

Sustainable Manufacturing: Trends in the use and reuse of cutting tools (and chips)

Prof. Dr.-Ing. Berend Denkena, M. Sc. Florian Schaper

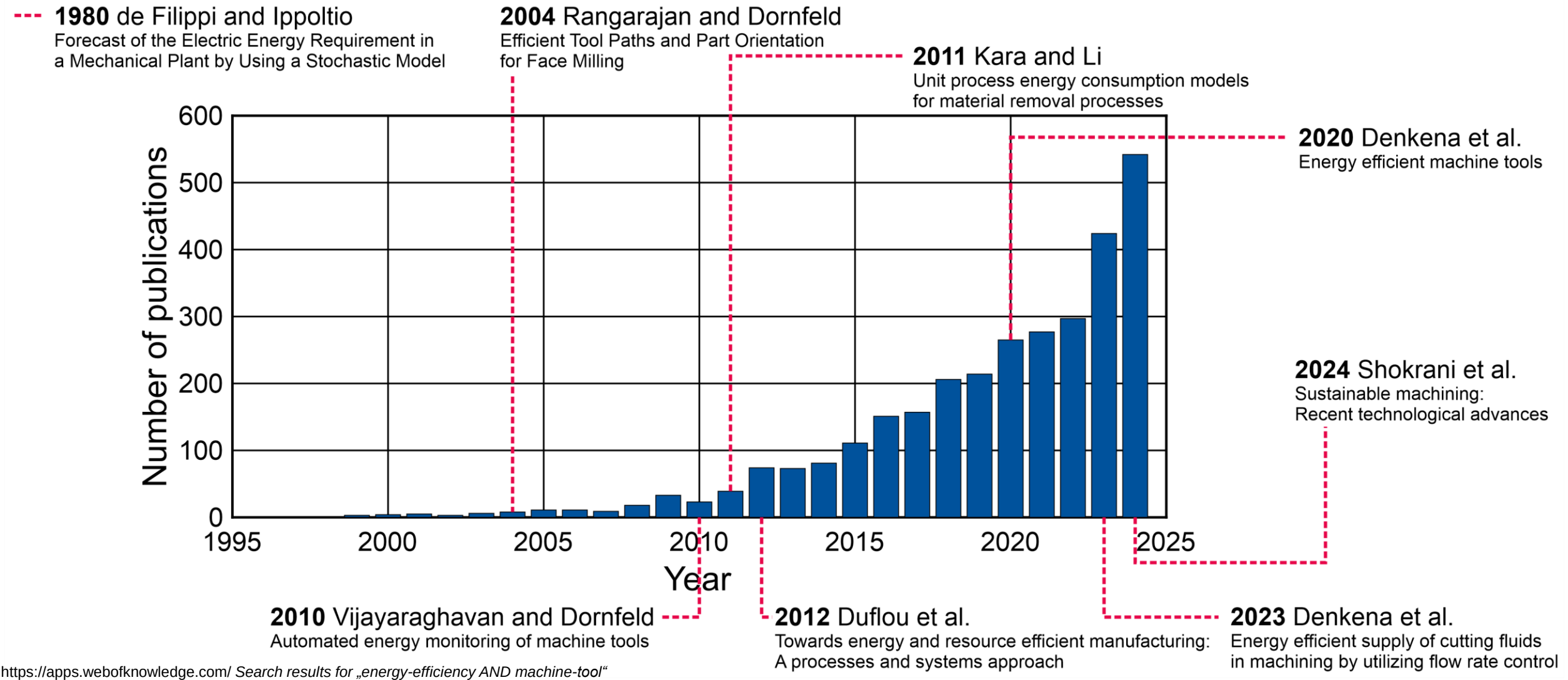
UTIS 2025



April 22nd, 2016

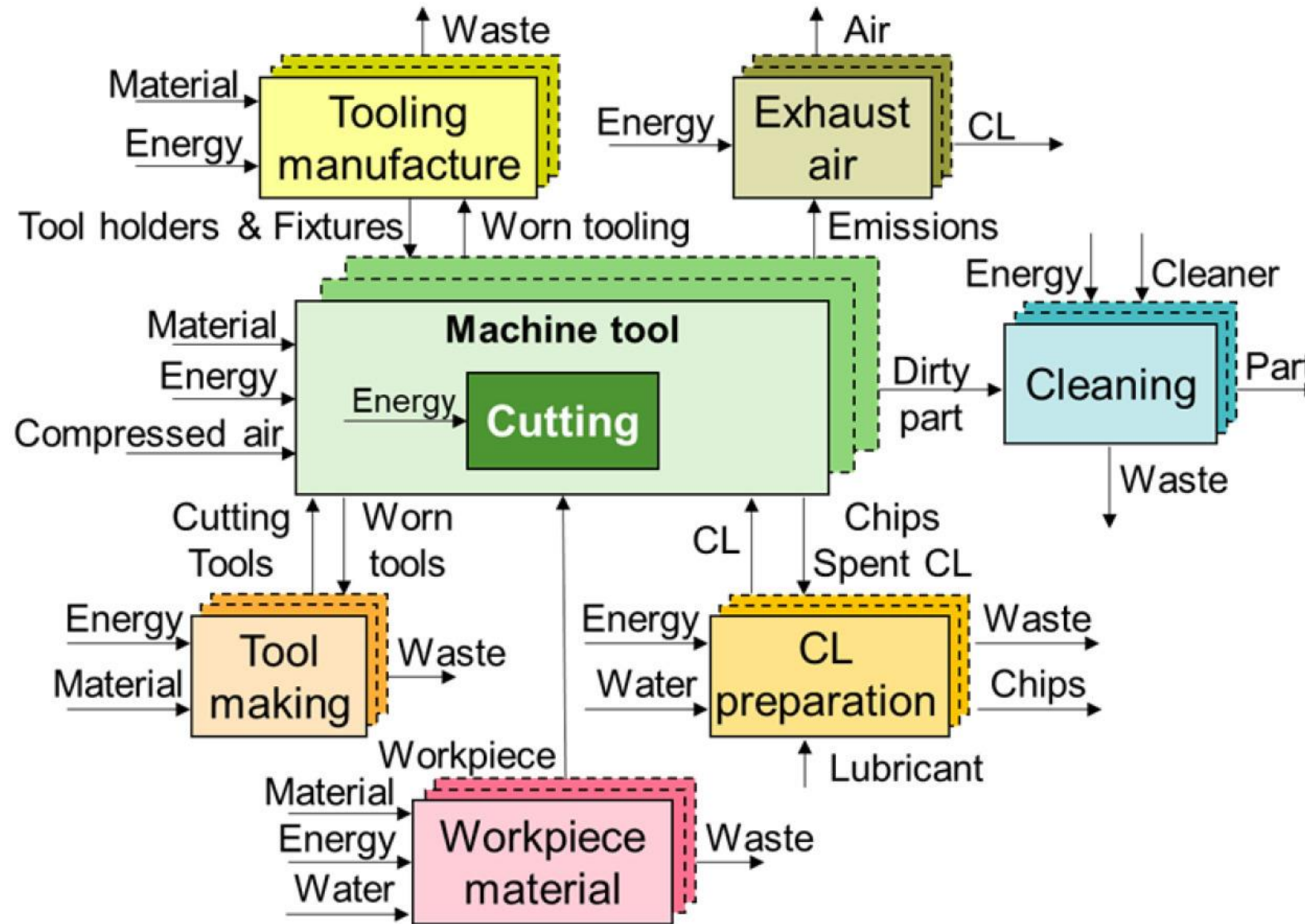
Research activities (with selected CIRP papers)

Scientific publications concerning machine tools and energy efficiency



https://apps.webofknowledge.com/Search_results_for_„energy-efficiency AND machine-tool“

Inputs and outputs of a machining system



CIRP Keynote 2024:
Sustainable Machining
By Shokrani et al.

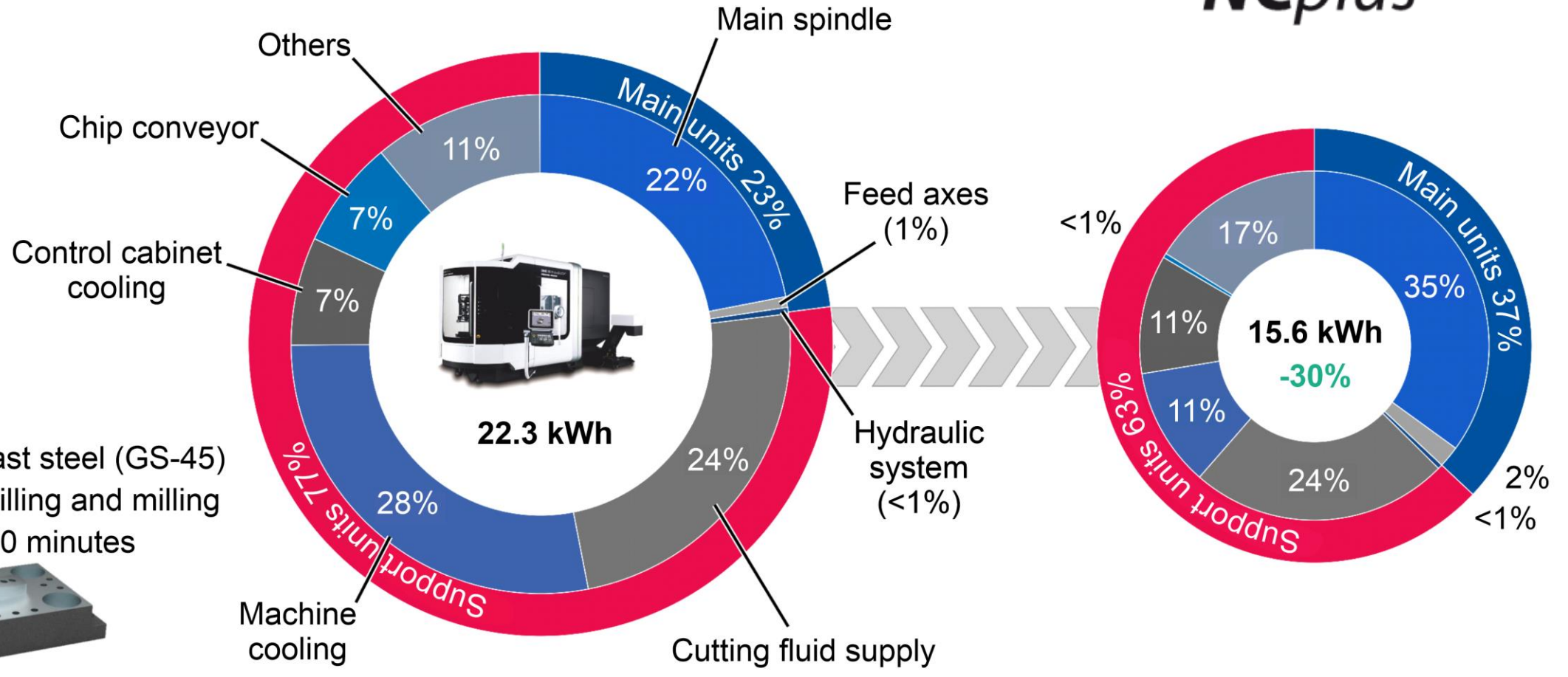
A. Shokrani, P.J. Arrazola, D. Biermann, P. Mativenga, I.S. Jawahir: Sustainable machining: Recent technological advances, CIRP Annals, Volume 73, Issue 2, 2024, Pages 483-508.

Energy efficiency evaluation for an industrial application scenario

Savings potential through coordinated energy efficiency measures

– Deckel Maho MC 80 H duoBlock

NCplus⁺

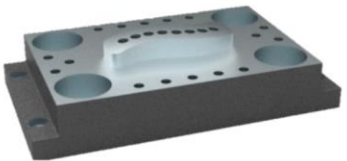


Workpiece

Material: Cast steel (GS-45)

Operation: Drilling and milling

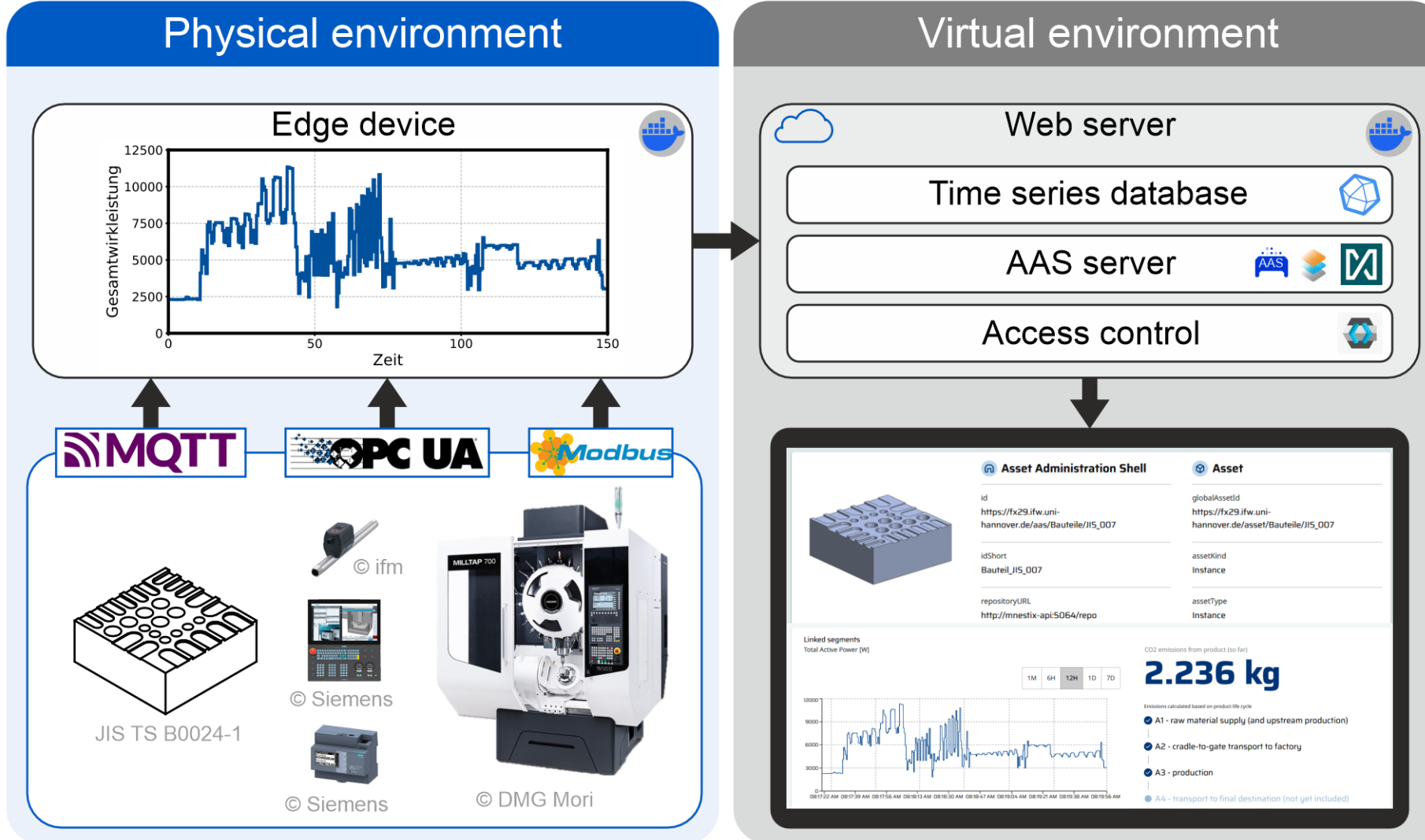
Time: 140 minutes



B. Denkena, E. Abele, C. Brecher, M.-A. Dittich, S. Kara, M. Mori: Energy efficient machine tools, CIRP Annals, Volume 69, Issue 2, 2020, Pages 646-667.

Denkena B (2013) Abschlussbericht zum BMBF-Verbundprojekt NCplus: Prozess- und wertschöpfungsorientiert gesteuerte Werkzeugmaschine. Report, Leibniz University Hannover.

Digital Twin to document energy consumption and carbon footprint



Current project with DMG MORI, SIEMENS and other partners:

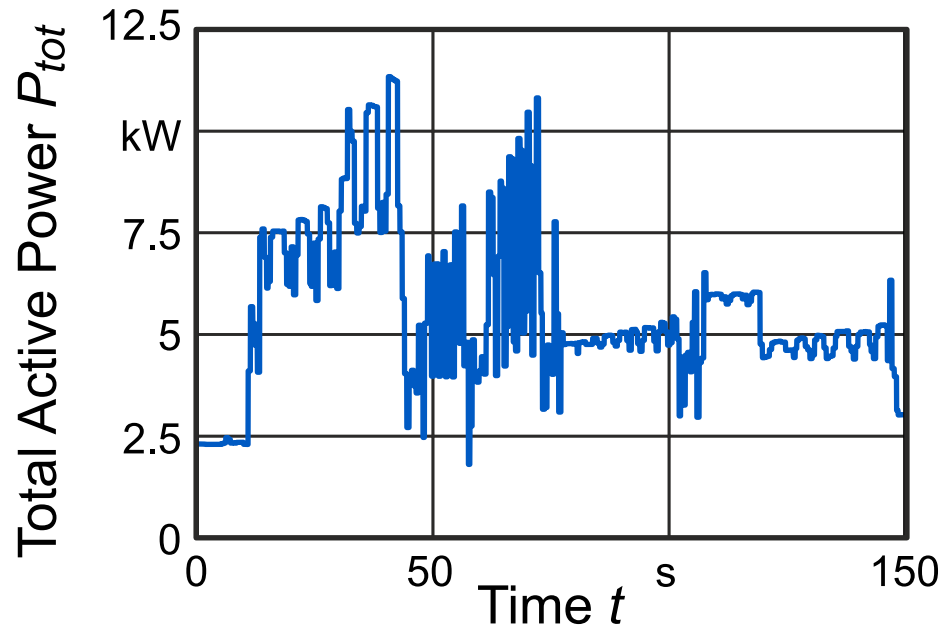


Metamodel according to Industrial Digital Twin Association: Specification of the Asset Administration Shell, IEC 63278-1:2023

IDTA – Industrial Digital Twin Association e. V. (Hrsg.) (2025): Specification of the Asset Administration Shell Part 1: Metamodel. IDTA, Frankfurt a. M.

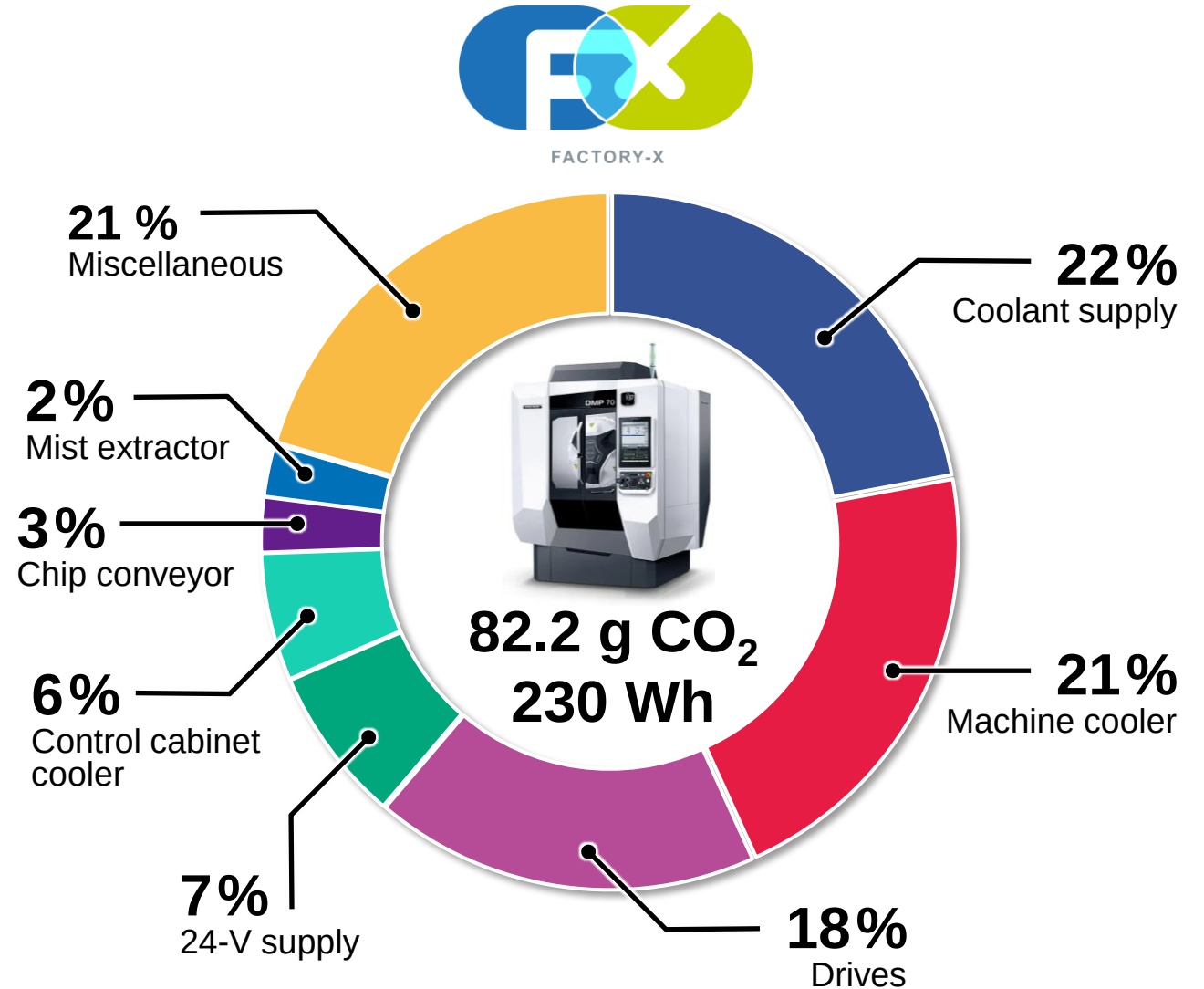
B. Denkena: Interoperable Energiedatenbereitstellung mittels Verwaltungsschale. Zeitschrift für wirtschaftlichen Fabrikbetrieb, Volume 120, Issue 7–8, 2025, Pages 496–500.

Energy measurement is base of optimization



Asset Administration Shell

- Standardized digital representation
- Semantic data integration
- Interoperable data exchange



IDTA – Industrial Digital Twin Association e. V. (Hrsg.) (2025): Specification of the Asset Administration Shell Part 1: Metamodel. IDTA, Frankfurt a. M.

B. Denkena: Interoperable Energiedatenbereitstellung mittels Verwaltungsschale. Zeitschrift für wirtschaftlichen Fabrikbetrieb, Volume 120, Issue 7–8, 2025, Pages 496–500.

Implications for support units (with possible energy savings)

Cooling system Savings potential 20% to 75%

- Avoid hot gas bypass
- Cooling capacity modulation (Scroll compressor, air cooler)

Cutting fluid supply Savings potential up to 75%

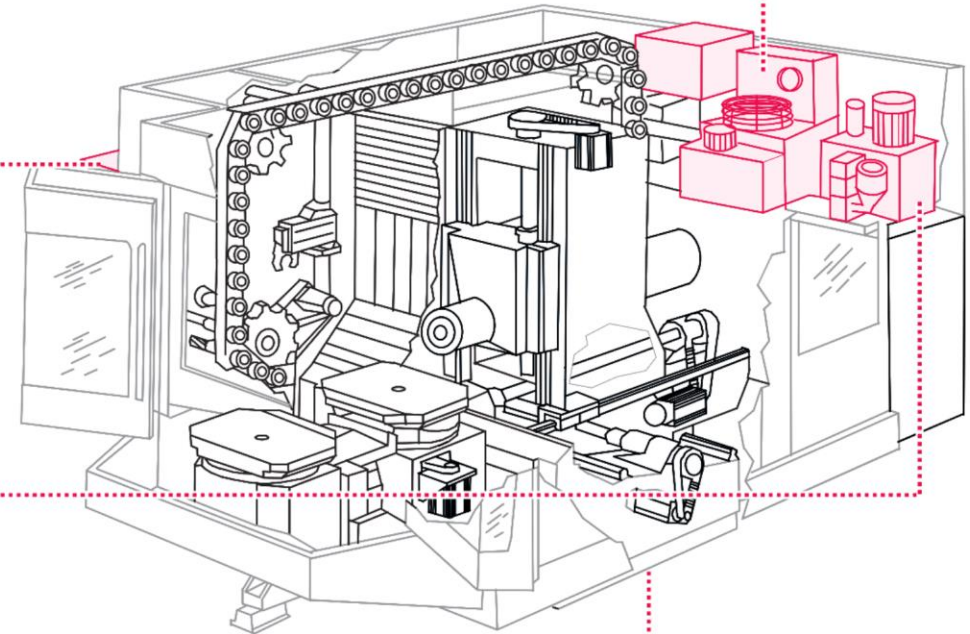
- Pump dimensioning (avoid oversizing)
- Adaption of supply parameters (inverter-controlled pumps)
- Increase effectivity (nozzle design, high-pressure supply)

Hydraulics Savings potential 25% to 75%

- Efficient circuit design (pressure accumulators and boosters)
- Minimize leakage

Other auxiliary components Savings potential up to 75%

- Avoid pneumatic systems
- Need-based control for extraction systems (oil mist or chips)

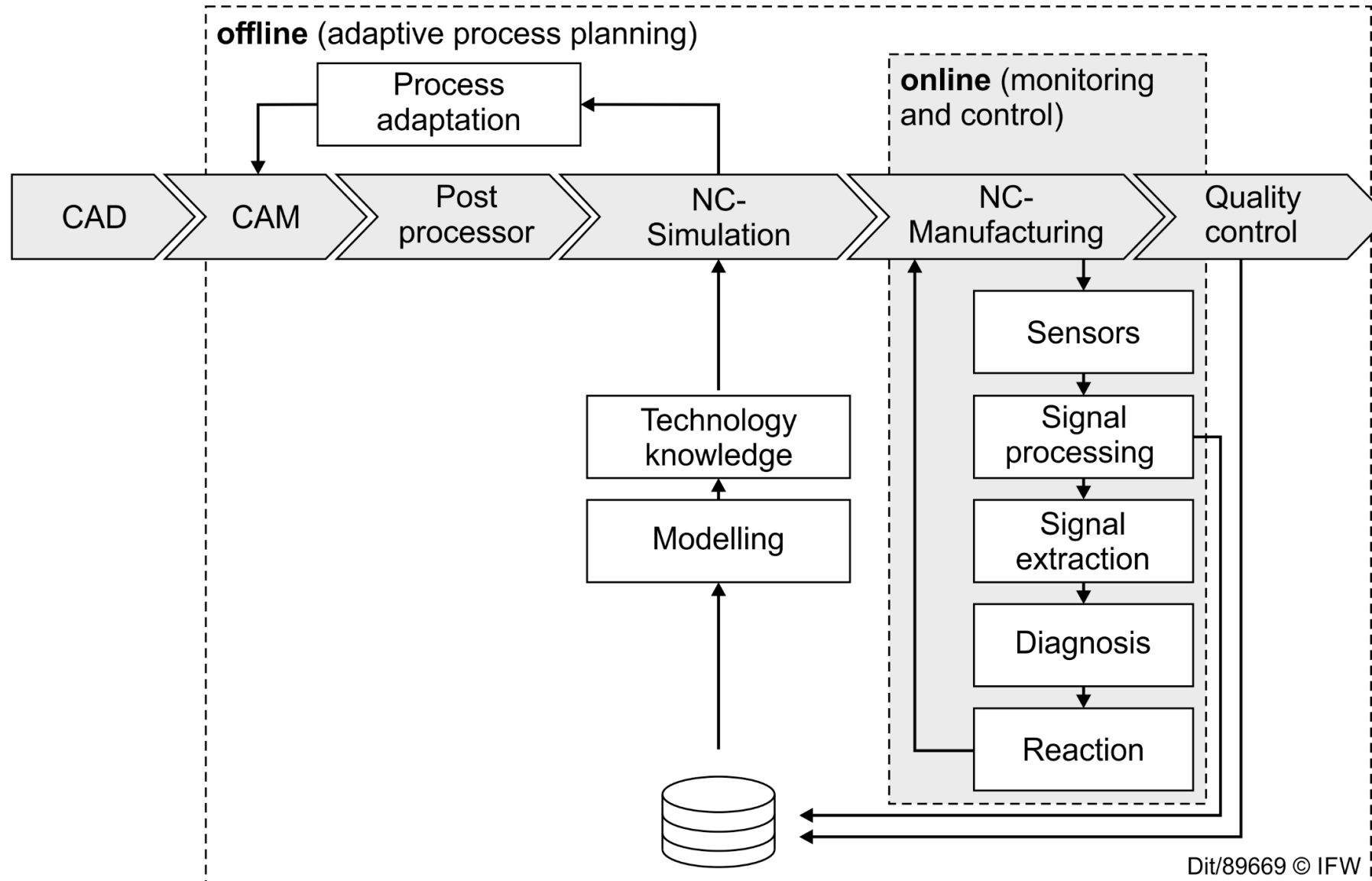


B .Denkena, E. Abele, C. Brecher, M.-A. Dittrich, S. Kara, M. Mori: Energy efficient machine tools, CIRP Annals, Volume 69, Issue 2, 2020, Pages 646-667.

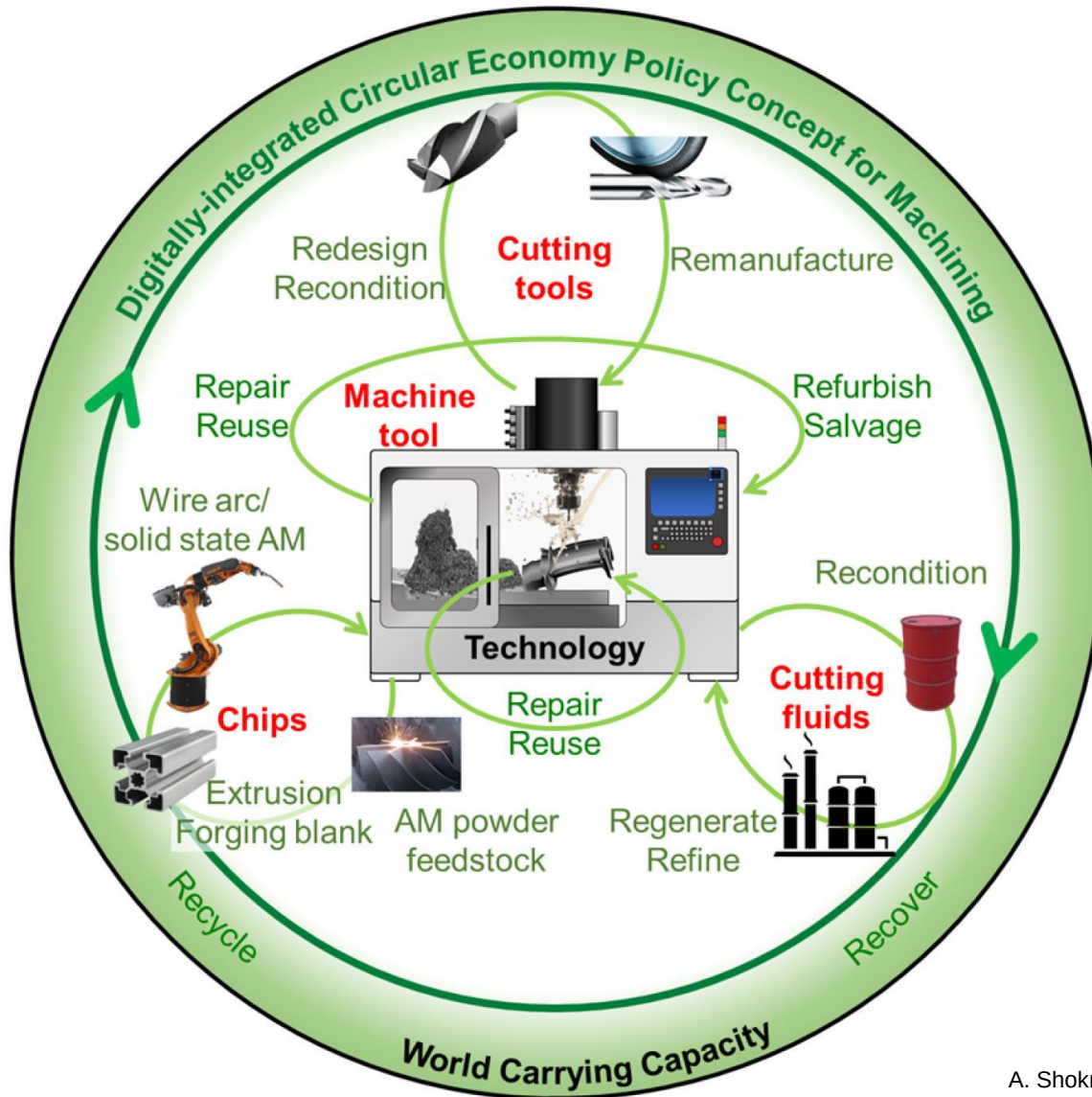
Deutsches Institut für Normung (2009) DIN EN 12417: Werkzeugmaschinen – Sicherheit – Bearbeitungszentren. Industrial norm, Beuth, Berlin.

C. Eisele: (2014) Simulationsgestützte Optimierung des elektrischen Energiebedarfs spanender Werkzeugmaschinen. PhD-Thesis, Technical University of Darmstadt.

In-process or pre-process adaptation to adapt machining system



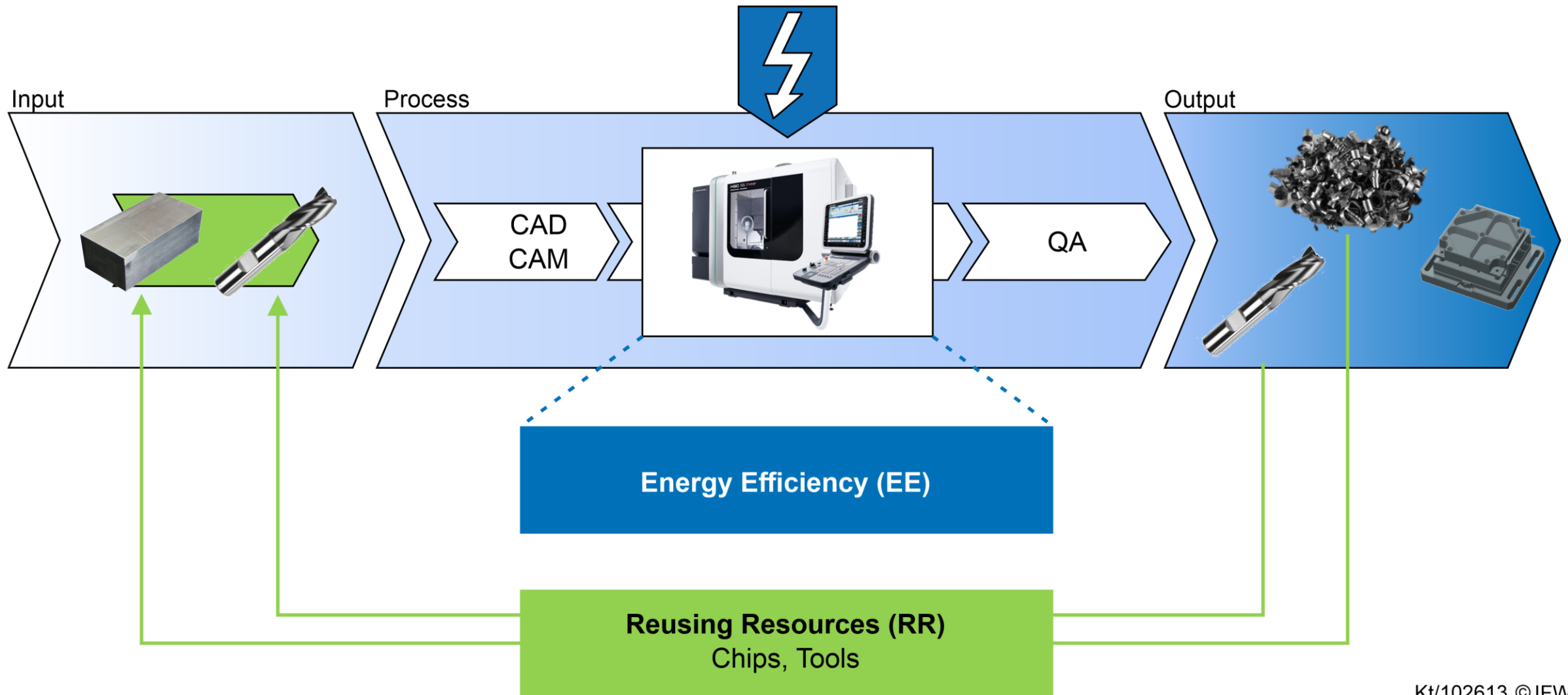
Vision of circularity in machining with closed-loops



- Circularity is a main goal
- But sustainability can also be promoted by improving subsystems

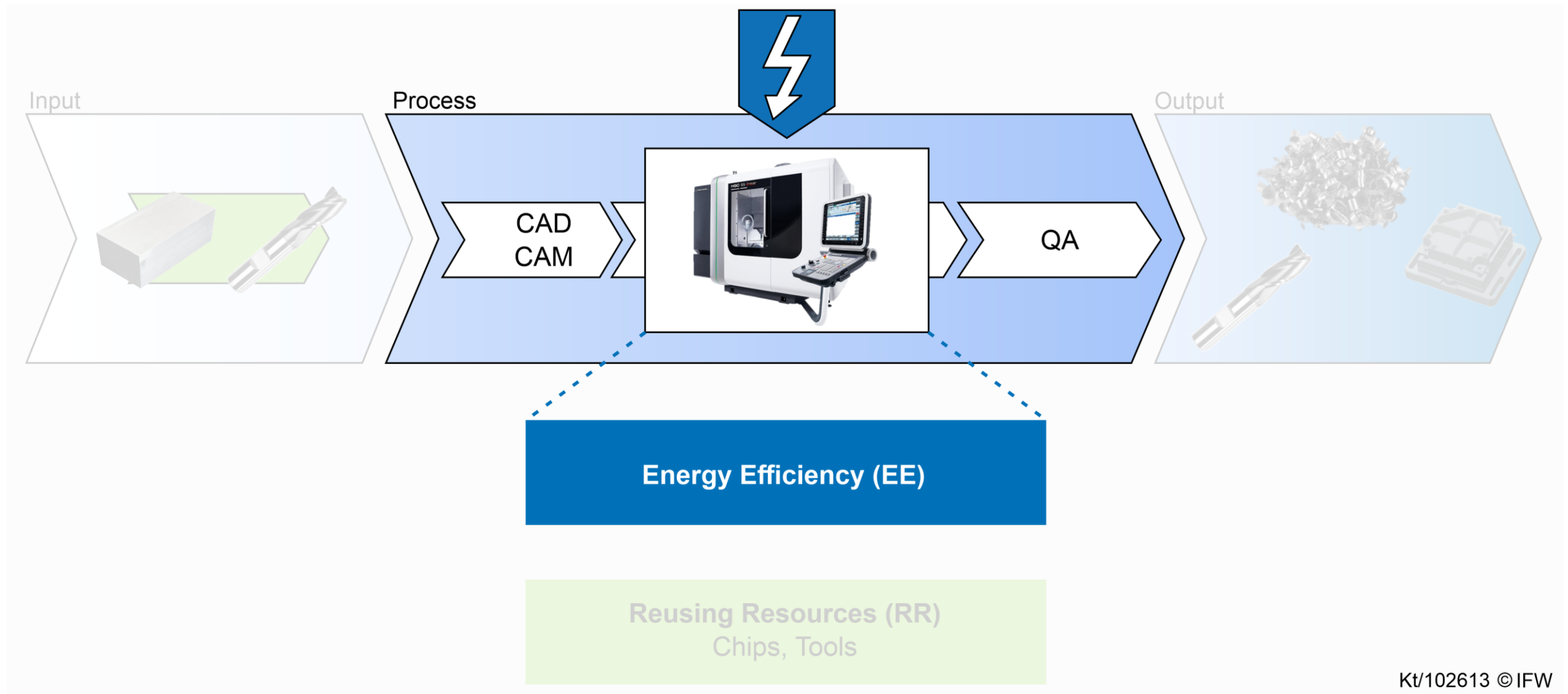
A. Shokrani, P.J. Arrazola, D. Biermann, P. Mativenga, I.S. Jawahir: Sustainable machining: Recent technological advances, CIRP Annals, Volume 73, Issue 2, 2024, Pages 483-508.

Outline of presentation



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Outline of presentation



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Savings potential of cutting fluid supply (internal)ö

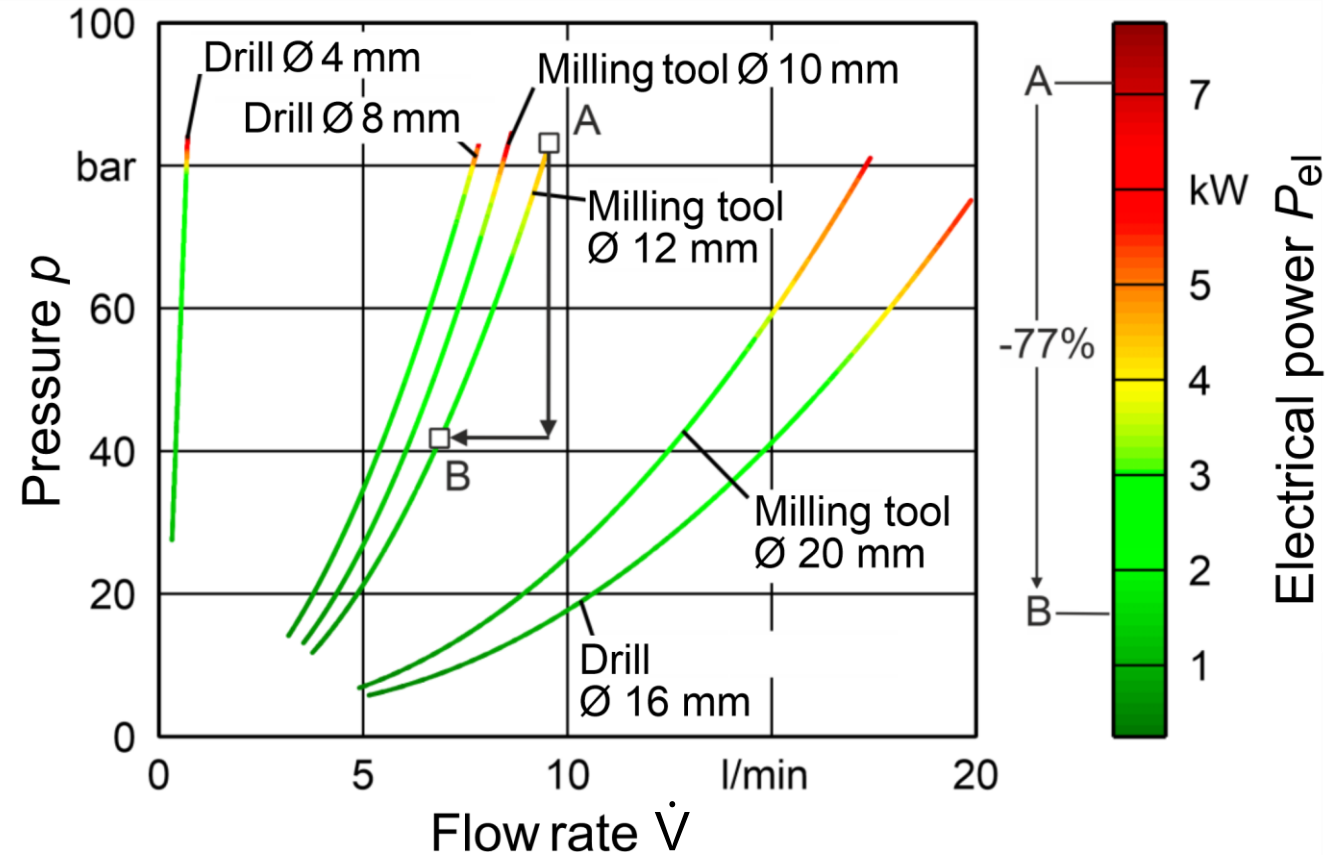
Control of the cutting fluid supply parameters

- High-pressure pump with frequency inverter
- Characteristic system diagram depends on machine tool configuration (e.g. cutting tool)
- Large potential to reduce power demand with minor variations of the supply parameters

How much cutting fluid is actually required?

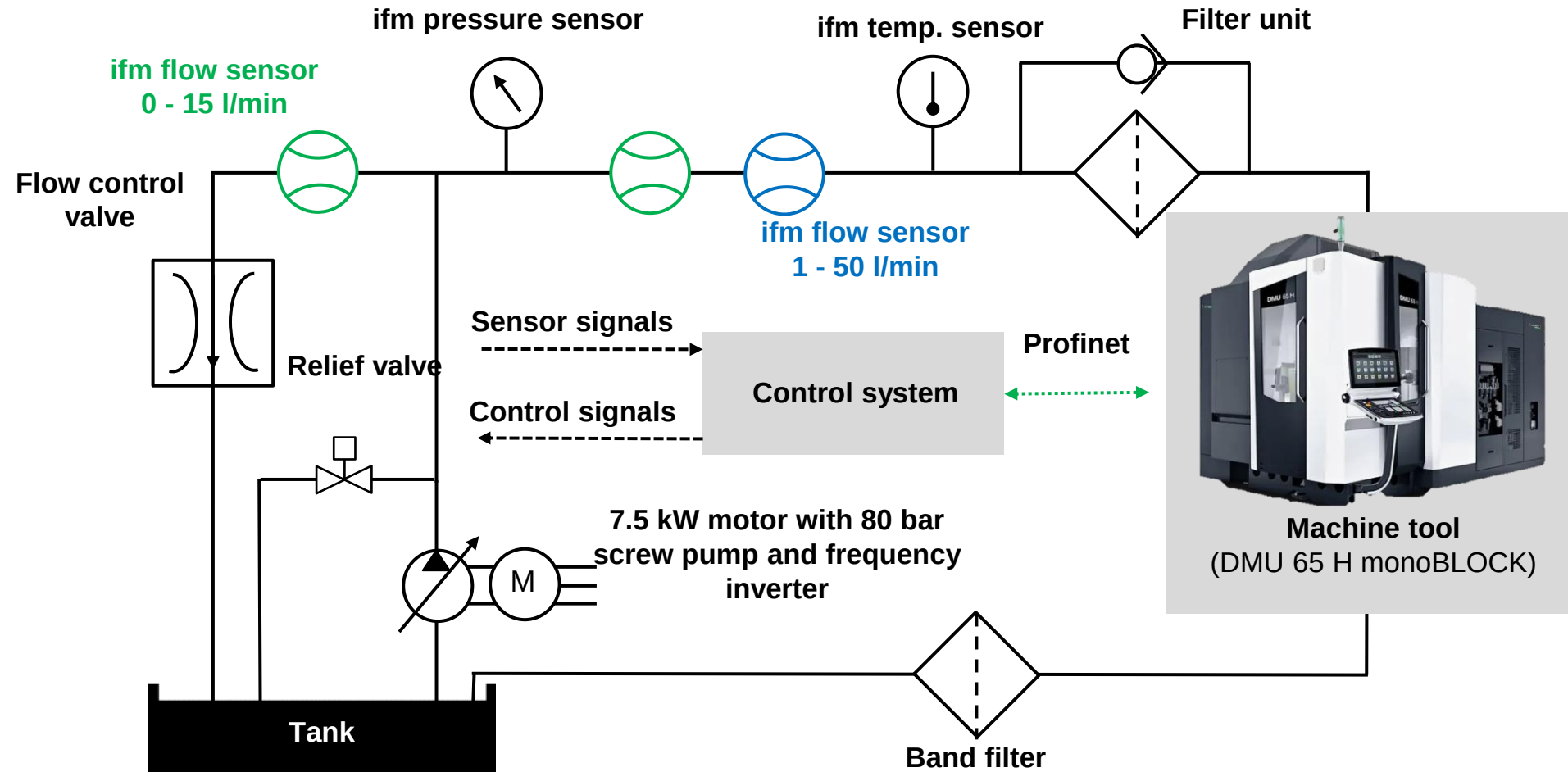
Savings potential for practical use cases?

Technological risks of reduced flow rates?



L. Hülsemeyer,.: Energy efficiency of cutting machine tools and demand-oriented operation using the example of internal cooling lubricant supply. PhD Thesis, Leibniz University Hannover, 2016.
B. Denkena, E. Abele, C. Brecher, M.-A. Dittich, S. Kara, M. Mori: Energy efficient machine tools, CIRP Annals, Volume 69, Issue 2, 2020, Pages 646-667.

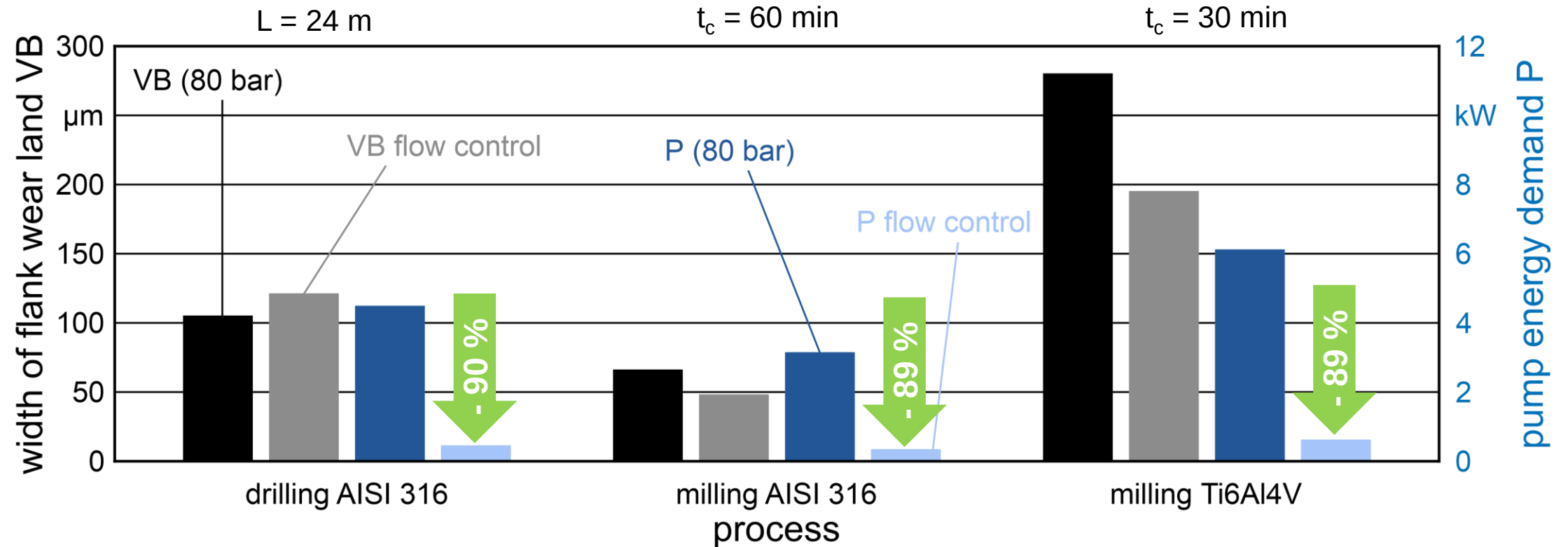
Cutting fluid supply system for flow control



- Sensors for flow measurement in the main line and in bypass
- Flow control by pump speed adjustment

B. Denkena, M. Mori, M.-A. Dittrich, N. Klages, J. Matthies: Energy efficient supply of cutting fluids in machining by utilizing flow rate control. CIRP Annals, Volume 72, Issue 1, 2023, Pages 349–352

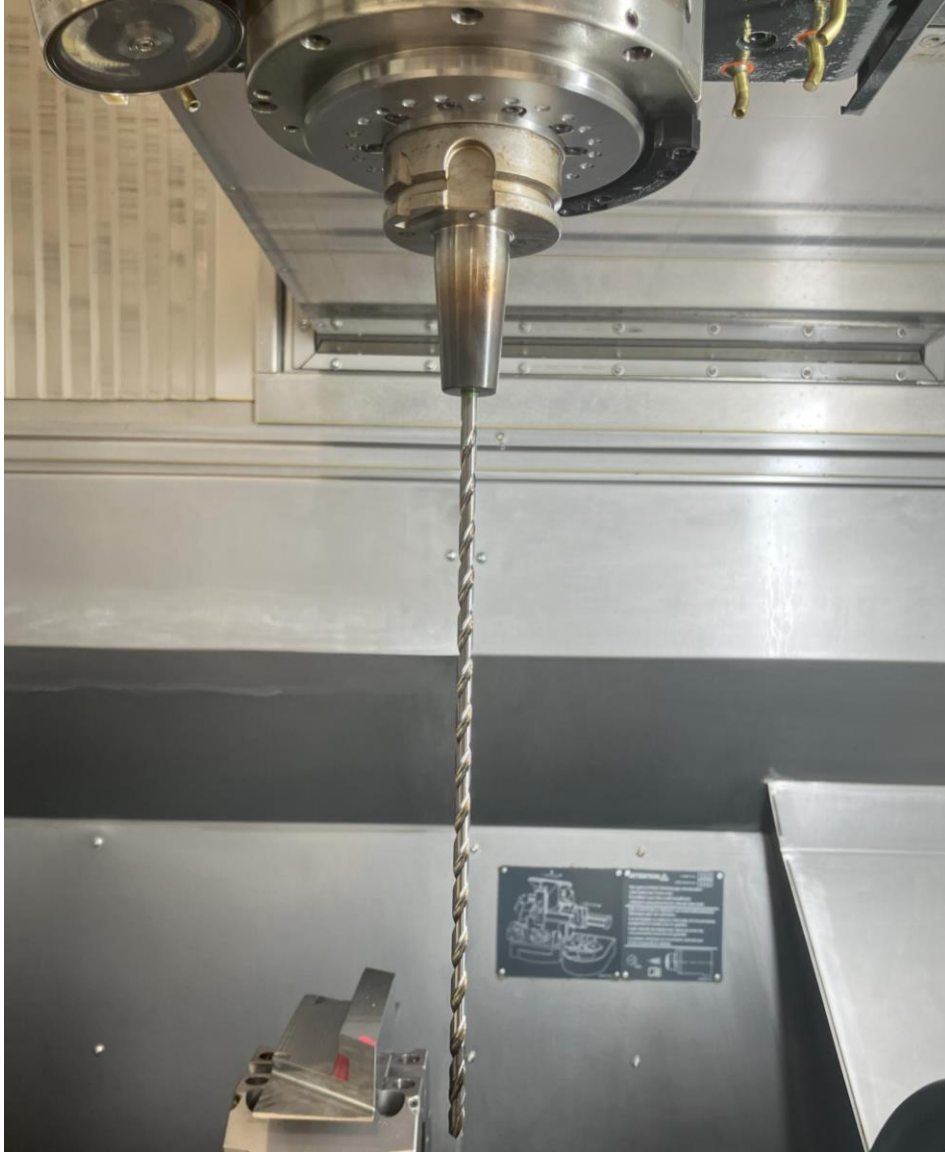
Coolant flow control in drilling and milling



Process	tool: KMT GT - 8.5 mm			tool: KMT Harvi 1TE - 10 mm	tool: KMT Mill 4-15 - 32 mm
parameters:					
Cutting speed:	$v_c = 50 \text{ m/min}$			$v_c = 70 \text{ m/min}$	$v_c = 75 \text{ m/min}$
Feed:	$f_z = 0.1 \text{ mm}$			$f_z = 0.08 \text{ mm}$	$f_z = 0.12 \text{ mm}$
Width of cut:				$a_e = 5 \text{ mm}$	$a_e = 10 \text{ mm}$
Depth of cut:				$a_p = 5 \text{ mm}$	$a_p = 5 \text{ mm}$

B. Denkena, M. Mori, M.-A. Dittrich, N. Klages, J. Matthies: Energy efficient supply of cutting fluids in machining by utilizing flow rate control. CIRP Annals, Volume 72, Issue 1, 2023, Pages 349–352

Gun drilling with adaptive coolant flow (ACF)



Request

- + high pressure pump **120 bar – 150 bar**
- + **Special cooling lubricant** due to high pressure and cutting force necessary = higher cost
- + **Material:** Steel 1.4418 (X4CrNiMo16-5-1) and Steel 1.6580 (30CrNiMo8)
- + **Vertical** drilling

Challenges

- + **Process stability** and **avoid tool breakage**
- + Using **standard cooling lubricant** for pressure with 80 bar
- + **Reduce high tool wear**

Botek Gun Drill Ø3/ 50xØ:

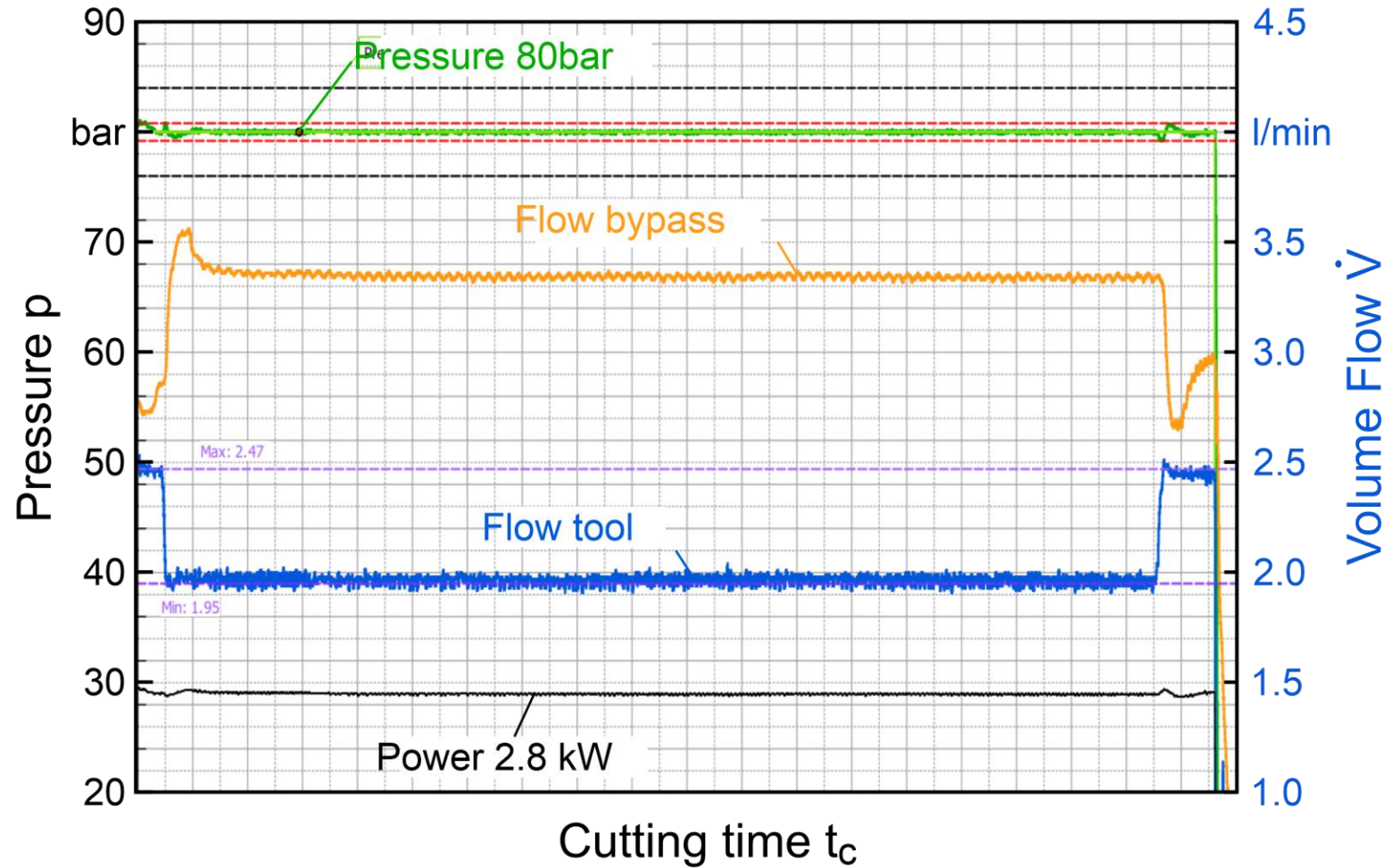
Steel 1.6580: $vc = 60 \text{ m/min}$, $f = 0.01 \text{ mm}$

Steel 1.4418: $vc = 40 \text{ m/min}$, $f = 0.01 \text{ mm}$

Source: DMG MORI Pfronten, Rolf Kettner

Gun drilling without adaptive coolant flow (ACF)

Steel 1.4418: Tool $\varnothing$ 3 mm x 110 mm



Process

- 80 bar stable process at 2.8 kW

Flow bypass

- 2.8 l/min $\rightarrow$ 3.4 l/min

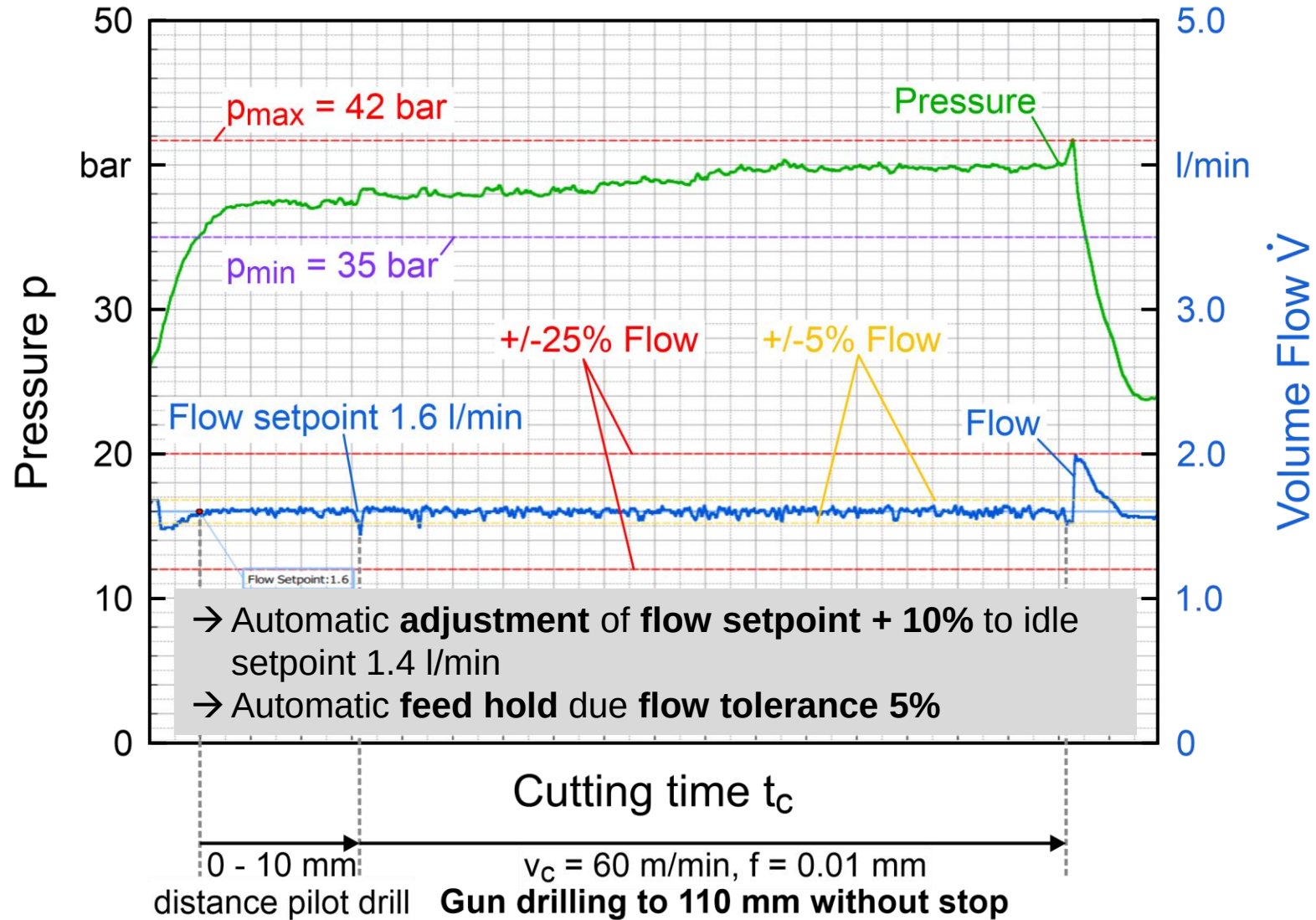
Flow tool

- 2.47 l/min $\rightarrow$ 1.95 l/min

Source: DMG MORI Pfronten, Rolf Kettner

Gun drilling with ACF

Steel 1.6580: Tool Ø 3 mm x 110 mm (36xD)



gunDRILL Process

- + Feed hold after exceeding the setting tolerance (e.g. 5%) of flow
- + **Automatic adjustment of flow**
+ 10% to idle setpoint
(1.4 l/min → 1.6 l/min)

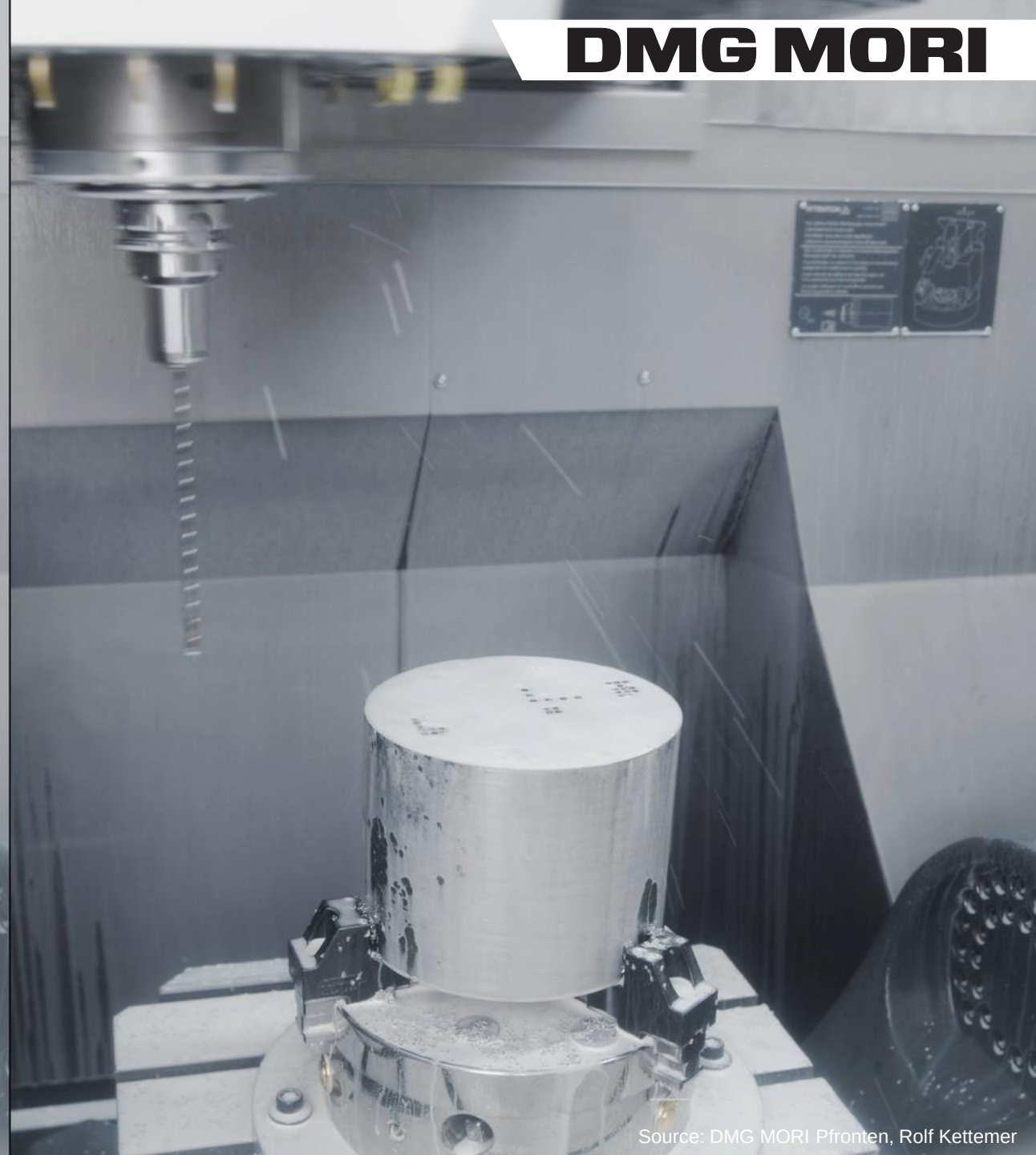
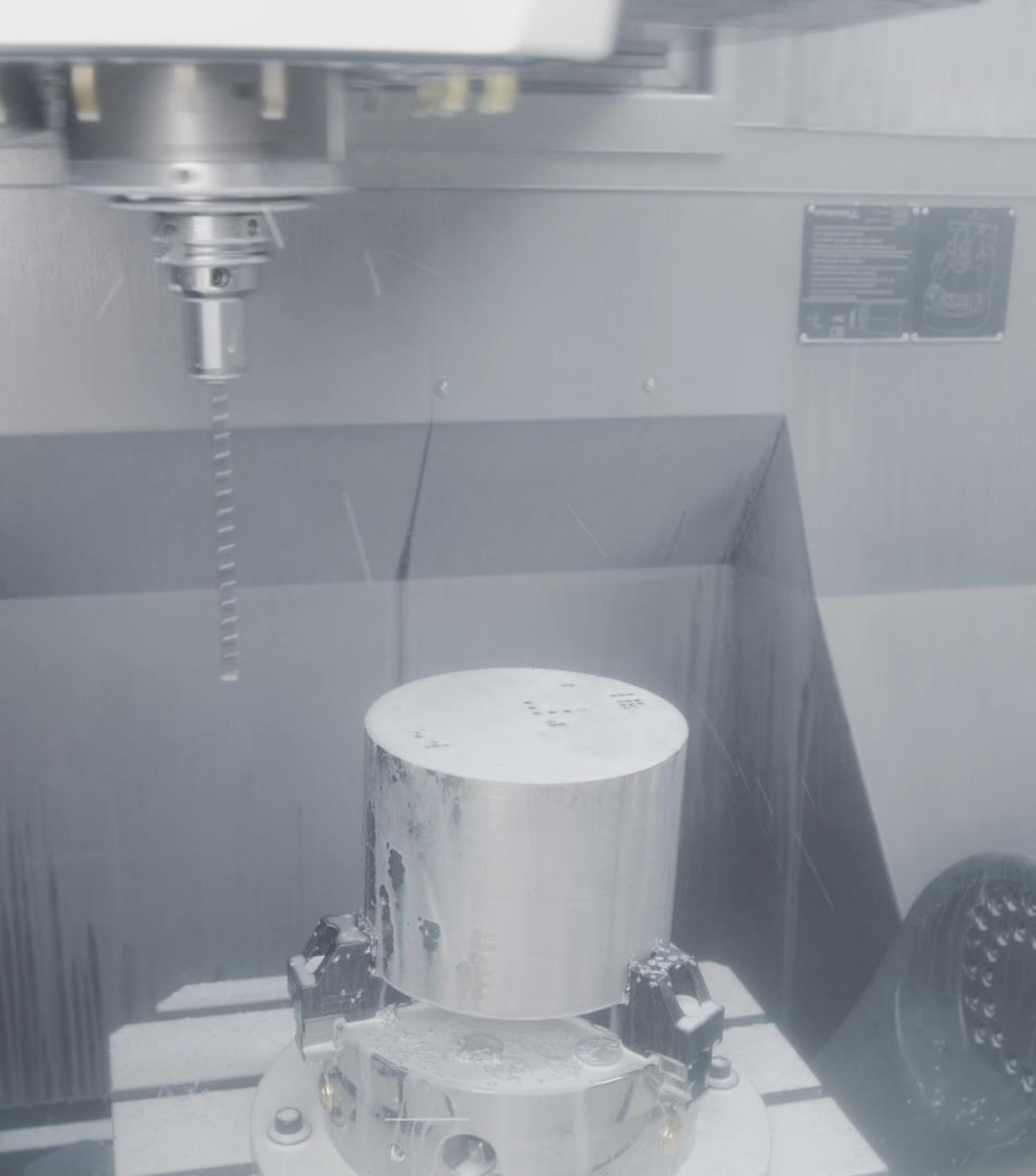
Advantages

- + process stability
- + avoid tool breakage
- + low programming effort

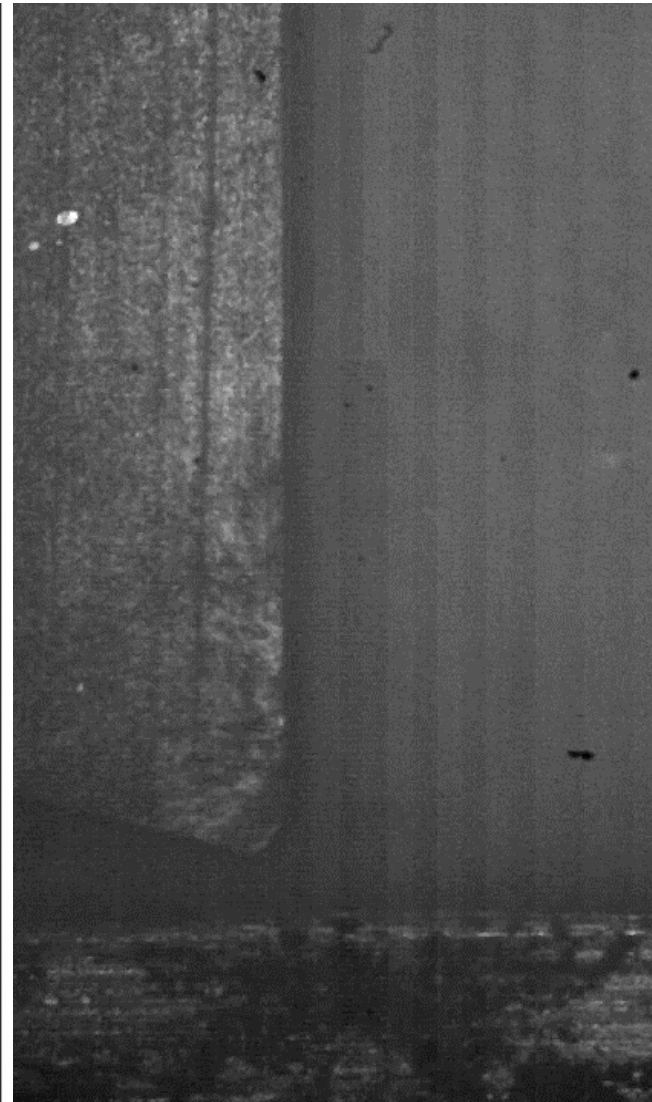
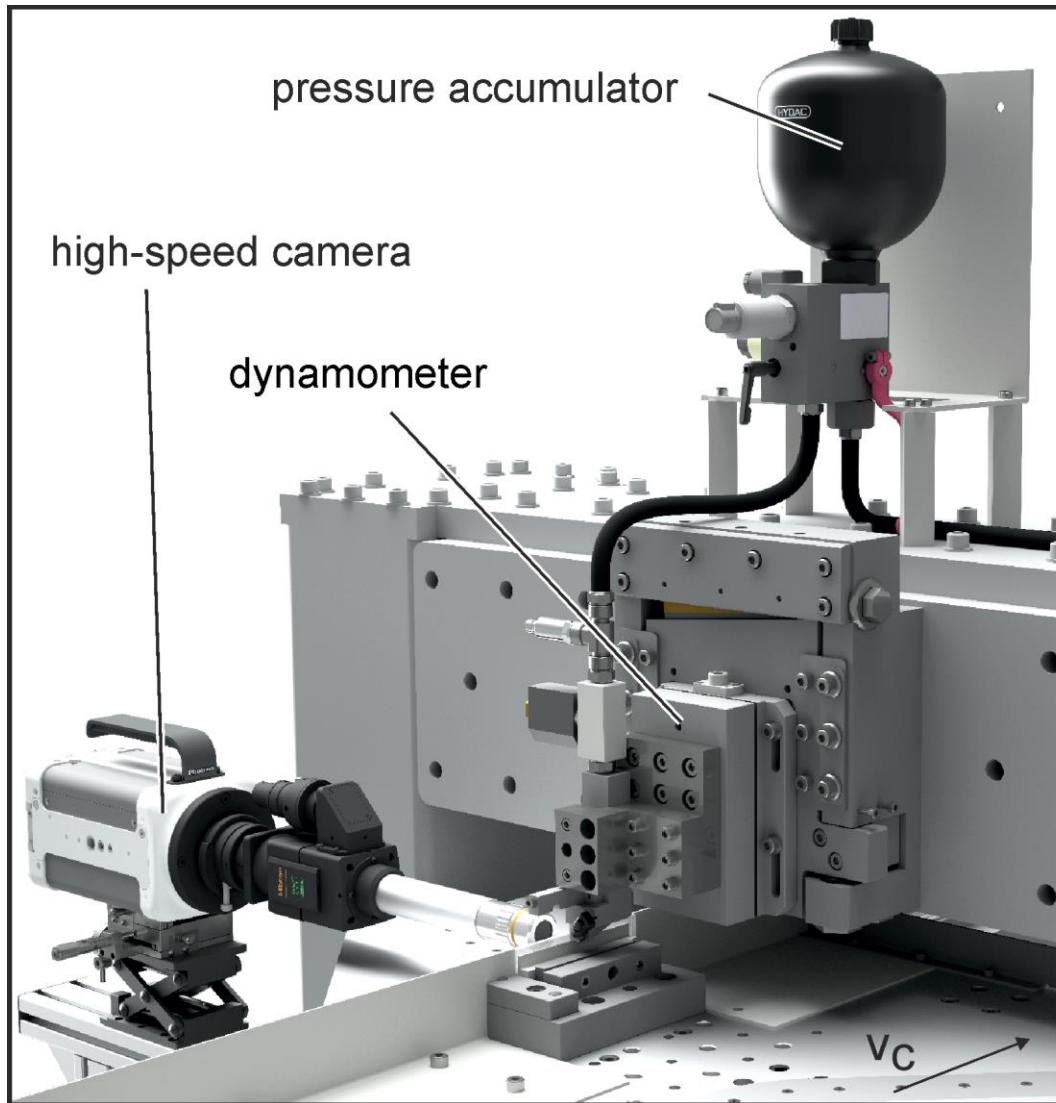
Summary Customer Test

- Vertical drilling
- Using standard cooling lubricant
- 80 bar coolant unit sufficient
- Reduce high tool wear (from 4-6 holes with one driller up to 10)

Source: DMG MORI Pfronten, Rolf Kettner



Basic research: High-speed microcinematography with CF-supply



cutting fluid

type: Emulsion, 11 %
 pressure: $p = 90 \text{ bar}$
 nozzle: $d = 1 \text{ mm}$

tool

tool material: WC-Co/TiAlN
 clearance angle: $\alpha = 15^\circ$
 rake angle: $\gamma = 0^\circ$
 cutting edge: $\bar{S} = 37 \mu\text{m}$

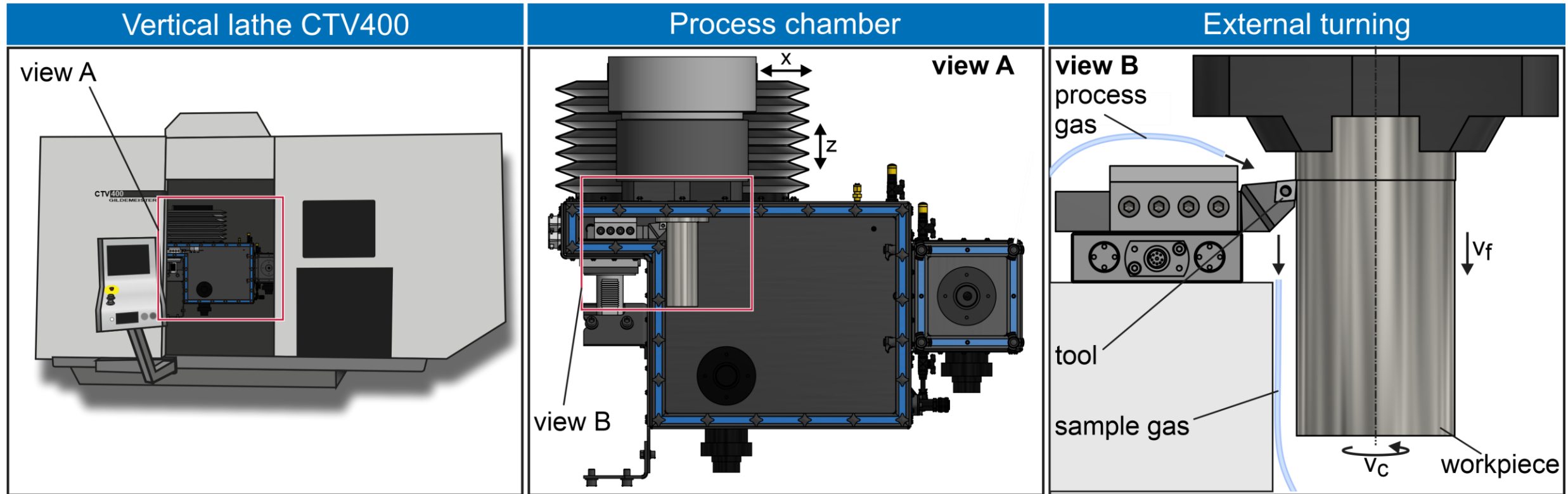
process parameters

cutting speed: $v_c = 350 \text{ m/min}$
 undef. chip thickness: $h = 0.1 \text{ mm}$
 width of undef. chip: $b = 2 \text{ mm}$

workpiece: AISI4140+QT

Sch/122128 © IFW

Idea: Oxygen-free machining (XHV-adequate atmosphere)



Sca/ 105288 © IFW

B. Bergmann, F. Schaper: Study of the effect of oxygen level on tool wear in machining Ti-6Al-4V. CIRP Annals, Volume 73, Issue 1, 2024, Pages 41-44.

Methodology – XHV-adequate atmosphere

reduction of the oxygen content

air

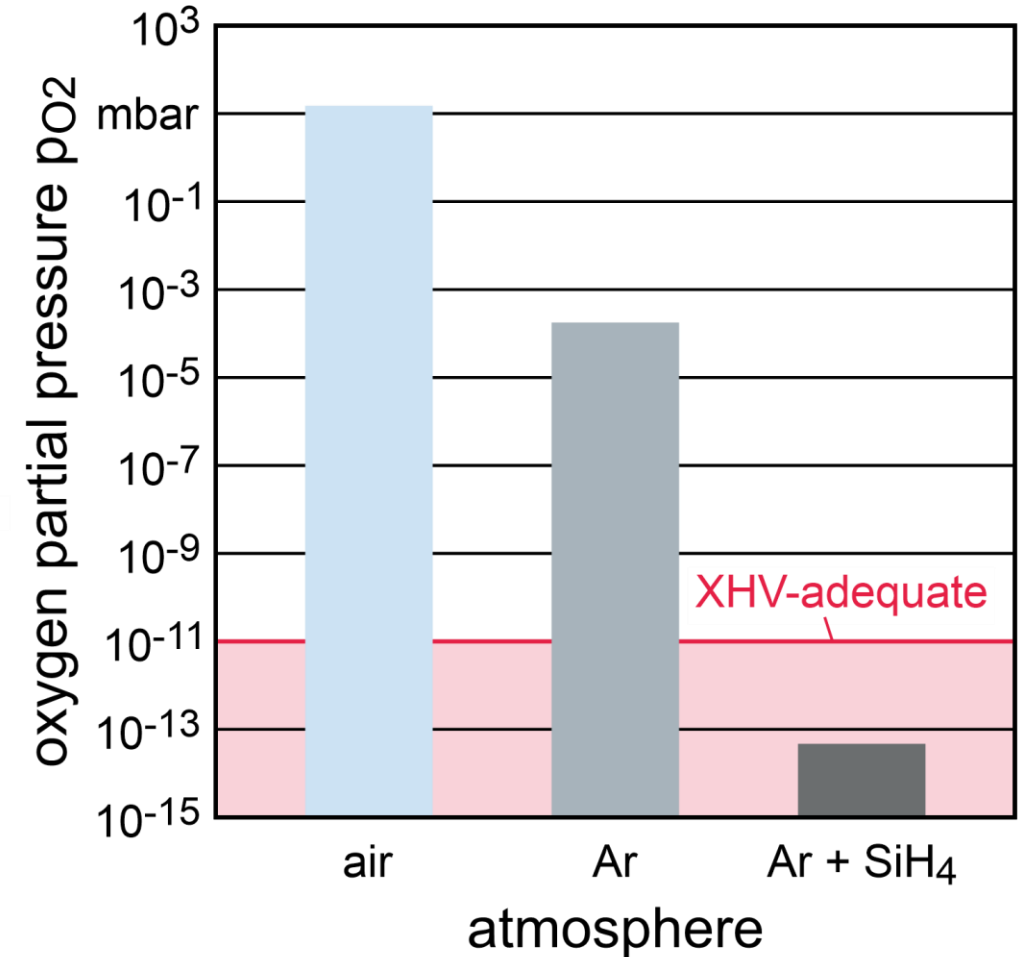
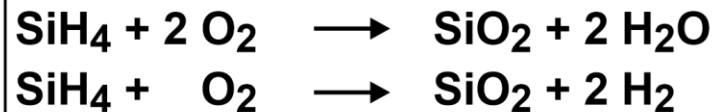
- residual oxygen content = $2.1 \cdot 10^2$ mbar

argon 5.0

- residual oxygen content = $2.0 \cdot 10^{-4}$ mbar
- inert gas purging

argon 5.0 + silane

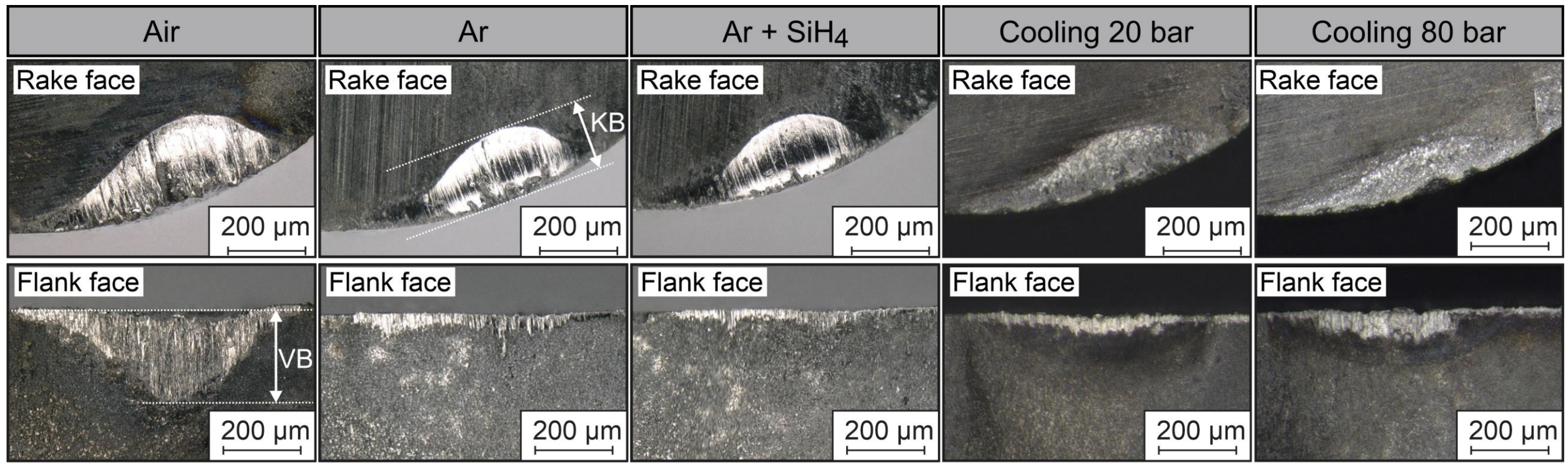
- residual oxygen content $< 1.0 \cdot 10^{-11}$ mbar
- inert gas purging and active gas reaction



Sca/ 105283 © IFW

B. Denkena, B. Bergmann, F. Schaper.: Investigation of chip formation of Ti-6Al-4V in oxygen-free atmosphere. International Journal of Advanced Manufacturing Technology, Volume 124, 2023, Pages 3601-3613.

Tool wear during titanium turning



Tool:

Cutting tool material:
cemented carbide

cutting edge: $\bar{S} = 6\text{ }\mu\text{m}$

rake angle: $\gamma = -6^\circ$

clearance angle: $\alpha = 6^\circ$

Atmospheres:

air (213 mbar O₂)

Ar ($5 \cdot 10^{-3}$ mbar O₂)

Ar + SiH₄ ($<1 \cdot 10^{-17}$ mbar O₂)

Material: Ti-6Al-4V

Cutting fluid: XTREME CUT 290G, 8 %

Process:

external turning

cutting speed

feed

depth of cut

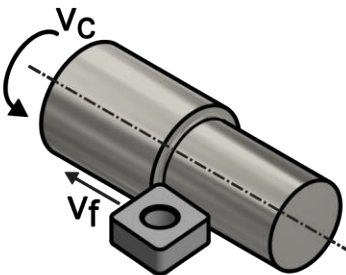
cutting time

$v_c = 120\text{ m/min}$

$f = 0.25\text{ mm}$

$a_p = 0.15\text{ mm}$

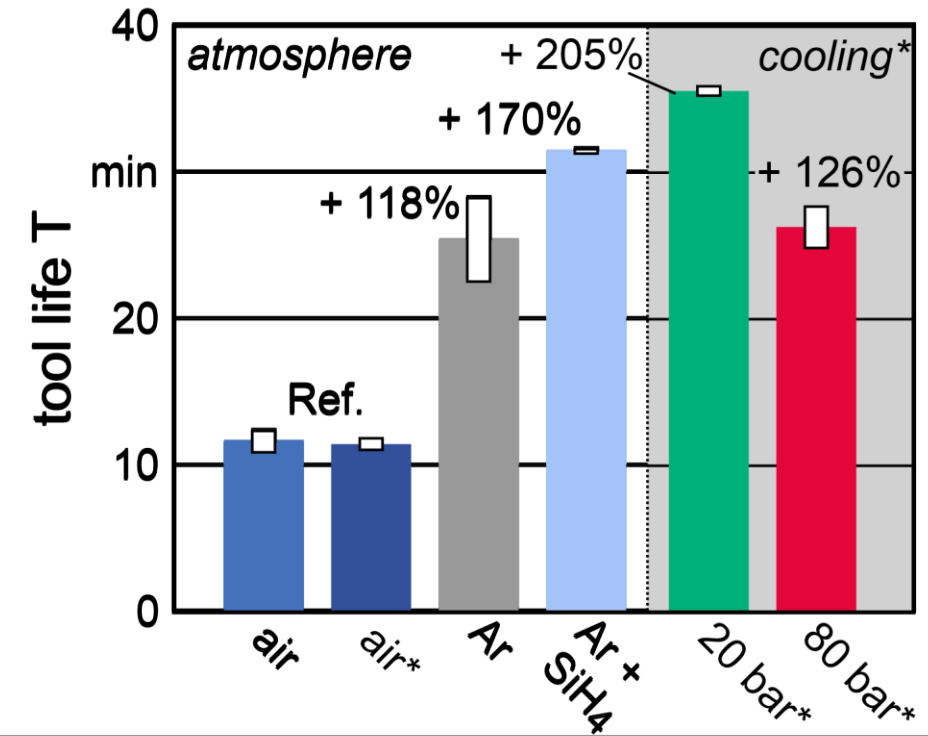
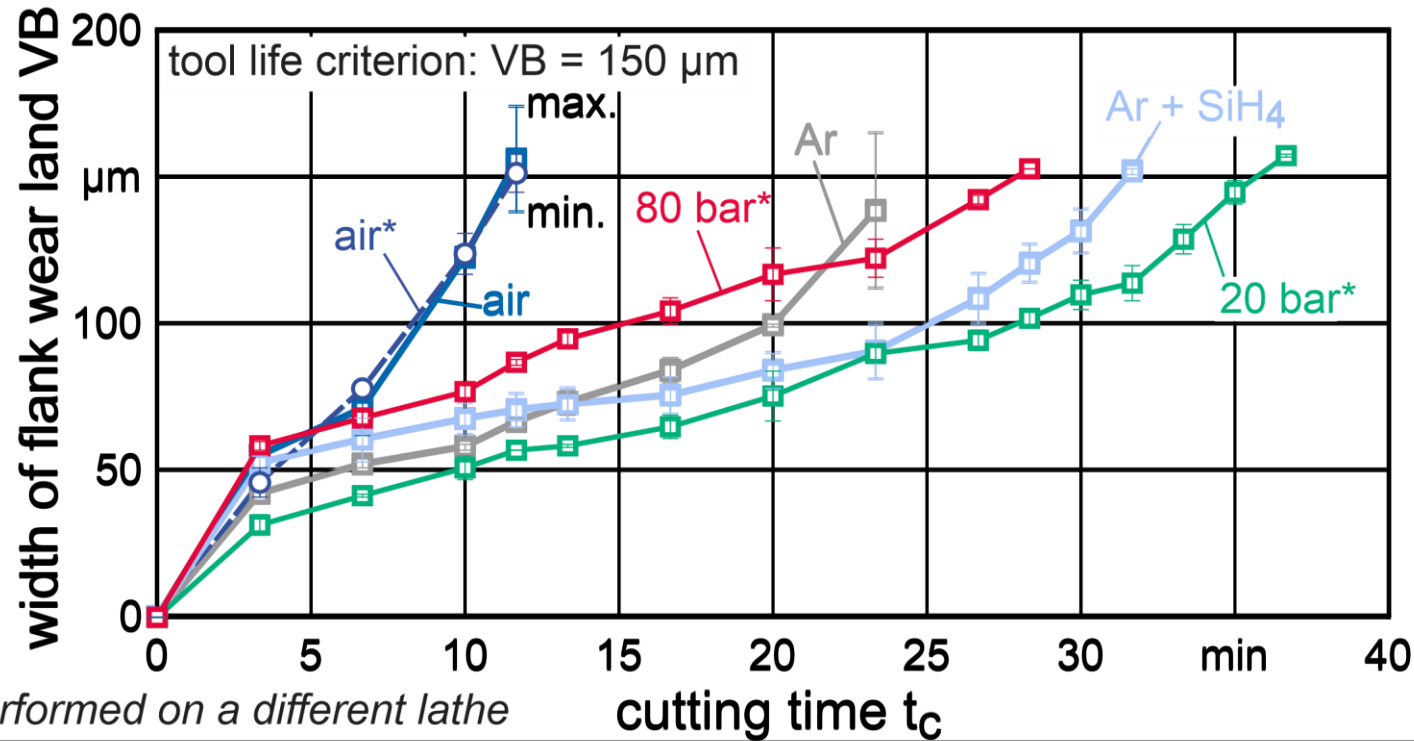
$t_c = 11.5\text{ min}$



Sca/105323 © IFW

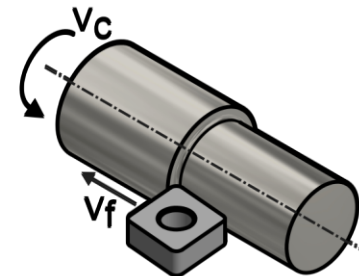
B. Bergmann, F. Schaper: Study of the effect of oxygen level on tool wear in machining Ti-6Al-4V. CIRP Annals, Volume 73, Issue 1, 2024, Pages 41-44.

Tool wear during titanium turning



Tool:	Atmospheres:	Process:
Cutting tool material:	air (213 mbar O ₂)	external turning
cemented carbide	Ar ($5 \cdot 10^{-3}$ mbar O ₂)	cutting speed
cutting edge: $\bar{S} = 6 \mu m$	Ar + SiH ₄ ($< 1 \cdot 10^{-17}$ mbar O ₂)	feed
rake angle: $\gamma = -6^\circ$	Material: Ti-6Al-4V	depth of cut
clearance angle: $\alpha = 6^\circ$	Cutting fluid: XTREME CUT 290G, 8 %	cutting time

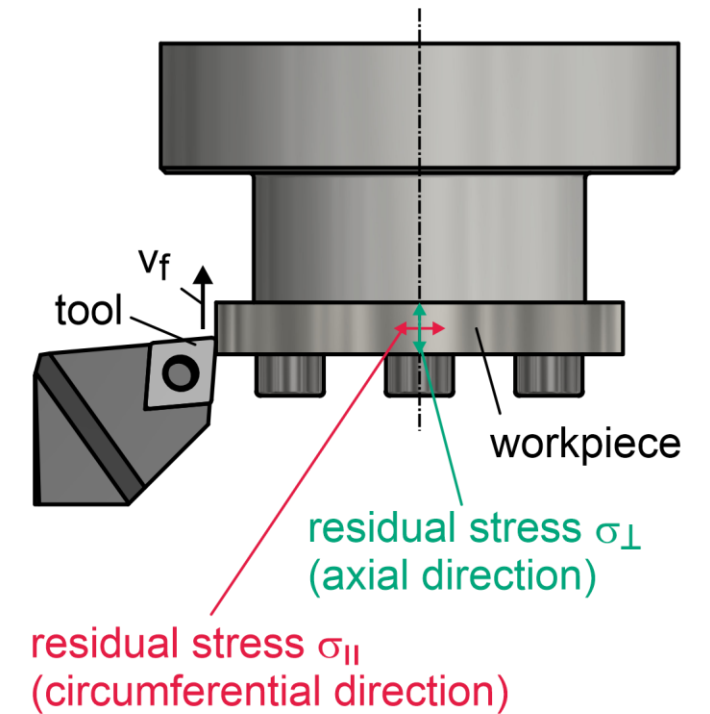
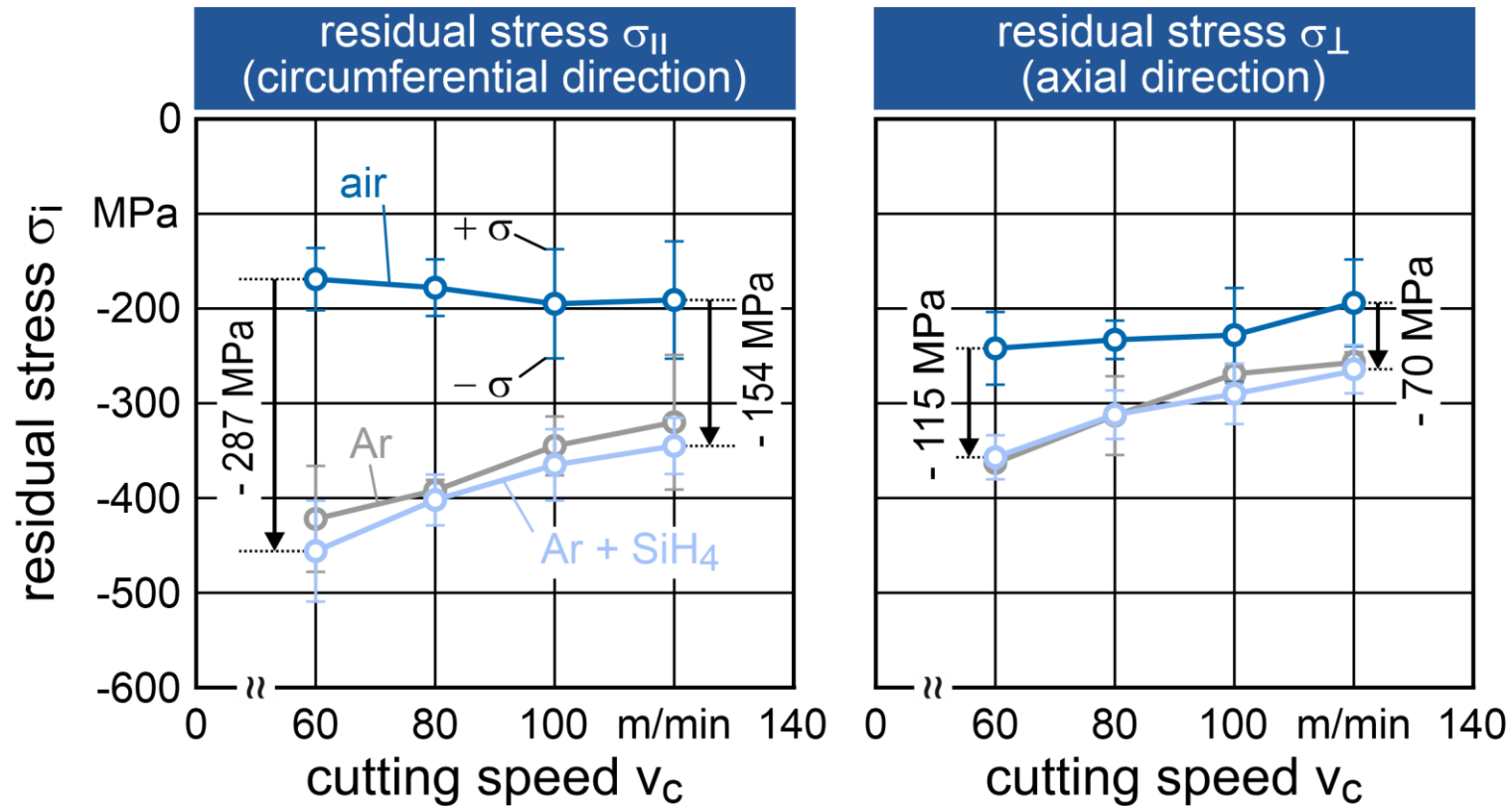
$v_c = 120 \text{ m/min}$
 $f = 0.25 \text{ mm}$
 $a_p = 0.15 \text{ mm}$
 $t_c = 11.5 \text{ min}$



Sca/105324a© IFW

B. Bergmann, F. Schaper: Study of the effect of oxygen level on tool wear in machining Ti-6Al-4V. CIRP Annals, Volume 73, Issue 1, 2024, Pages 41-44.

Influence of the atmosphere on residual stresses in workpiece subsurface



Atmospheres

air	(213	mbar O ₂)
Ar	(5·10 ⁻³	mbar O ₂)
Ar + SiH ₄	(<1·10 ⁻¹⁷	mbar O ₂)

Material: Ti-6Al-4V

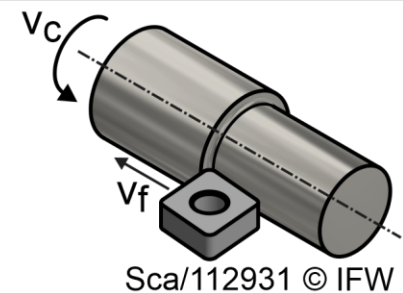
Tool

CNMA 120412
cemented carbide, uncoated
94 m.-% WC, 6 m.-% Co

Process: external turning

Process parameters

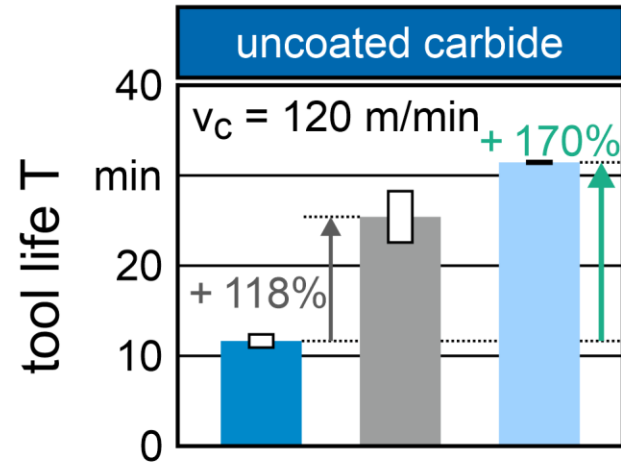
cutting speed: $v_c = \text{var.}$
feed: $f = 0.2 \text{ mm}$
depth of cut: $a_p = 0.15 \text{ mm}$



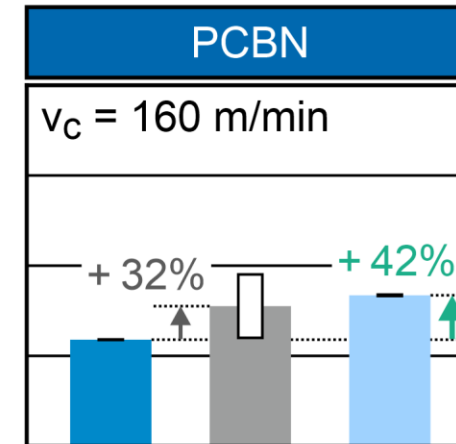
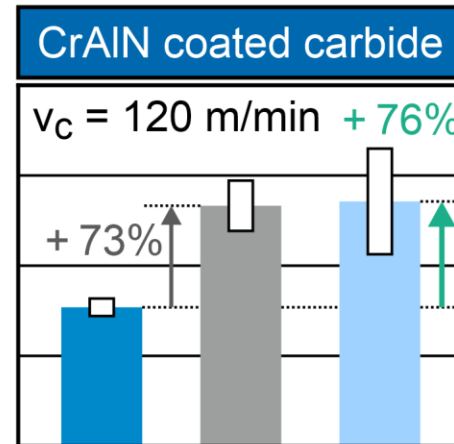
Transfer to other cutting tool materials and workpiece materials

tool life criterion: $VB = 150 \mu\text{m}$

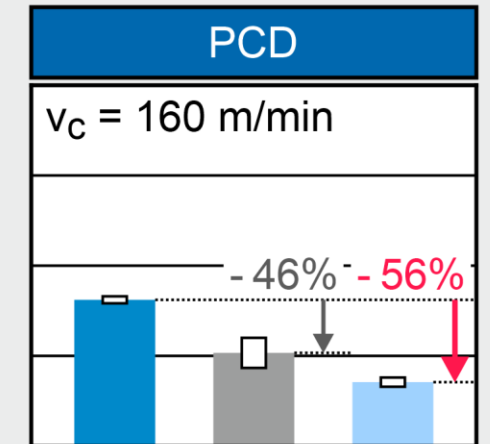
variation of the
cutting tool material
material: Ti-6Al-4V



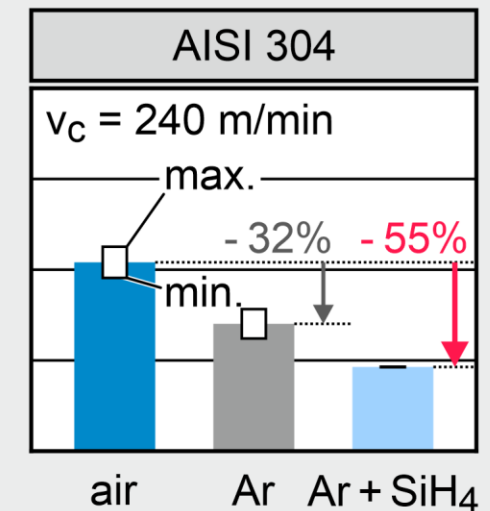
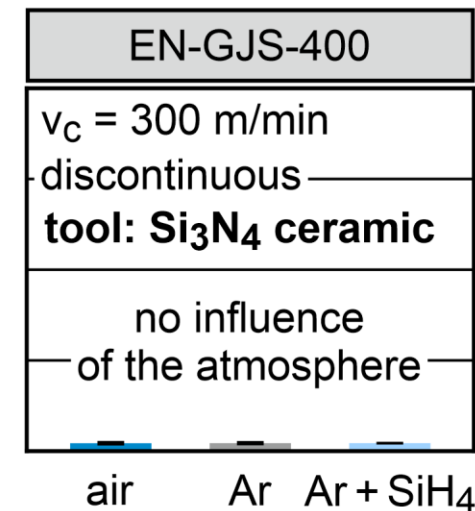
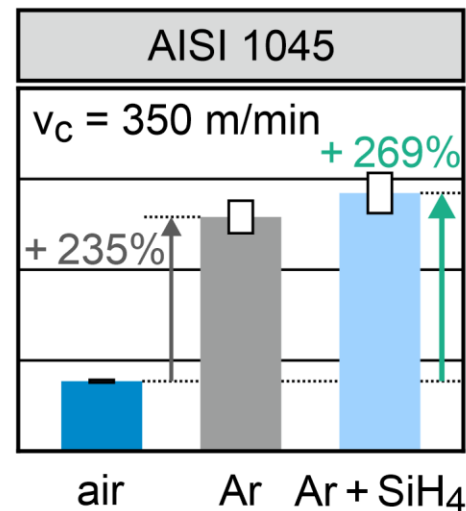
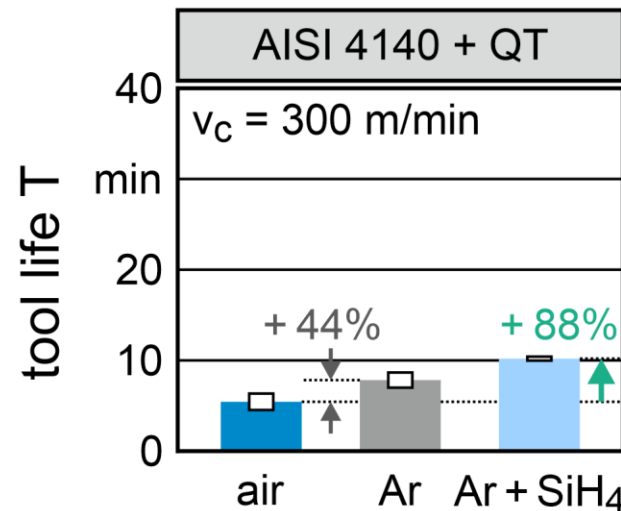
increase in tool life



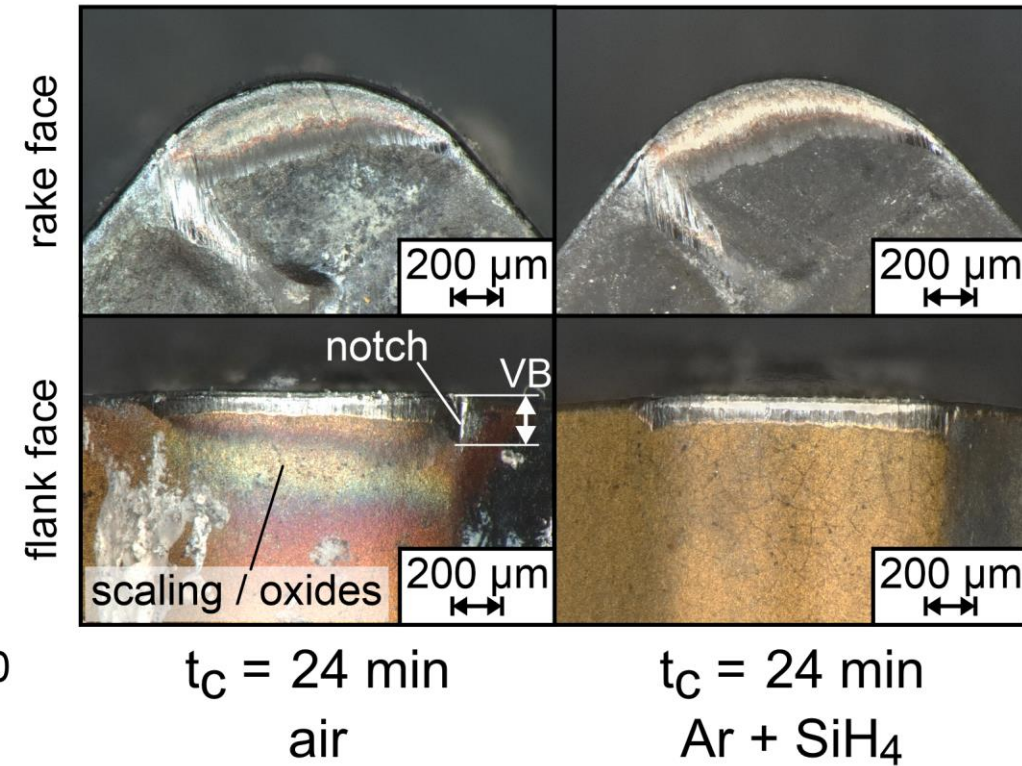
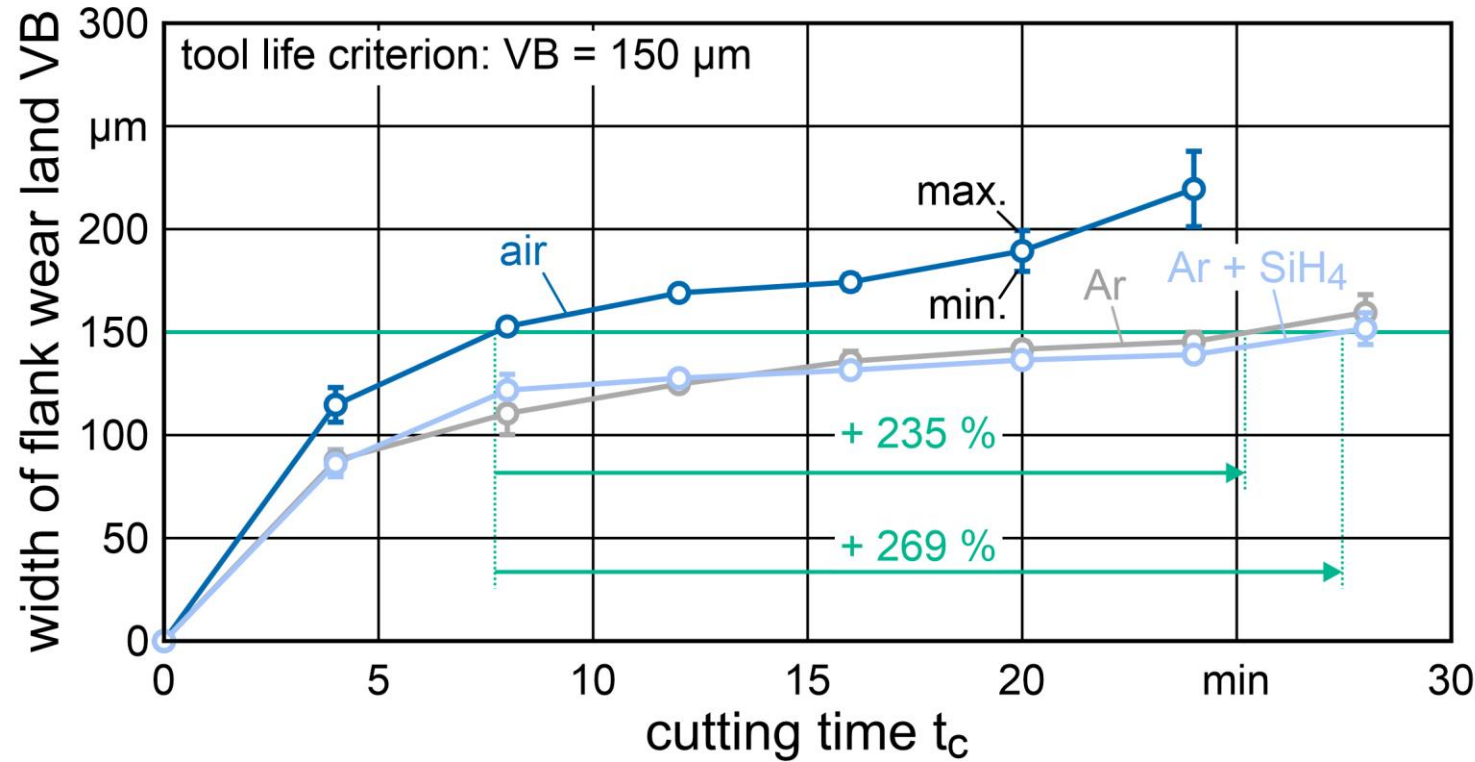
decrease in tool life



variation of the
material
tool: coated carbide



Tool wear during turning of AISI 1045



atmospheres

air	(213	mbar O_2)
Ar	($5 \cdot 10^{-3}$	mbar O_2)
Ar + SiH_4	(< $1 \cdot 10^{-17}$	mbar O_2)

workpiece: AISI 1045

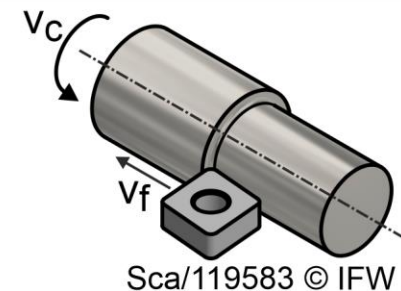
tool

Kennametal
CNMG120408FV
KCP25C

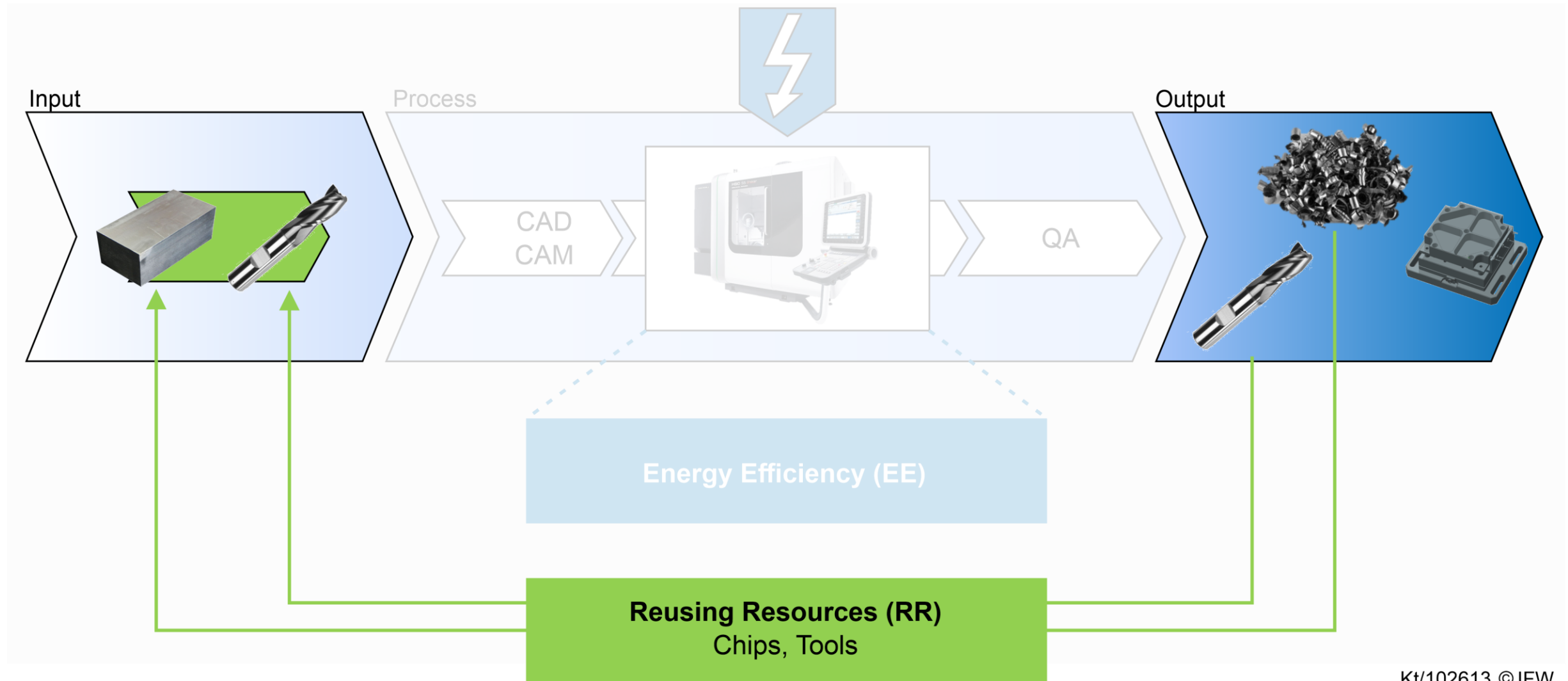
process: external turning

process parameters

cutting speed: $v_c = 350 \text{ m/min}$
feed: $f = 0.12 \text{ mm}$
depth of cut: $a_p = 0.8 \text{ mm}$

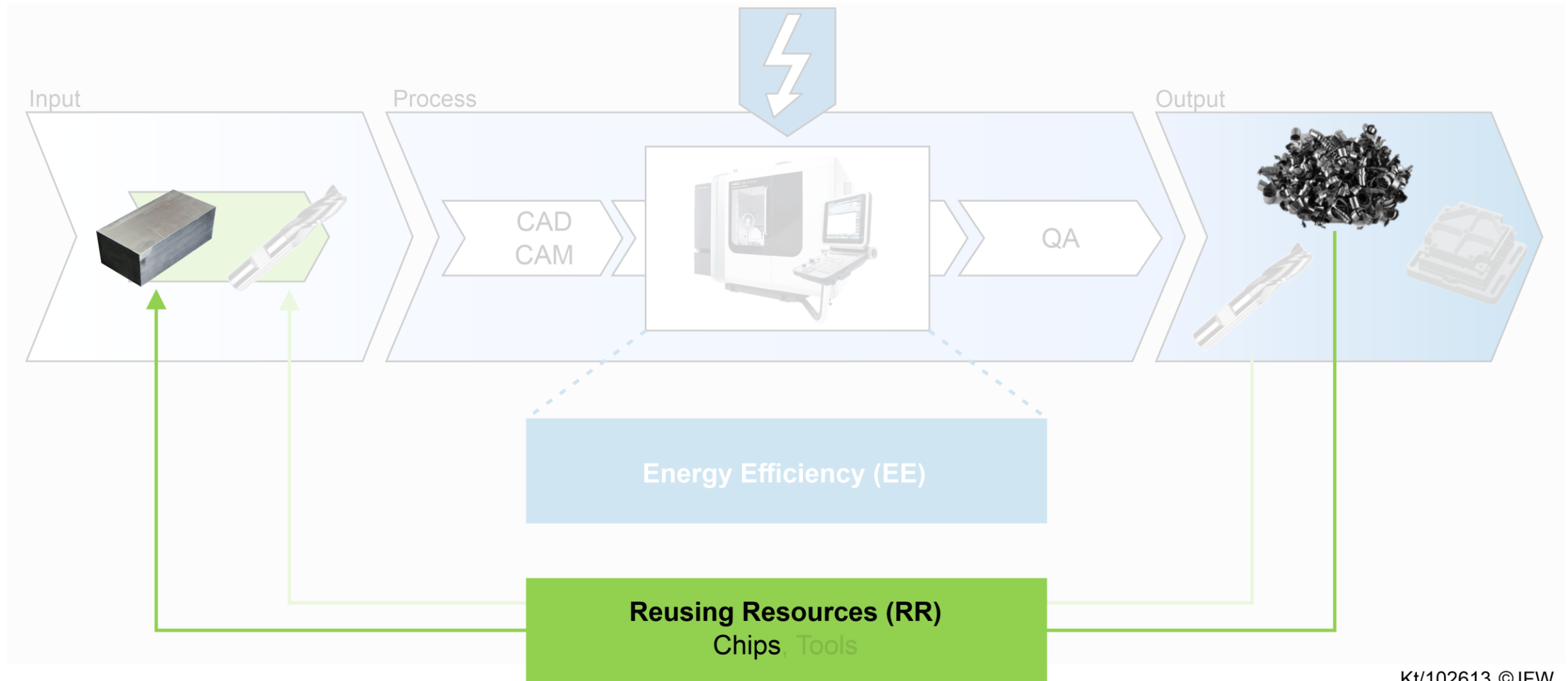


Outline of presentation



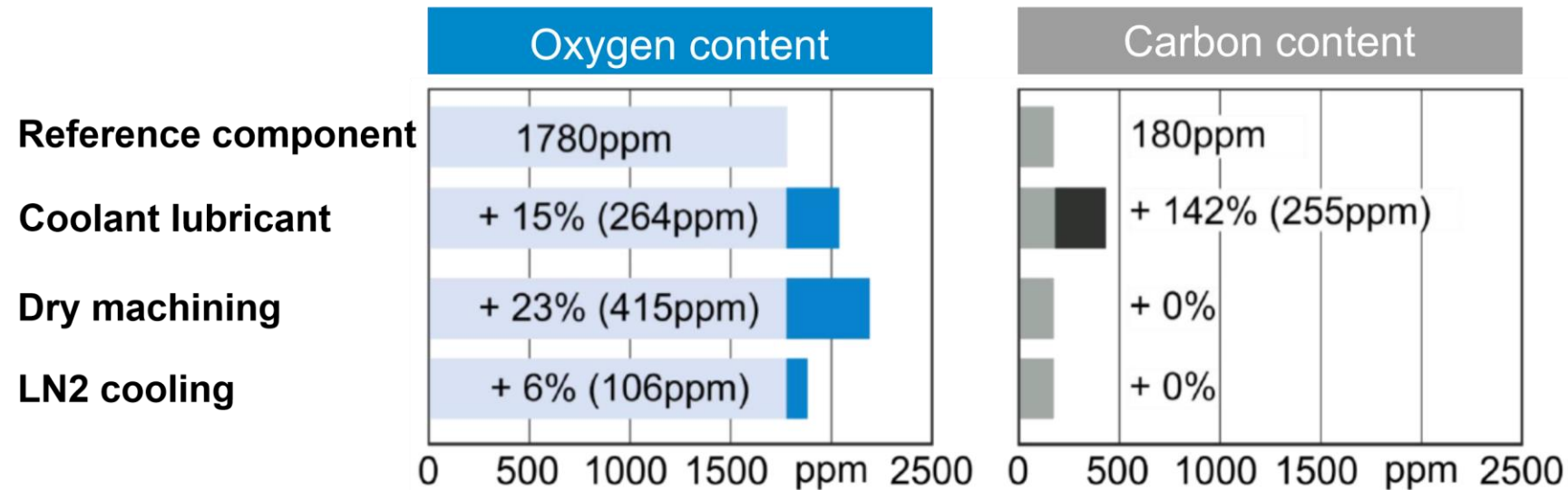
Kt/102613 © IFW

Outline of presentation



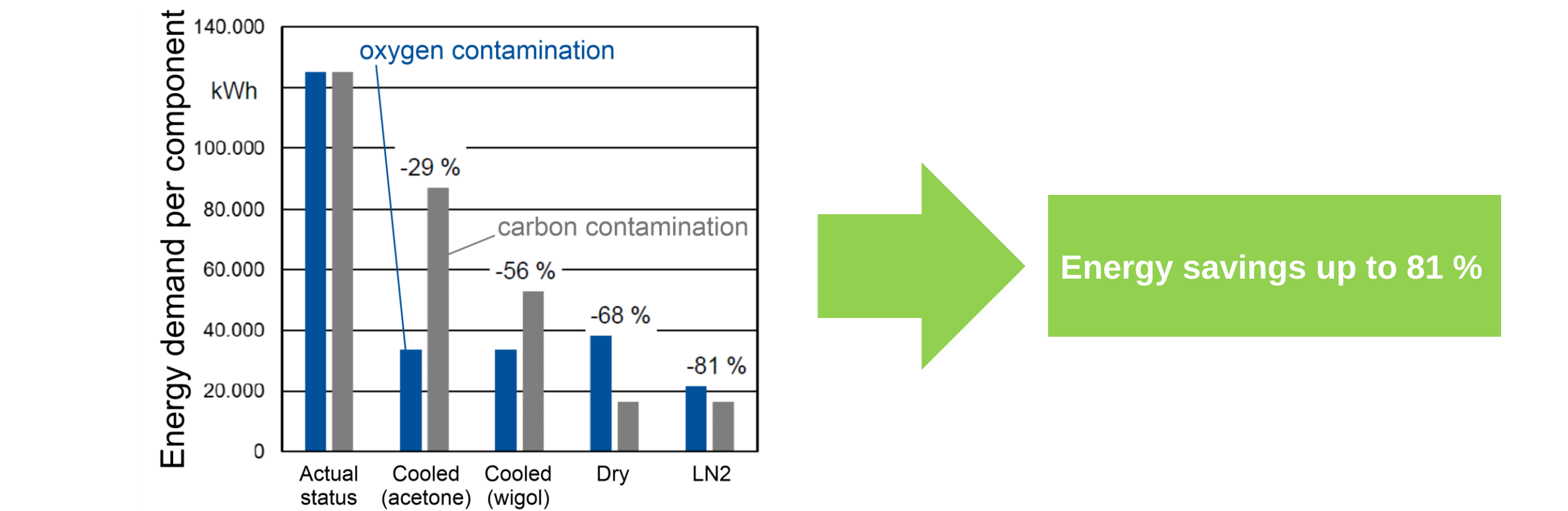
Kt/102613 © IFW

Titanium chip contamination in aircraft manufacturing (milling)



B. Denkena, M.-A. Dittrich, S. Jacob: Energy efficiency in machining of aircraft components. Procedia CIRP, Volume 48, 2016, Pages 479-482.

Titanium chip contamination in aircraft manufacturing (milling)



Recycling rate	O ₂	-	85 %	85 %	78 %	93 %
	C	-	34 %	65 %	100 %	100 %

B. Denkena, M.-A. Dittrich, S. Jacob: Energy efficiency in machining of aircraft components. Procedia CIRP, Volume 48, 2016, Pages 479-482.

Conventional and new approach for titanium chips recycling

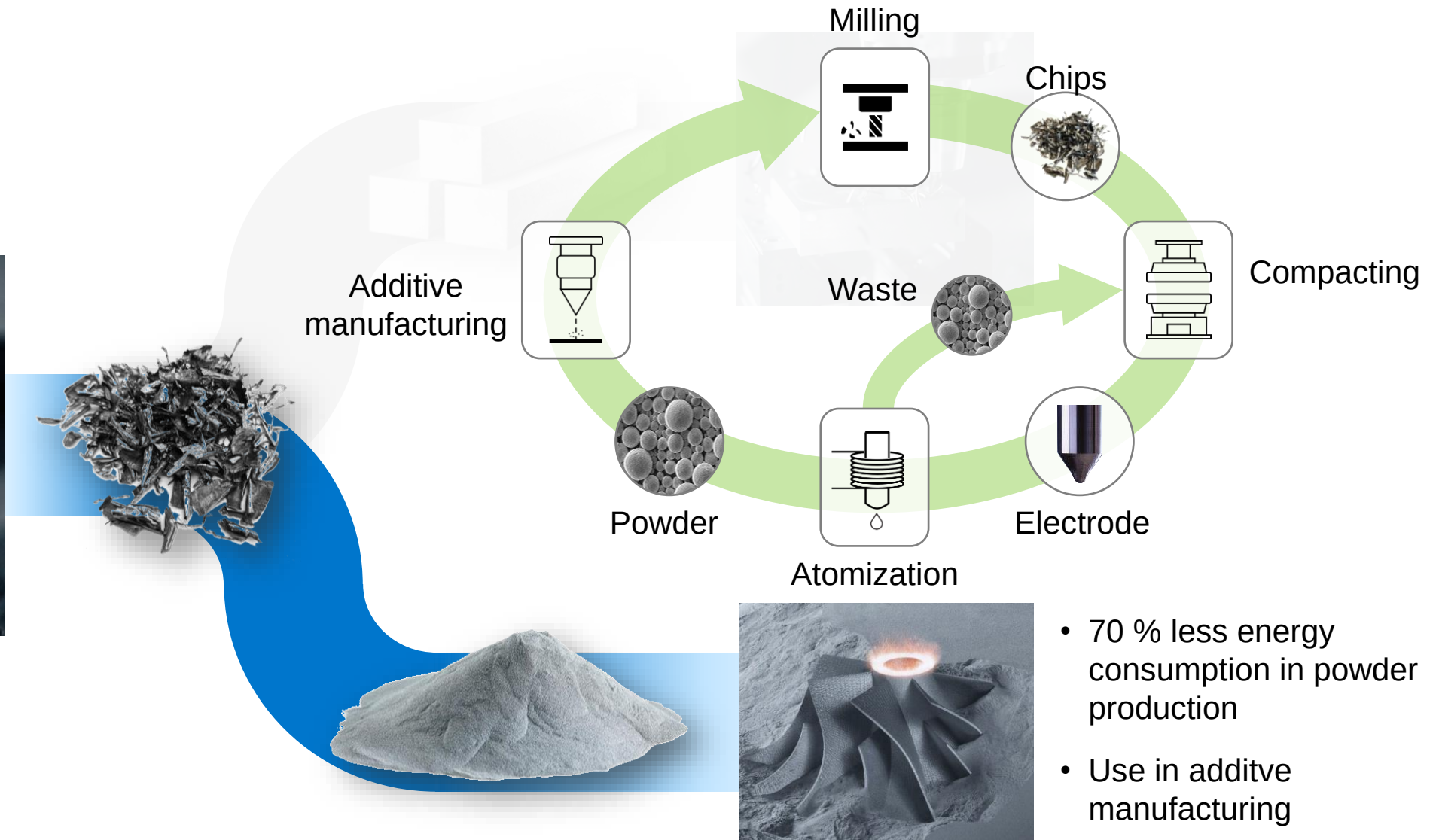
Return I Route



- Energy-intensive melting and remelting necessary
- No energy savings compared to primary material

Conventional and new approach for titanium chips recycling

Return II Route

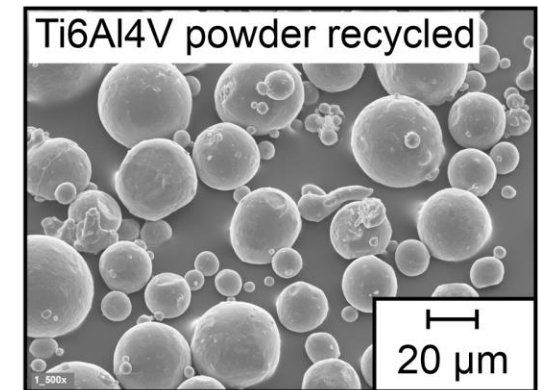
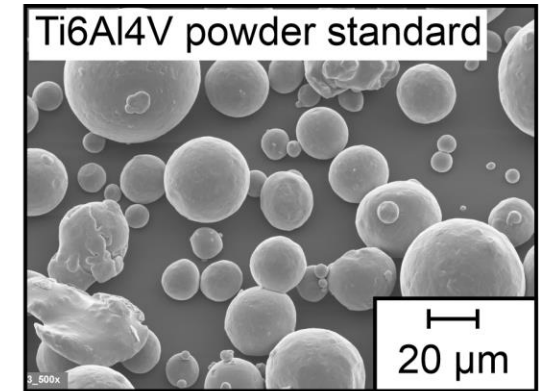
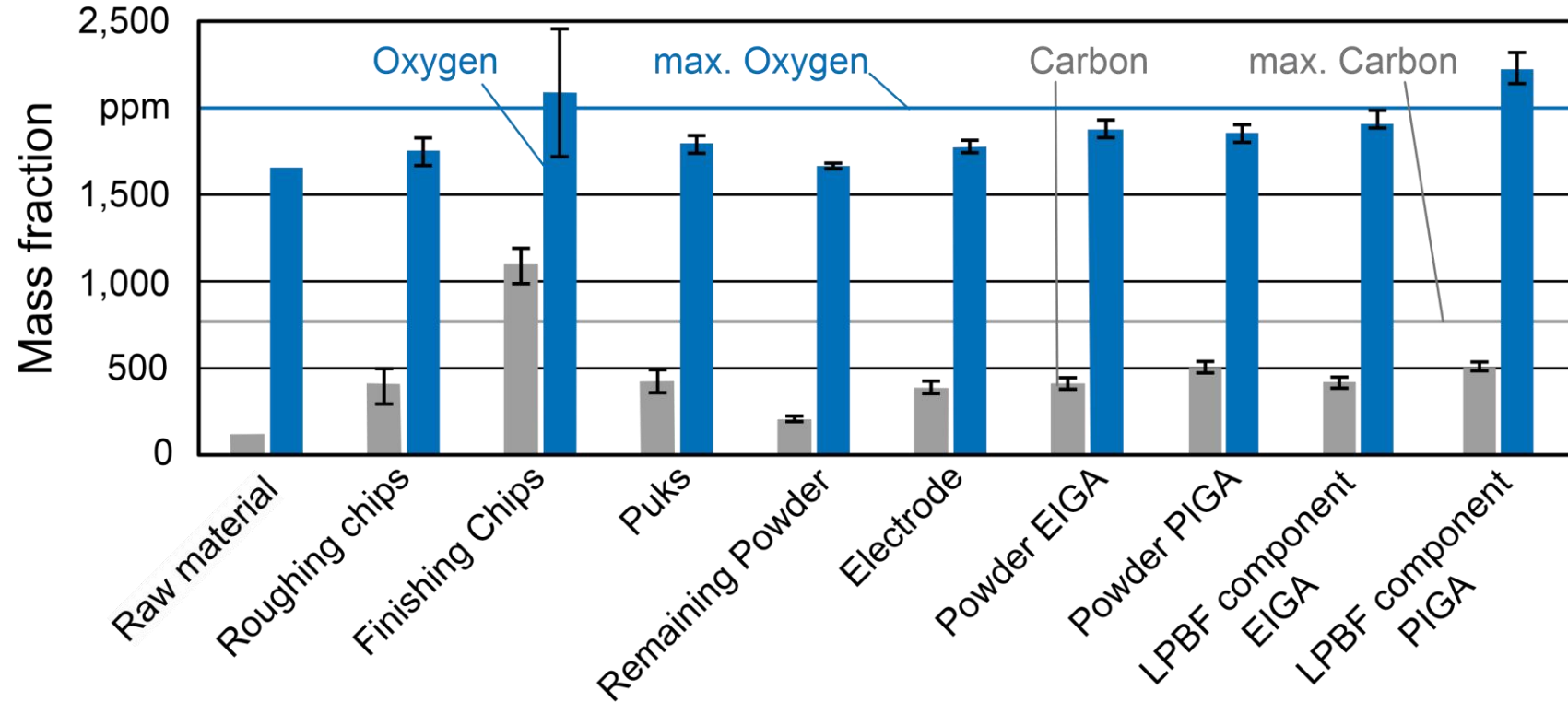


- 70 % less energy consumption in powder production
- Use in additive manufacturing

Kt/102601 © IFW

B. Denkena, M.-A. Dittrich, V. Suntharakumaran, S. Kettelmann: Recycling of Ti-6Al-4V chips for closed-loop manufacturing. CIRP Annals, Volume 73, Issue 1, 2024, Pages 73-76.

Maintaining Grade 5 standards along the process route



Oxygen analysis:

Non-dispersive infrared absorption, Leco TC 500

Carbon analysis:

Carbon incineration, Leco CS 200

Temperature: 2,300 °C

Atmosphere: 4.8 % Oxygen

Imaging:

Scanning electron microscope, SEM

Zeiss EVO 60VP

Manufacturing process:

Electrode Induction Gas Atomising, EIGA

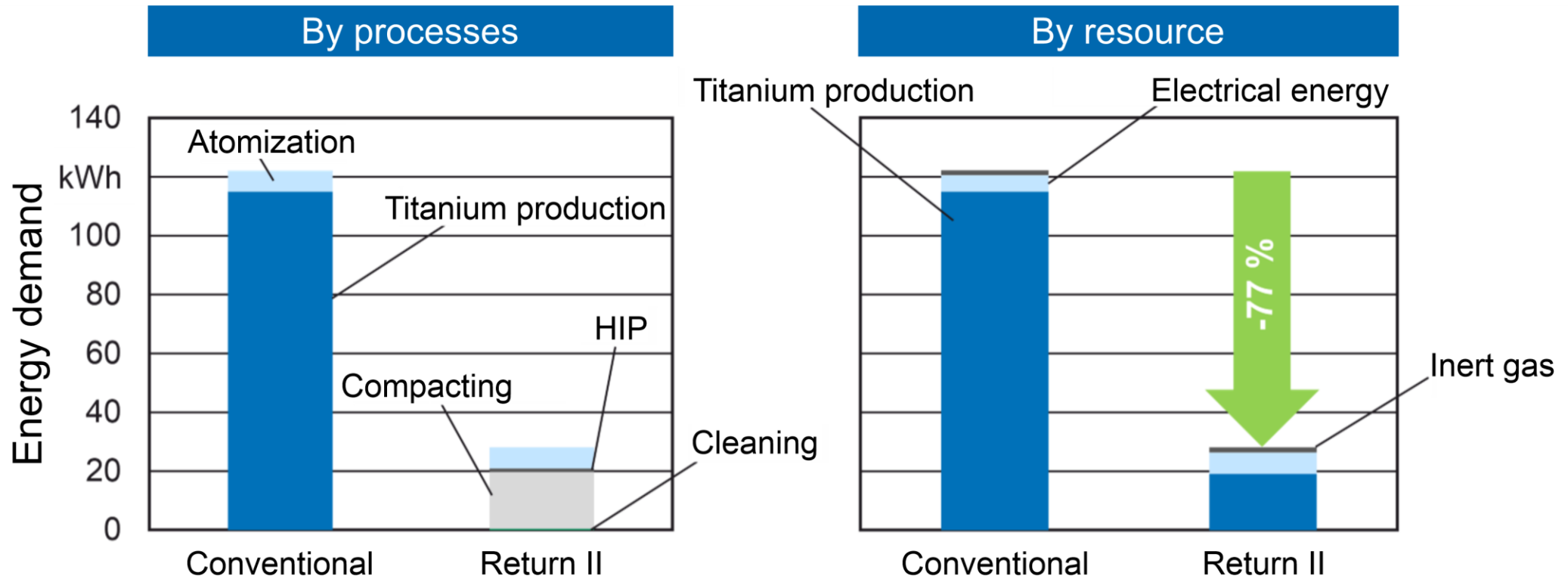
Powder size: 20 - 60 µm



Mat / 114892 © IFW

B. Denkena, M.-A. Dittich, V. Suntharakumaran, S. Kettelmann: Recycling of Ti-6Al-4V chips for closed-loop manufacturing. CIRP Annals, Volume 73, Issue 1, 2024, Pages 73-76.

Energy consumption in titanium production based on chip recycling

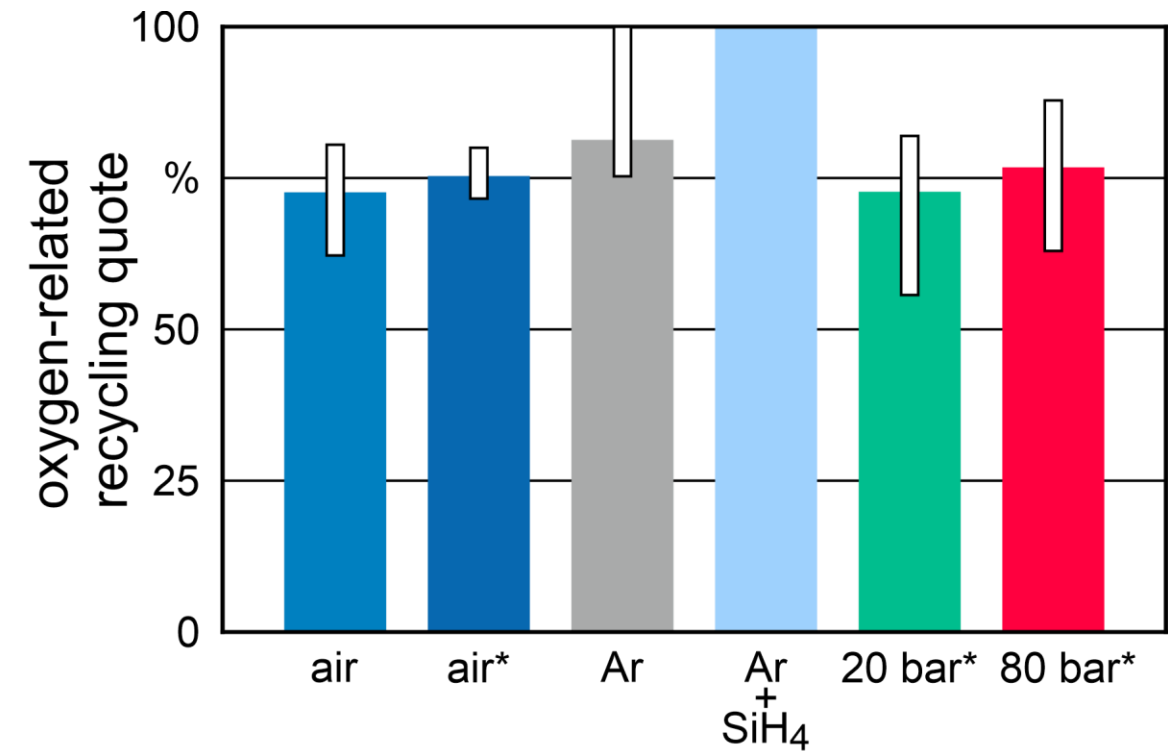
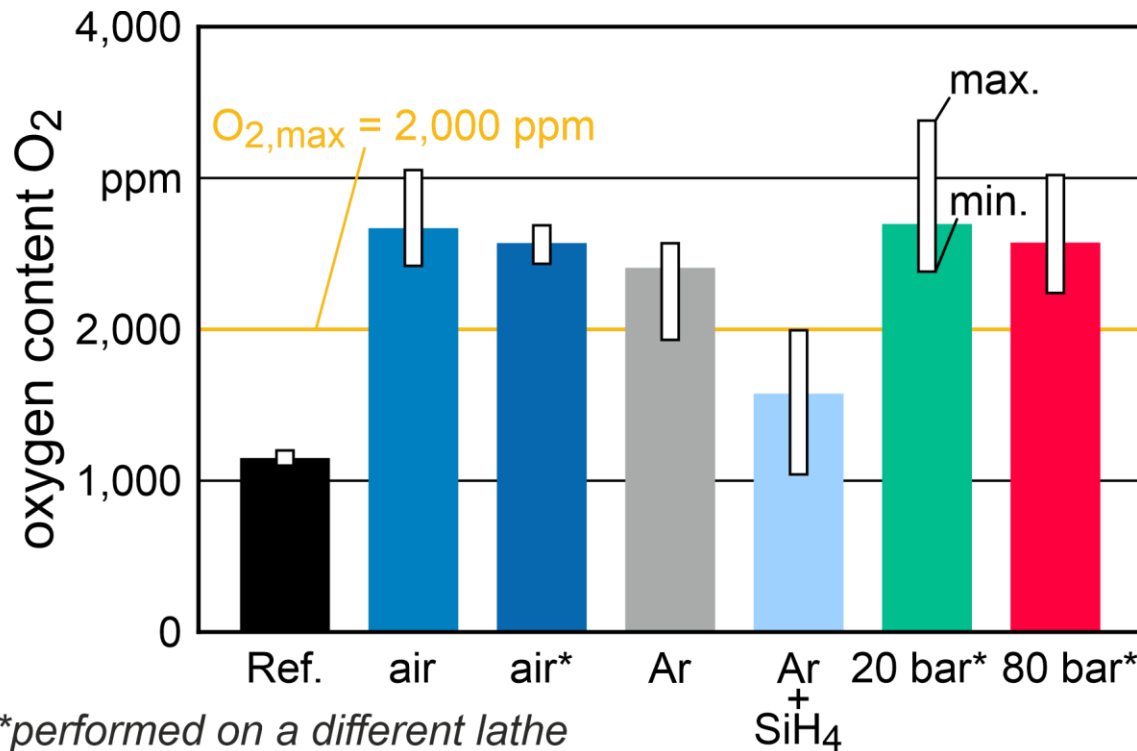


Process steps: Cleaning, pressing, electrode manufacturing, hot isostatic pressing (HIP), atomization
 Atomization process: EIGA (Electrode Induction Melting Inert Gas Atomization)
 Calculation base: Produced powder per kg
 Indicator: Cumulative energy demand

KI/102600 © IFW

B. Denkena, M.-A. Dittrich, V. Suntharakumaran, S. Kettelmann: Recycling of Ti-6Al-4V chips for closed-loop manufacturing. CIRP Annals, Volume 73, Issue 1, 2024, Pages 73-76.

Recycling of the chips – Oxygen content of chips in turning



Tool:

Cutting tool material:
cemented carbide
cutting edge: $\bar{S} = 6 \mu\text{m}$
rake angle: $\gamma = -6^\circ$
clearance angle: $\alpha = 6^\circ$

Atmospheres:

air (213 mbar O₂)
Ar ($5 \cdot 10^{-3}$ mbar O₂)
Ar + SiH₄ ($< 1 \cdot 10^{-17}$ mbar O₂)

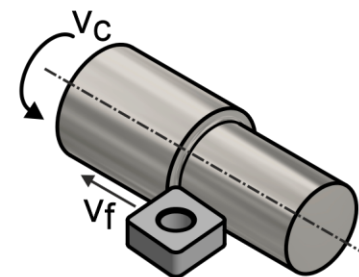
Material: Ti-6Al-4V

Cutting fluid: XTREME CUT 290G, 8 %

Process:

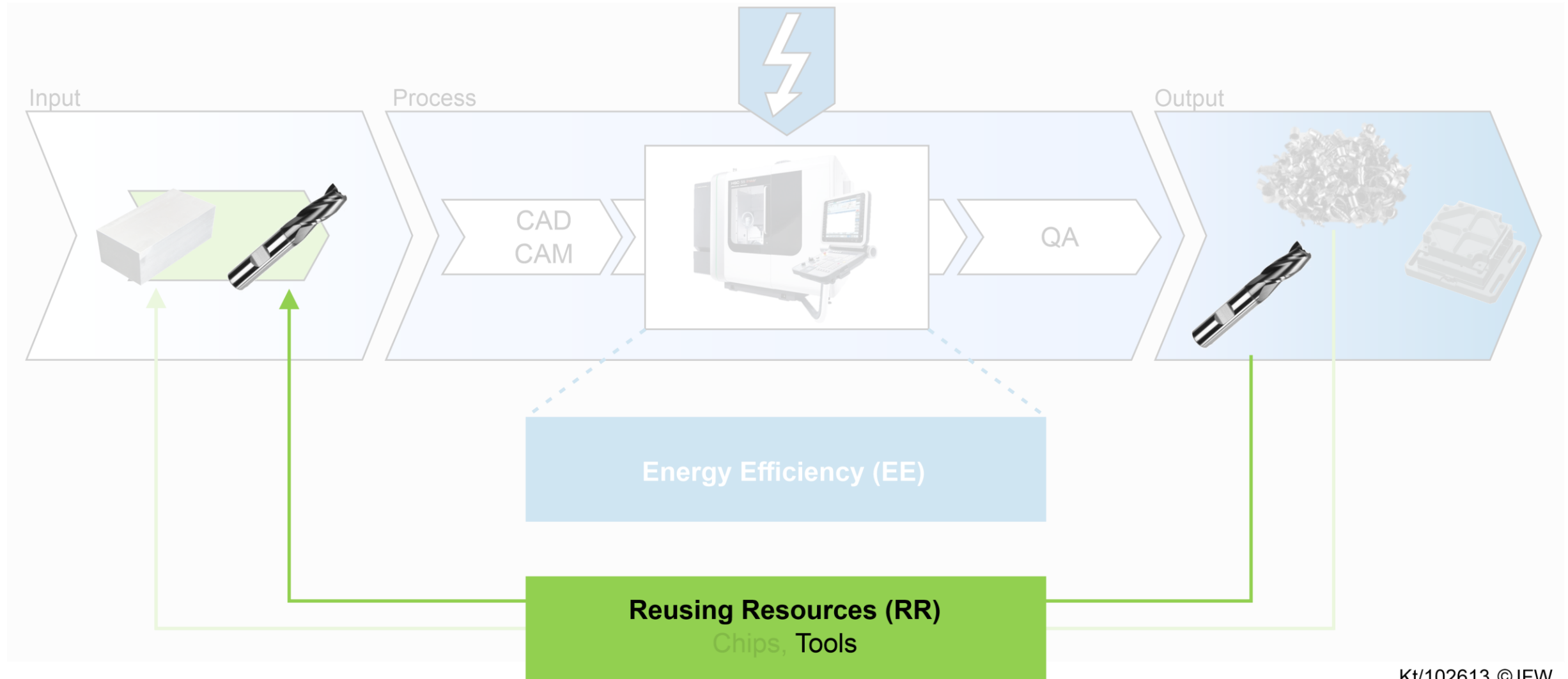
external turning
cutting speed
feed
depth of cut
cutting time

$v_c = 120 \text{ m/min}$
 $f = 0.25 \text{ mm}$
 $a_p = 0.15 \text{ mm}$
 $t_c = 0.5 \text{ min}$



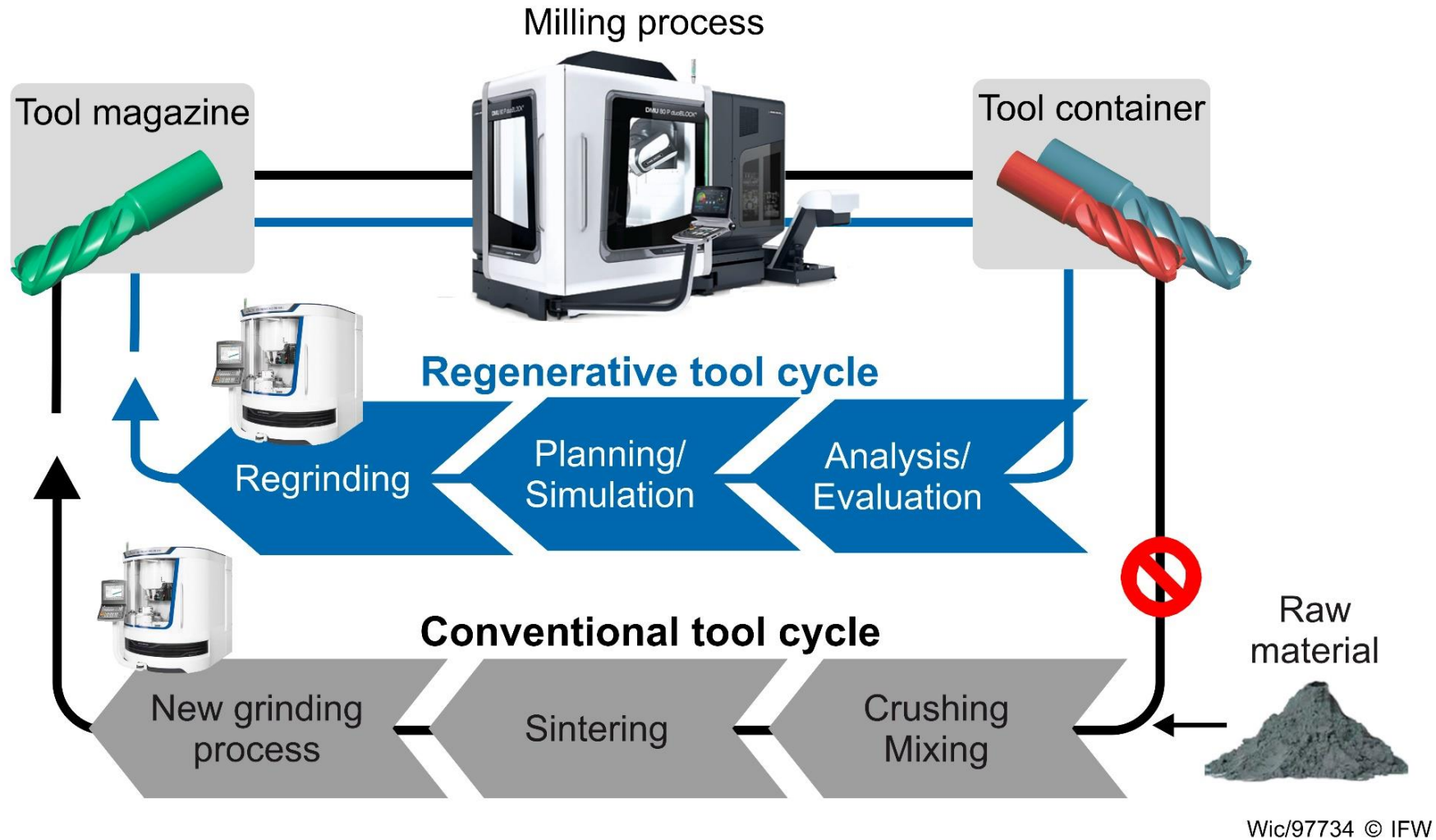
Sca/119590 © IFW

Outline of presentation



Kt/102613 © IFW

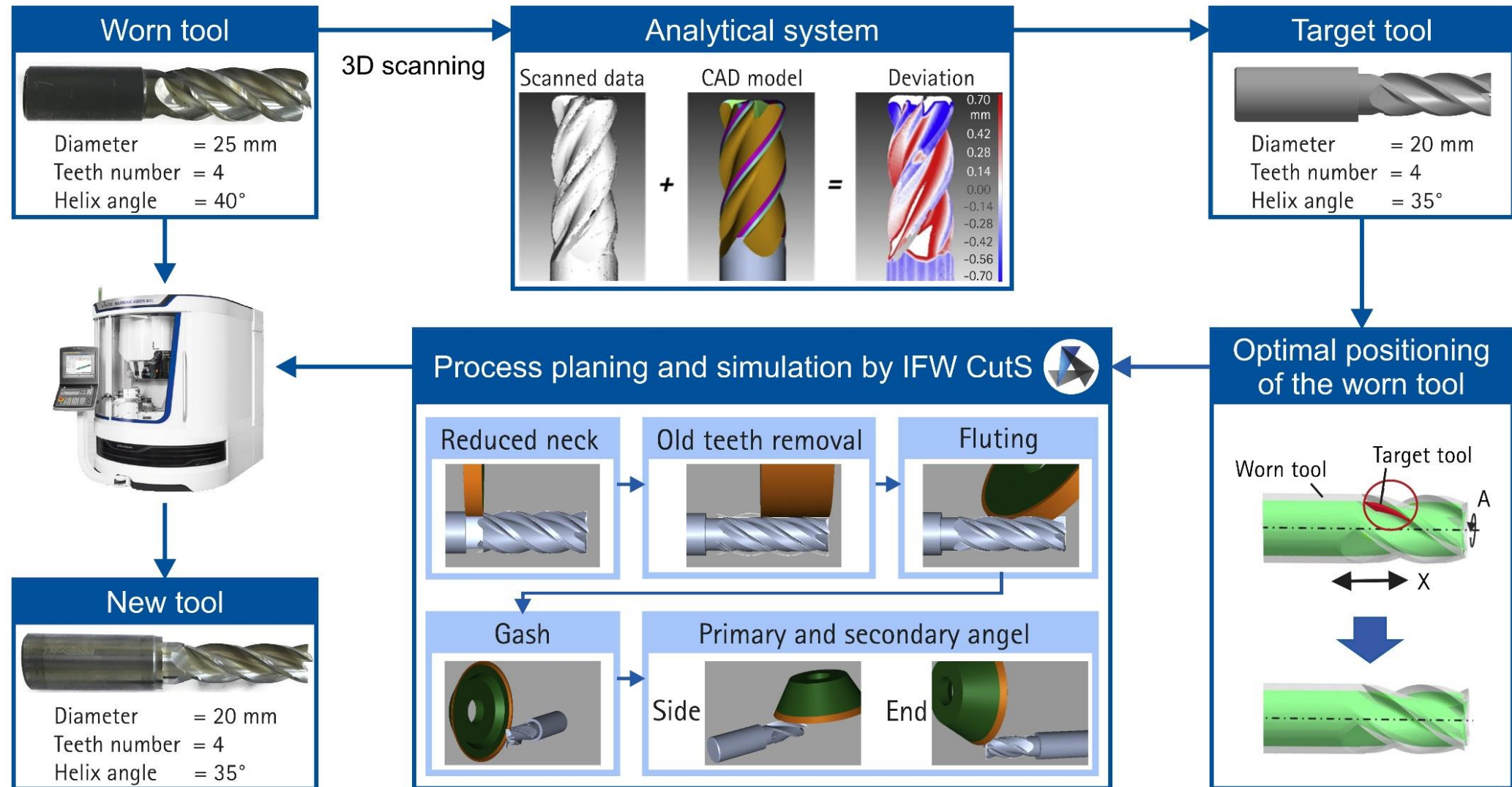
Approach for regrinding of used tools



B. Denkena, M.-A. Dittrich, Y. Liu: A new process chain for recycling of cemented carbide milling tools. Prod. Eng. Res. Dev., Volume 12, 2018, Pages 547–553.

M. Wichmann, B. Denkena, M.-A. Dittrich, S. Friebe: Ressourceneffizientes Umschleifen verschlissener VHM-Werkzeuge. WT Werkstattechnik, Volume 111, Issue 6, 2021, Pages 430-434.

Method for regrinding of used tools

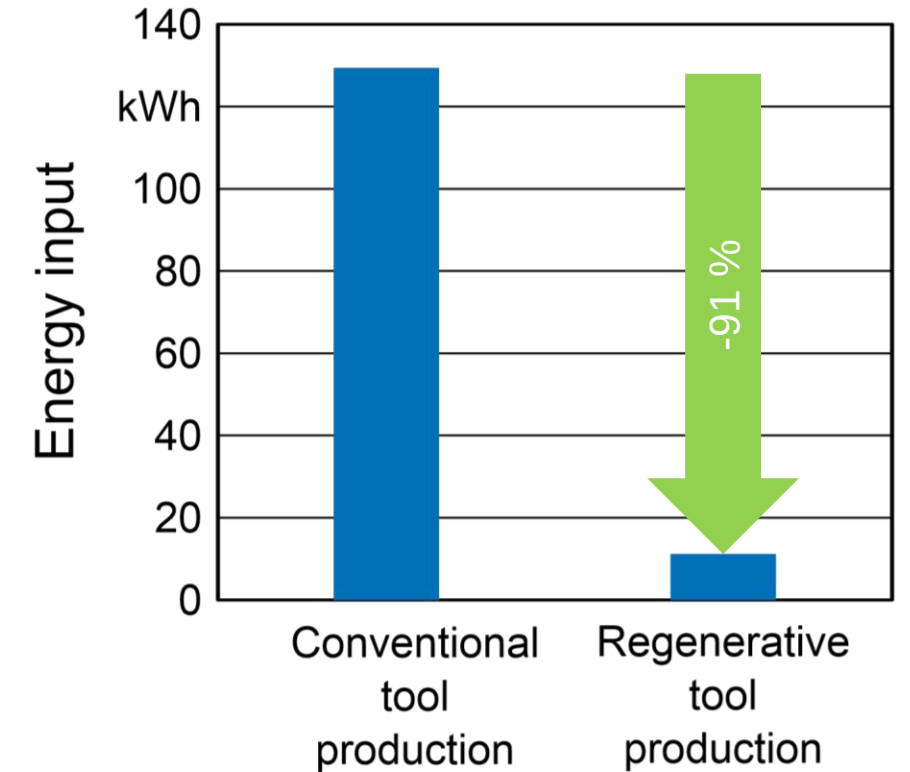
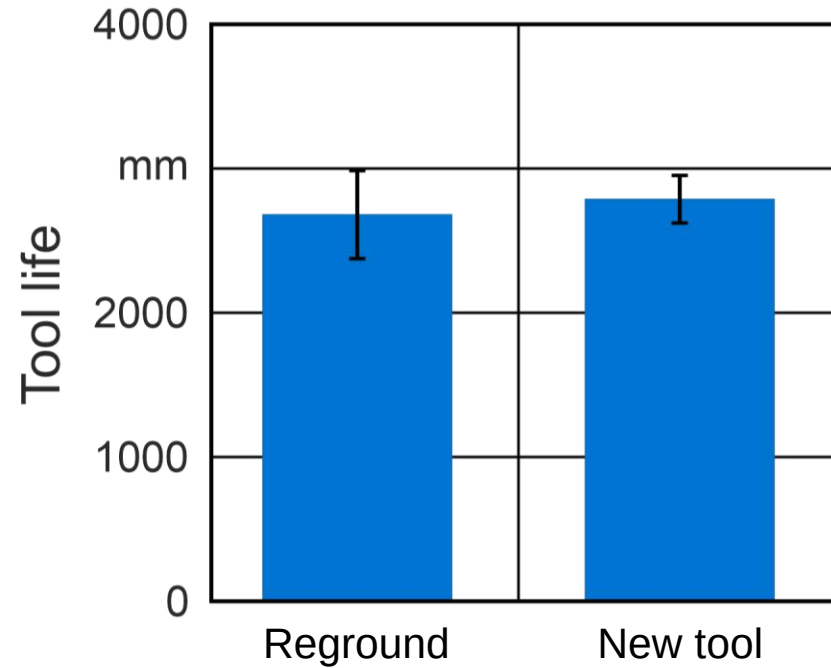


Wic/97737 © IFW

B. Denkena, M.-A. Dittrich, Y. Liu: A new process chain for recycling of cemented carbide milling tools. Prod. Eng. Res. Devel., Volume 12, 2018, Pages 547–553.

M. Wichmann, B. Denkena, M.-A. Dittrich, S. Friebe: Ressourceneffizientes Umschleifen verschlissener VHM-Werkzeuge. WT Werkstattstechnik, Volume 111, Issue 6, 2021, Pages 430-434.

Tool properties and energy input

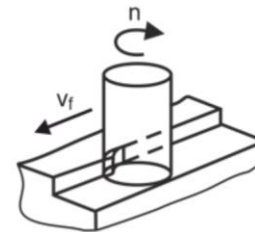


Flank milling process

machine: Heller H5000
material: TiAl6V4
tool: Ø 16 mm

Process parameters

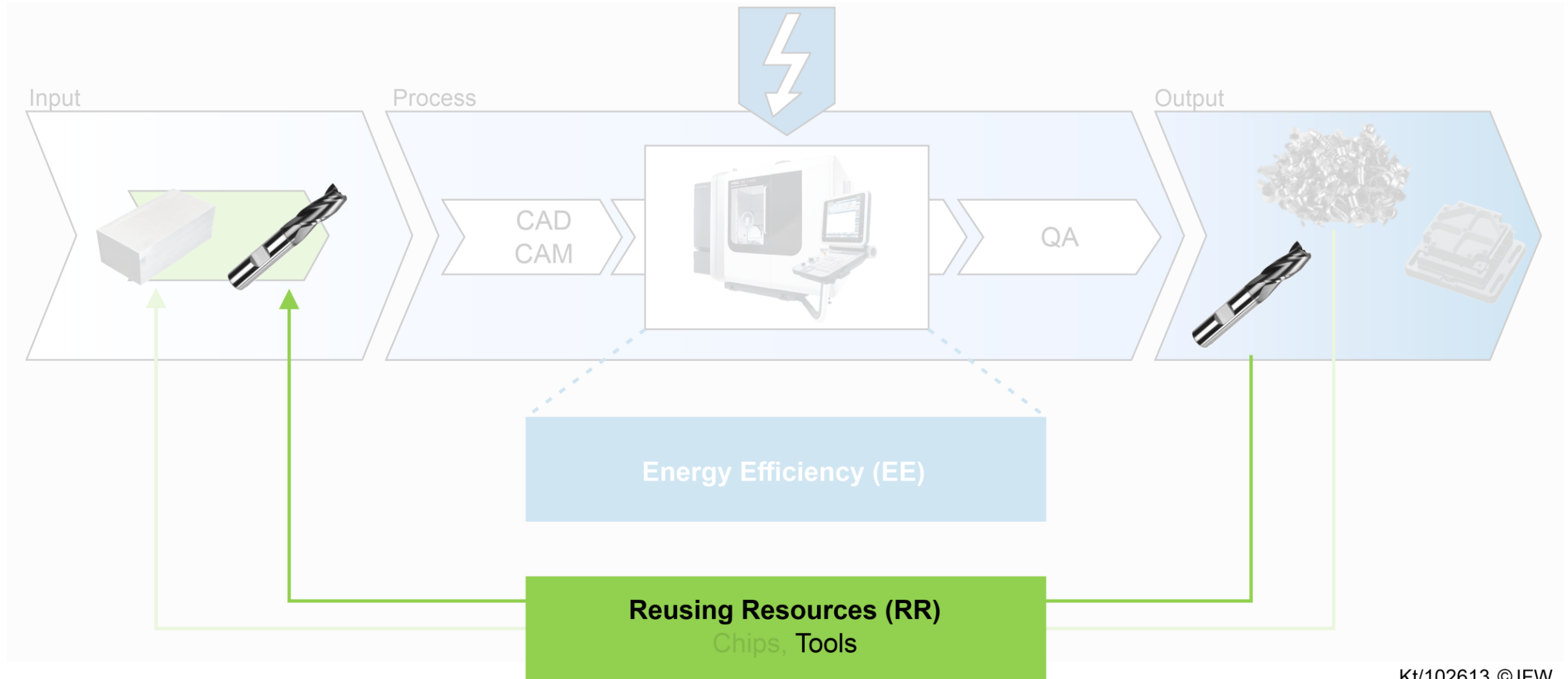
$a_p = 24 \text{ mm}$ $v_c = 90 \text{ m/min}$
 $a_e = 2 \text{ mm}$ $f_z = 0.1 \text{ mm}$
Exterior & interior cooling (60 bar)



Wic/97739 © IFW

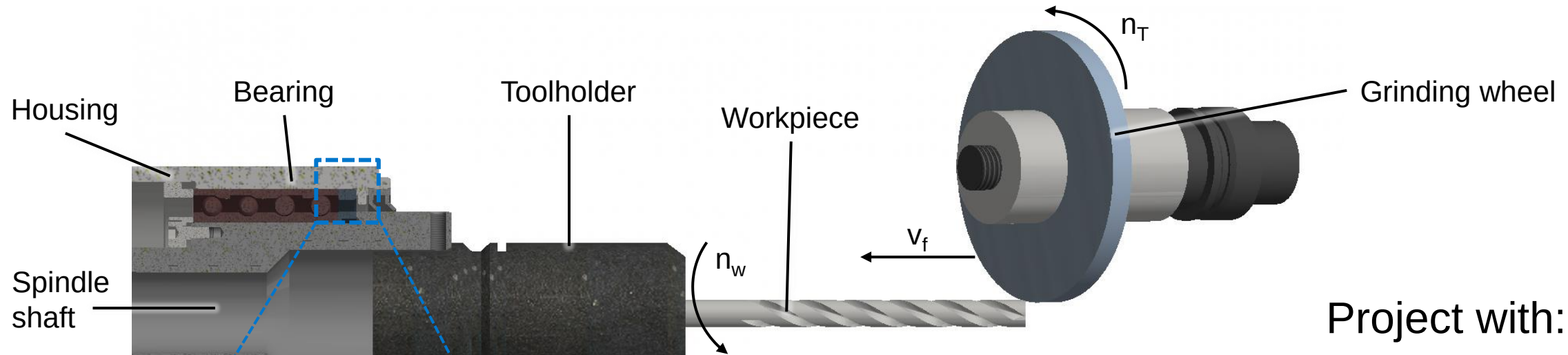
B. Denkena, M.-A. Dittrich, S. Friebe, Y. Liu: Regenerative grinding of worn milling tools. CIRP Winter Meeting, February 20th 2020, Paris.

Outline of presentation

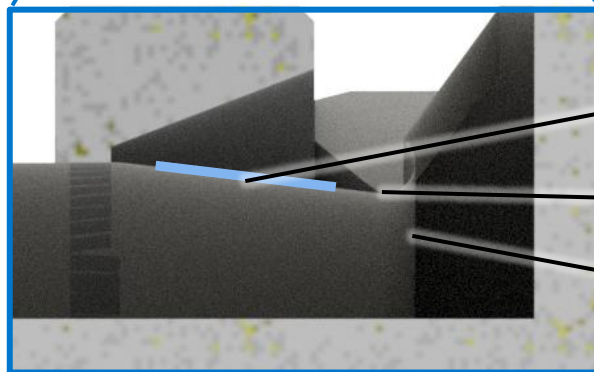


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Concept of measuring workpiece spindle in tool grinding machine



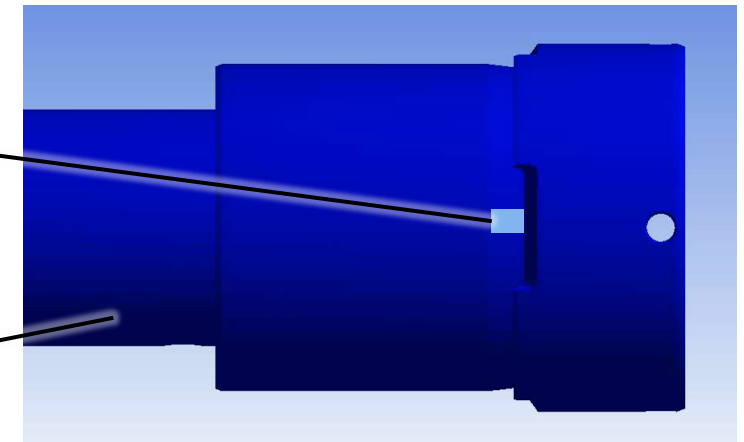
Project with:



Semiconductor
strain gauge

Notch

Spindle shaft

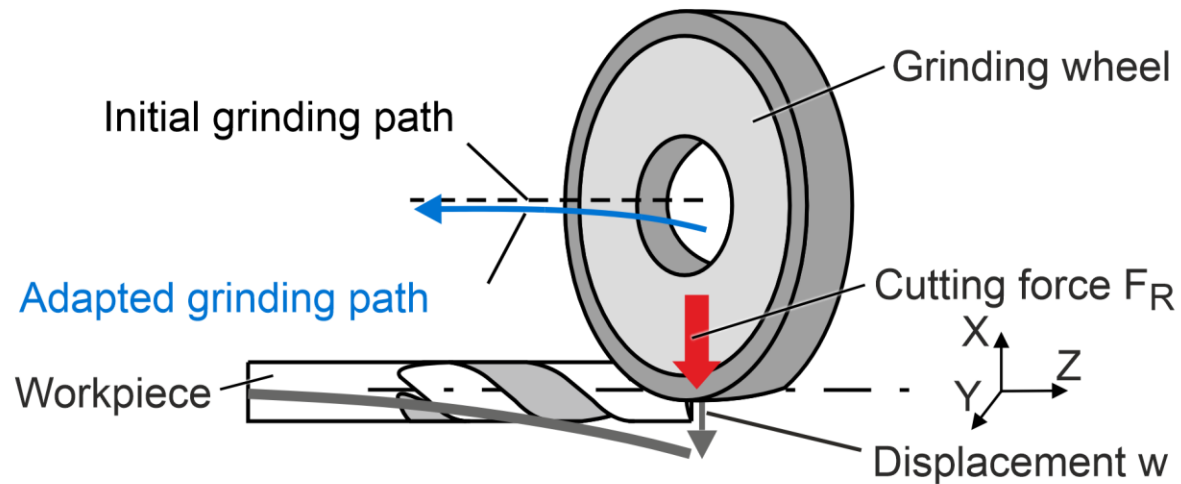


H. Buhl: Kraftsensitive Spindel zur Formfehlerkompensation beim Schleifen lang auskragender Schaftwerkzeuge. PhD Thesis, Leibniz University Hannover, 2025.

Force-sensitive spindle for form error compensation when grinding long cantilevered cylindrical tools

Shape error compensation using measuring workpiece spindle

Adapted grinding path



Initial grinding path

```
(snKBEA Nut 1)
N0094 G00 G91 Y1=-0.0099 X1=-14.9141
N0096 G01 Z1=-1.6624 A1=-18.3363 F150.000
N0098 #CONTOUR MODE ON
N0100 Z1=-1.0606 A1=-11.6957 F125.000
N0102 Z1=-1.0606 A1=-11.6958
N0104 Z1=-1.0605 A1=-11.6958
N0106 Z1=-1.0606 A1=-11.6958
```

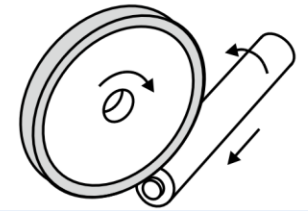
Adapted grinding path

```
(snKBEA Nut 1)
N0094 G00 G91 Y1=-0.0099 X1=-14.9141
N0096 G01 Z1=-1.6624 A1=-18.3363 F150.000
N0098 #CONTOUR MODE ON
N0100 Z1=-1.0606 X1= 0.3755 A1=-11.6957 F125.000
N0102 Z1=-1.0606 X1=-0.0118 A1=-11.6958
N0104 Z1=-1.0605 X1=-0.0113 A1=-11.6958
N0106 Z1=-1.0606 X1=-0.0113 A1=-11.6958
```

Project with:

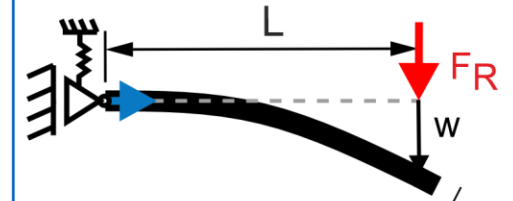


Force-sensitive spindle



F_R

Bending line model



w

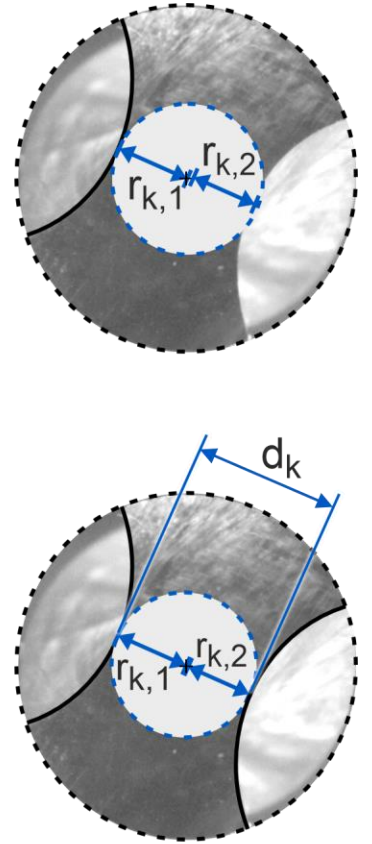
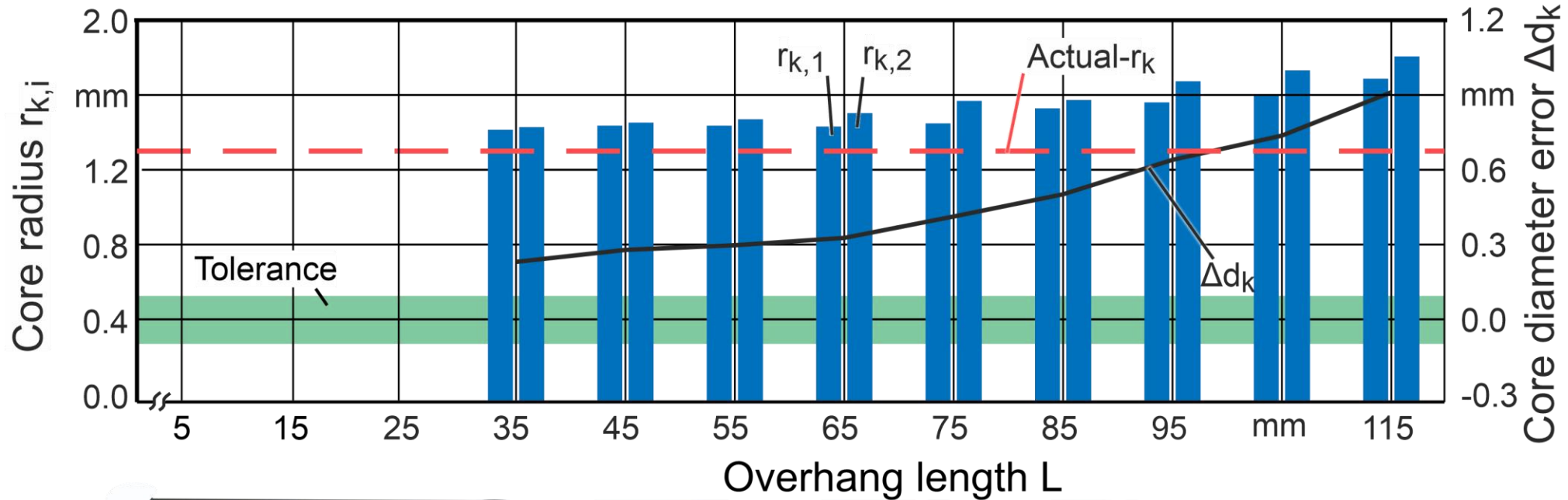
NC-Code adaption

```
(snKBEA Nut 1)
N01 G01 Z1=-1.6624 A1=...
N02 #CONTOUR MODE ON
N03 Z1=-1.0606 X1= 0.3755 A1=...
N04 Z1=-1.0606 X1=-0.0118 A1=...
```

H. Buhl: Kraftsensitive Spindel zur Formfehlerkompensation beim Schleifen lang auskragender Schaftwerkzeuge. PhD Thesis, Leibniz University Hannover, 2025.
Force-sensitive spindle for form error compensation when grinding long cantilevered cylindrical tools

Shape error compensation for twist drills (example: core radius)

Uncompensated

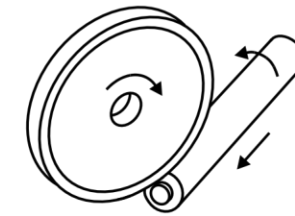


Workpiece

Material T10MG
Diameter d = 8 mm
Overhang length L = 110 mm

Process parameters

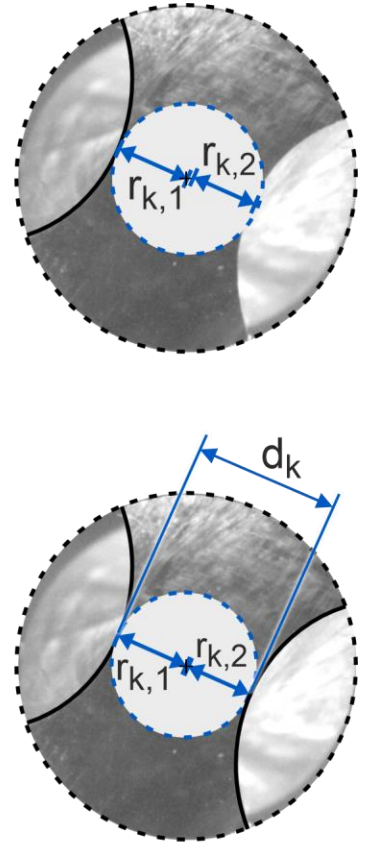
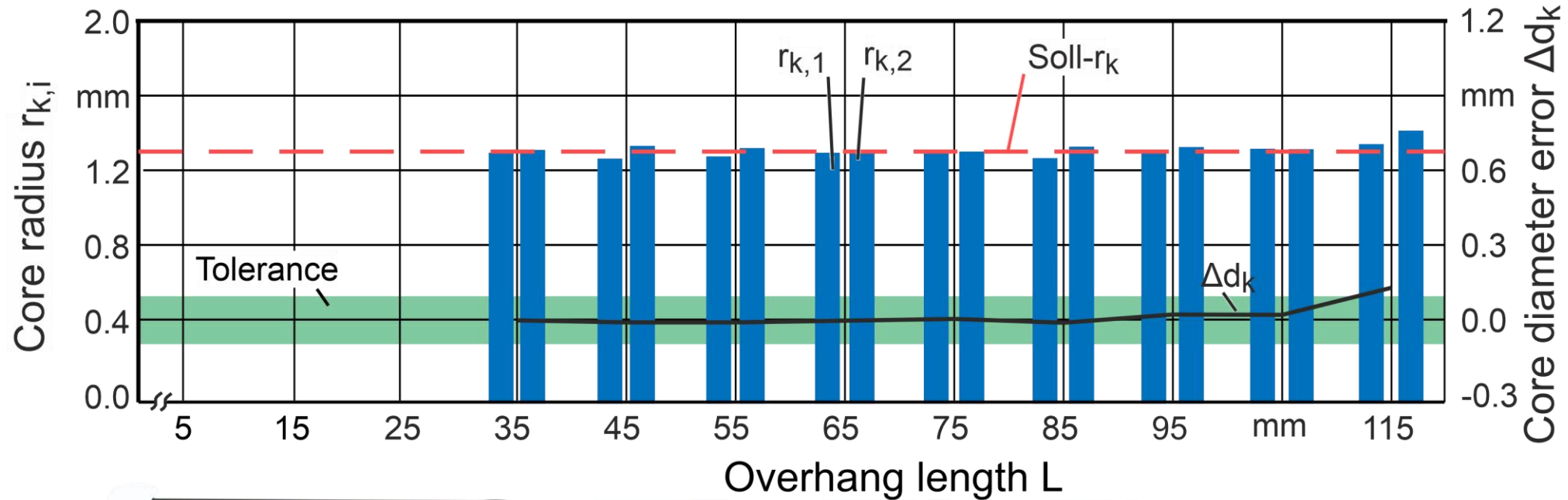
Cutting speed v_c = 18 m/s
Feed rate v_f = 110 m/min
Cutting depth a_p = 2.7 mm



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Force-sensitive spindle for form error compensation when grinding long cantilevered cylindrical tools

Shape error compensation for twist drills (first tool is good tool, less scap)

Compensated

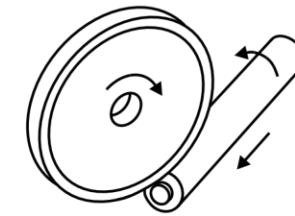


Workpiece

Material T10MG
Diameter d = 8 mm
Overhang length L = 110 mm

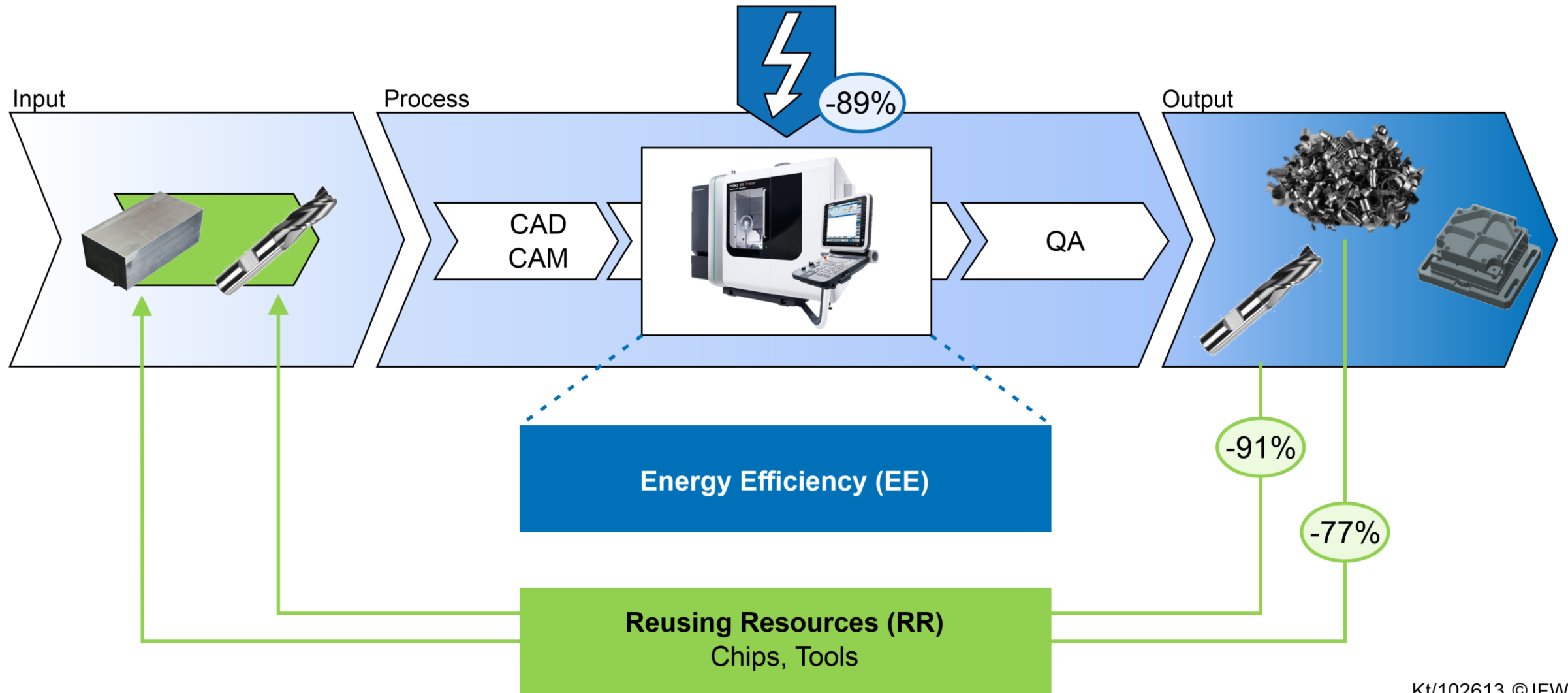
Process parameters

Cutting speed v_c = 18 m/s
Feed rate v_f = 110 m/min
Cutting depth a_p = 2.7 mm

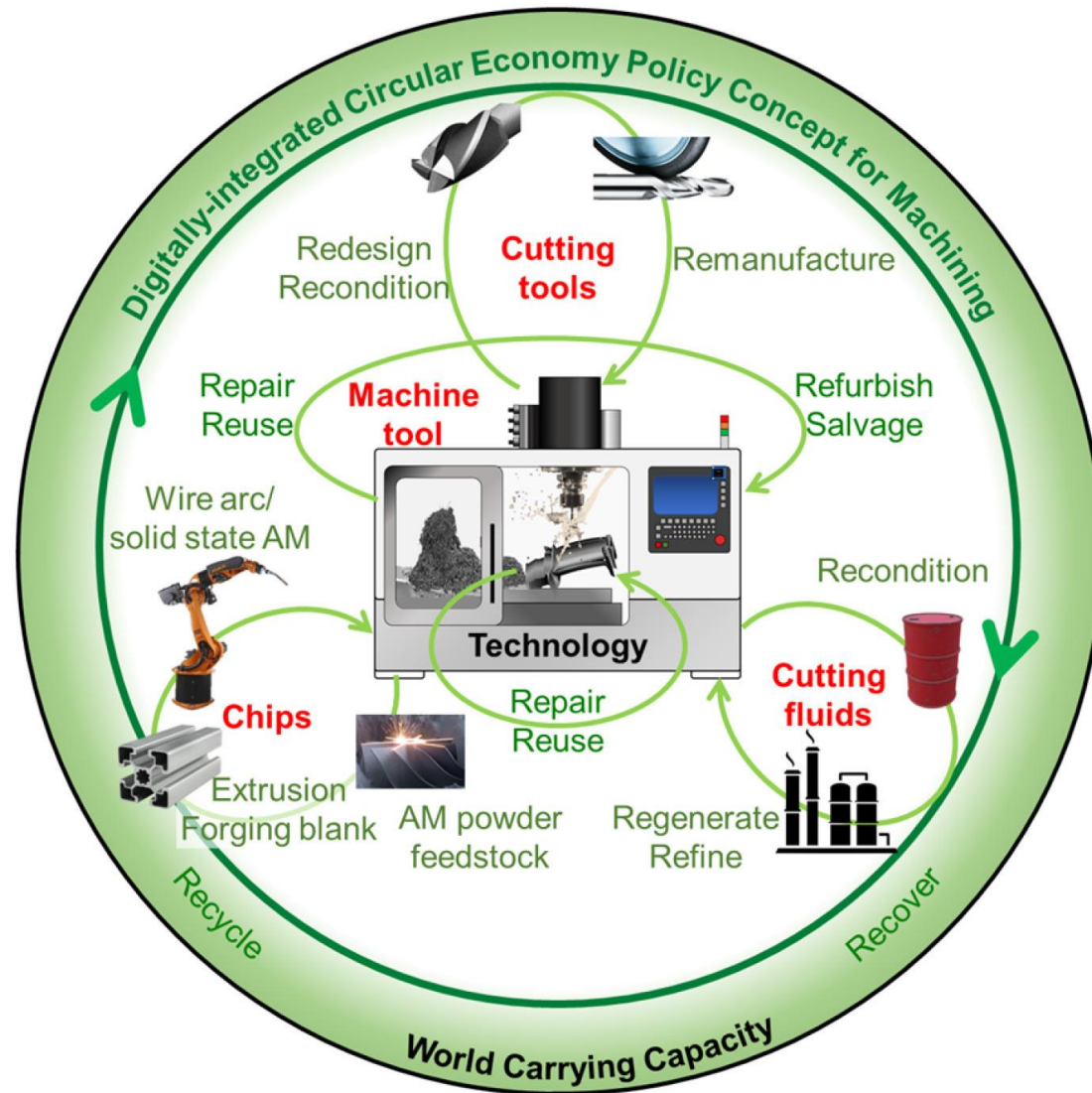


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Summary



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Let us all work together to innovate machining processes and make them more sustainable.

Many more possibilities to improve sustainability in machining:

- Machine tools
- Manufacturing processes
- Cutting tools
- Chips
- Cutting fluids
- Also process chains



Thanks for your attention!