control unit (W)
$P_{EAF,f}$	Exhaust air filter power demand of the filtration unit (W)
$P_{EAF,proc}$	Exhaust air filter power demand processing state (decentralised) (W)
$P_{EAF,proc,total}$	Exhaust air filter power demand processing state (central) (W)
$P_{EAF,v}$	Exhaust air filter power demand of the ventilator drive (W)
P_{el}	Electrical power demand (W)
$P_{GM,idle}$	Grinding machine power demand idle state (W)
$P_{GM,proc,d}$	Grinding machine power demand processing state, dressing (W)
$P_{GM,proc,g}$	Grinding machine power demand processing state, grinding (W)
P_{GS}	Grinding system power demand (W)
P_{hu}	Power demand of the hydraulic unit (W)
P_{mech}	Mechanical pump power demand (W)
$P_{s,d}$	Power demand of the dressing spindle (W)
$P_{s,gw}$	Power demand of the grinding wheel spindle (W)
$P_{s,i}$	Power demand of spindle i (W)
$P_{s,w}$	Power demand of the workpiece spindle (W)
P_{scl}	Power demand of the spindle cooling and lubrication unit (W)
Q_{ca}	Compressed air volume flow (Nm^3/h)
Q_{cf}	Cutting fluid volume flow (decentralised) (l/min)
$Q_{cf,total}$	Total cutting fluid volume flow (central) (l/min)
Q_{ea}	Exhaust air volume flow (decentralised) (m^3/h)
$Q_{ea,total}$	Total exhaust air volume flow (central) (m^3/h)
Q_w	Material removal rate (mm^3/s)
Q'_w	Specific material removal rate (mm^3/(s mm))
R^2	Coefficient of determination (–)
R_a	Arithmetical mean roughness (µm)
R_a^*	Adjusted arithmetical mean roughness (µm)
R_{s,H_2O}	Specific gas constant for water vapour (J/(kg•K))
Sc	Schmidt number (–)
$\bar{T}$	Arithmetic mean of cutting fluid and air temperature (°C)
$\bar{T}_{cf}$	Mean cutting fluid temperature (°C)
ΔT_{cf}	Tolerated fluid temperature rise (°C)

T_{GM}	Machine tool interior temperature (°C)
T_{max}	Maximal grinding contact zone temperature (°C)
U_d	Dressing overlap ratio (–)
V_K	Grain volume (mm^3)
V_t	Tool wear volume (mm^3)
V'_t	Specific tool wear volume (mm^3/mm)
$V_t'^*$	Adjusted specific tool wear volume (mm^3/mm)
V_w	Workpiece material volume removed (mm^3)
V'_w	Specific workpiece material volume removed (mm^3/mm)
W	Wear volume (mm^3)
Y	Output indicator (–)
Y_i	Observed response (–)
$\bar{Y}_i$	Mean observed response (–)
$\hat{Y}_i$	Predicted response (–)

Lower Case Symbols

a	Half grain width (μm)
$a_{1,i}$	Regression coefficient of spindle i (–)
$a_{2,i}$	Regression coefficient of spindle i (–)
$a_{cf,i}$	Regression coefficient of cutting fluid i (–)
a_e	Cutting depth (μm)
a_{ed}	Dressing depth (μm)
a_p	Cutting width (mm)
a_{pd}	Axial dressing overlap (mm)
b	Half grain height (μm)
b_i	Regression coefficient of spindle i (–)
$b_{cf,i}$	Regression coefficient of cutting fluid i (–)
$b_{cu,max}$	Maximal uncut chip width (μm)
b_d	Effective dresser width (mm)
b_s	Grinding wheel width (mm)
c_0	Coefficient (–)
c_1	Coefficient (–)
$c_{cf,i}$	Regression coefficient of cutting fluid i (–)
c_k	Volume-related grain density ($1/mm^3$)
c_k^*	Surface area-related grain density ($1/mm^2$)
$c_{o,e}$	Energy-related overhead cost (%)
$c_{o,m}$	Material-related overhead cost (%)
$c_{o,s}$	System-related overhead cost (%)
$c_{o,w}$	Waste-related overhead cost (%)
$c_{p,cf}$	Specific heat capacity of the cutting fluid (J/(kg•K))
d_{eq}	Equivalent diameter (mm)
$d_{eq,cf,e}$	Equivalent diameter of the evaporation fluid area (m)
d_d	Rotational dresser external diameter (mm)

d_{groove}	Groove depth (μm)
d_k	Mean grain diameter (μm)
d_s	Grinding wheel external diameter (mm)
d_w	Workpiece diameter (mm)
e	Cutting efficiency (–)
f	Corrected target value (–)
f_{cf}	Interfacial friction coefficient of the cutting fluid (–)
f_{ad}	Traverse dressing lead (mm)
$f_{n,i}$	Normal force per grain i (N/grain)
f_s	Fraction of grits contacted during one pass of the dresser (–)
$f_{t,i}$	Tangential force per grain i (N/grain)
f_{U_d}	Conditioning process weighting factor (–)
h'	Height of the piled-up material (μm)
h_{cu}	Chip thickness (μm)
$h_{cu,max}$	Maximal uncut chip height (μm)
h_d	Number of needed dressing strokes (–)
$h_{d,total}$	Total number of possible dressing times (–)
k	Process physics-related constant (–)
k_m	Water transfer coefficient (–)
l	Dimensionless distance between adjacent tracks (–)
l_c	Cutting length (mm)
l_g	Contact length (mm)
l_{gs}	Grain spacing (μm)
l_w	Workpiece length (mm)
$\dot{m}_{cf,a}$	Cutting fluid loss rate due to aerosols (kg/s)
$m_{cf,a}$	Cutting fluid loss due to aerosols (kg)
$\dot{m}_{cf,e}$	Cutting fluid loss rate due to evaporation (kg/s)
$m_{cf,e}$	Cutting fluid loss due to evaporation (kg)
$\dot{m}_{cf,fm}$	Cutting fluid loss rate due to filtration material wetting (kg/kg)
$m_{cf,fm}$	Cutting fluid loss due to filtration material wetting (kg)
$\dot{m}_{cf,l}$	Cutting fluid loss/demand rate (kg/s)
$m_{cf,l}$	Cutting fluid loss/demand (kg)
$\dot{m}_{cf,s}$	Cutting fluid loss rate due to grinding swarf wetting (kg/kg)
$m_{cf,s}$	Cutting fluid loss due to grinding swarf wetting (kg)
$\dot{m}_{cf,w}$	Cutting fluid loss rate due to workpiece wetting (kg/piece)
$m_{cf,w}$	Cutting fluid loss due to workpiece wetting (kg)
n	Exponent (–)
n_i	Rotational speed of spindle i (1/min)
n_s	Grinding wheel rotational speed (1/min)
n_{sd}	Grinding wheel rotational speed when dressing (1/min)
n_w	Workpiece rotational speed (1/min)
p_{cf}	Pressure cutting fluid (bar)
p_e	Energy procurement price (€/kWh)
p_l	Labour price (€/h)

p_{m}	Total grinding system machine-hour rate (€/h)
$p_{m,CFF}$	Cutting fluid filter machine-hour rate (€/h)
$p_{m,EAF}$	Exhaust air filter machine-hour rate (€/h)
$p_{m,GM}$	Grinding machine machine-hour rate (€/h)
$p_{p,cf}$	Cutting fluid procurement price (€/kg)
$p_{p,fm}$	Filtration material procurement price (€/m^2)
$p_{p,gw}$	Grinding wheel procurement price (€/piece)
$p_{s,air}$	Water vapour pressure of the ambient air (bar)
p_{s,H_2O}	Saturation pressure of water vapour (bar)
$p_{w,cf}$	Cutting fluid disposal price (€/kg)
$p_{w,fm}$	Filtration material disposal price (€/m^2)
$p_{w,gm}$	Grinding wheel disposal price (€/piece)
$p_{w,s}$	Grinding swarf disposal price (€/kg)
q	Deviation or offset (–)
q_{d}	Dressing speed ratio (–)
q_{m}	Grit aspect ratio (–)
r	Ratio between uncut chip width and height (–)
r_{d}	Radius of the dresser (mm)
r_{mean}	Mean grain radius (µm)
r_{g}	Grain tip radius (µm)
Δr_{s}	Radial grinding wheel wear (µm)
s	Sliding distance (m)
t_{c}	Grinding time (s)
t_{cf}	Cutting fluid dripping time (s)
$t_{cf,l}$	Cutting fluid service life (s)
t_{d}	Dressing time (s)
t_{idle}	Idle time (s)
t_{h}	Handling time (s)
t_{p}	Processing time (s)
t_{t}	Tool travel time (s)
u	Process and system parameter and state conditions (–)
v_{air}	Air velocity (m/s)
v_{c}	Cutting speed (m/s)
v_{cf}	Cutting fluid jet velocity (m/s)
v_{d}	Dressing tool speed (m/s)
v_{fad}	Traverse dressing speed (m/s)
v_{fr}	Radial infeed speed (m/s)
v_{s}	Grinding wheel speed (m/s)
v_{w}	Workpiece speed (m/s)
w_{m}	Average grit mesh size (µm)
w	Target value (–)
x_{i}	Input variables (–)

y	Actual value (–)
z	Disturbance value (–)

Greek Symbols

α	Attack angle (°)
$\beta_{u/b}$	Water transfer coefficient (according to VDI 2089-1) (–)
γ	Angle of piled-up material (°)
δ_t	Grain fracture strength (GPa)
η	Efficiency (–)
η_{CFO}	Cutting fluid orifice efficiency (–)
η_{el}	Pump drive electrical efficiency (–)
η_{sust}	Sustainable efficiency indicator (–)
θ_{cf}	Cutting fluid water content (%)
μ	Friction coefficient/Force ratio (–)
ν	Grain loss factor (–)
ν_{cf}	Kinematic viscosity of the cutting fluid (mm^2/s)
ρ_{cf}	Density of the cutting fluid (kg/m^3)
ρ_{gw}	Density of the grinding wheel (kg/m^3)
ρ_w	Density of the workpiece (kg/m^3)
σ_{cf}	Surface tension of the cutting fluid (mN/m)
τ	Distance between the mean line of an array of grooves and the initial workpiece surface level (μm)
ϕ_{air}	Relative air humidity (%)

Abbreviations

BCSD	Business Council for Sustainable Development
cBN	Cubic boron nitride
CCA	Conventional cost accounting
CNC	Computer numerical controlled
cvx	Disciplined convex programming
DIN	Deutsches Institut für Normung
EEA	European Environment Agency
EE-portfolio	Portfolio of the environmental impact reduction factor and the economic value factor
EN	European Norm
EU	European Union
EU27	European Union (member states until June 2013)
EU28	European Union (member states since June 2013)
FEM	Finite element method
GPI	Green productivity index
GWP	Global warming potential

hBN	Hexagonal boron nitride
HPHT	High pressure and high temperature
HPJAM	High pressure jet-assisted machining
ISO	International Standard Organisation
LCA	Life cycle assessment
LCC	Life cycle costing
MFCA	Material flow cost accounting
MRR	Material removal rate
OECD	Organisation for Economic Co-operation and Development
PROMETHEE	Preference Ranking Organisation Method for Enrichment of Evaluations
SEC	Specific energy consumption
TE-portfolio	Portfolio of the environmental impact reduction factor and the technological value factor
UN	United Nations
VDI	Verein Deutscher Ingenieure
VDMA	Verband Deutscher Maschinen- und Anlagenbau
WBCSD	World Business Council for Sustainable Development