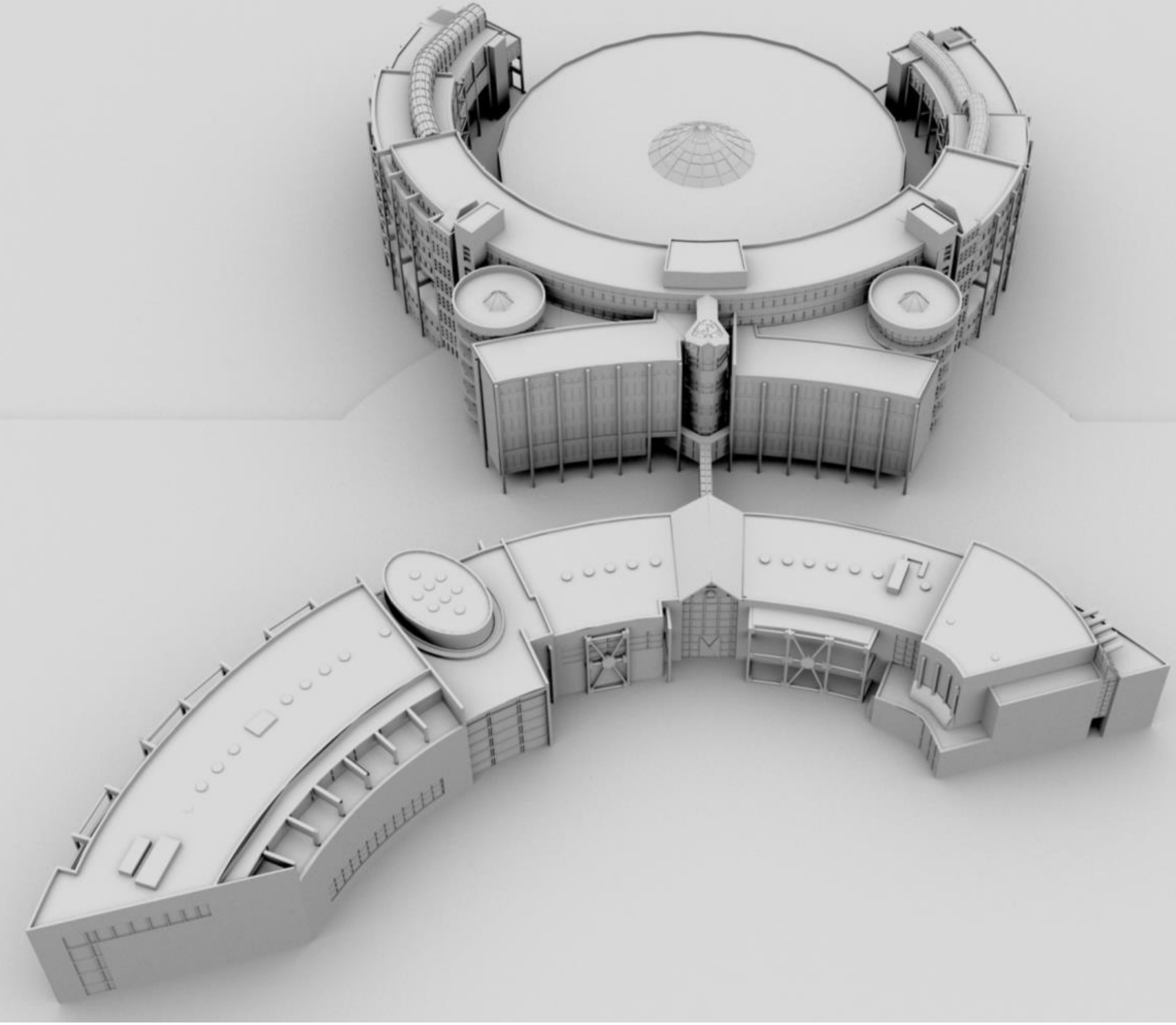

CERN Accelerator School

Mechanical & Materials Engineering

for Particle Accelerators and Detectors

05.06.2024, Sint-Michielsgestel

Julius Tschöpel, M. Eng.
Chair of Machine Tools and Manufacturing Technology
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Fraunhofer Institute for Production Systems and Design
Technology IPK, Germany

Prof. Dr. h. c. Dr.-Ing. Eckart Uhlmann

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TECHNISCHE UNIVERSITÄT BERLIN

The CERN Accelerator School

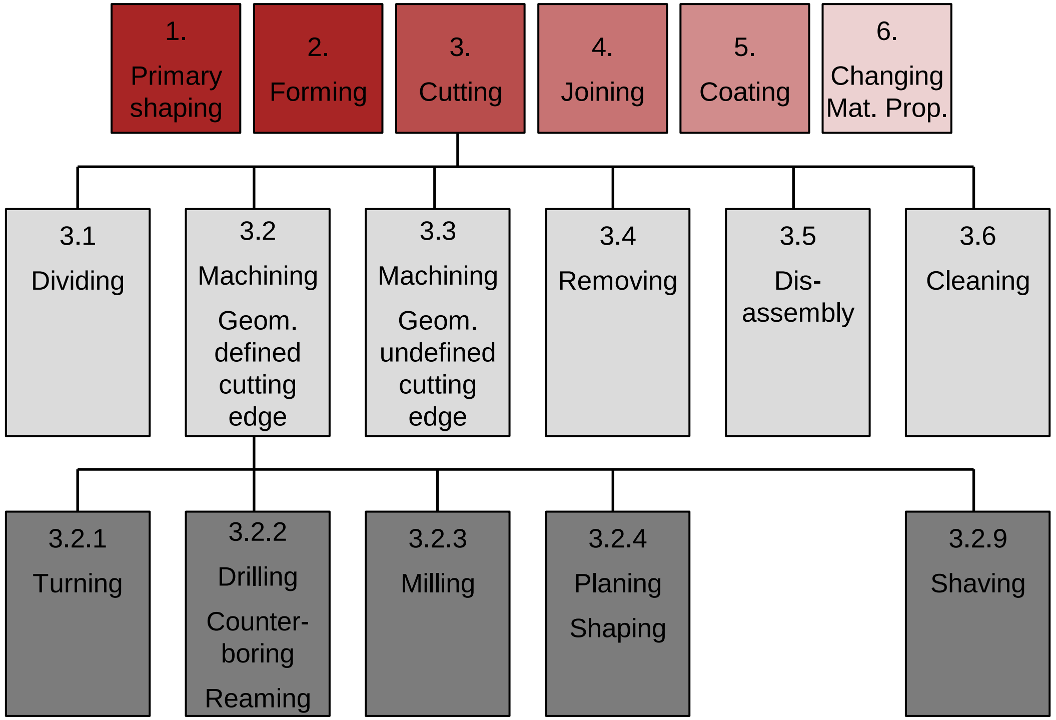
CONTENT

- Fundamentals of Machining Technology
- Motivation and Recent Challenges
- Developments in Advanced Machining
  - Innovative Sensing Methods
  - Advanced Process Technologies
  - Innovative Spindle Systems
  - Adaptive Machine Tools
  - Data Science in Precision Machining
- Institute for Machine Tools and Factory Management IWF

Fundamentals of Machining Technology


© Zachary Tong, Breaking Taps LLC.

SEM-Images of a ductile cutting process of AlMgSi0.5


1. Primary shaping
2. Forming
3. Cutting
4. Joining
5. Coating
6. Changing Mat. Prop.

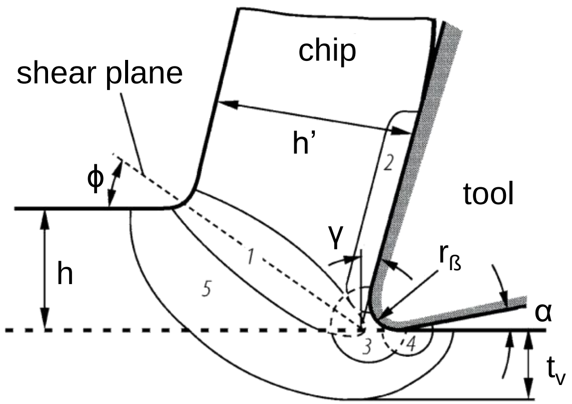
3.1 Dividing
3.2 Machining Geom. defined cutting edge
3.3 Machining Geom. undefined cutting edge
3.4 Removing
3.5 Dis-assembly
3.6 Cleaning

3.2.1 Turning
3.2.2 Drilling Counter-boring Reaming
3.2.3 Milling
3.2.4 Planing Shaping
3.2.9 Shaving

Classification of the different manufacturing technologies according to DIN 8580

Fundamentals of Machining Technology

© Dubbel Taschenbuch



1: Primary shear zone

2: Secondary shear zone

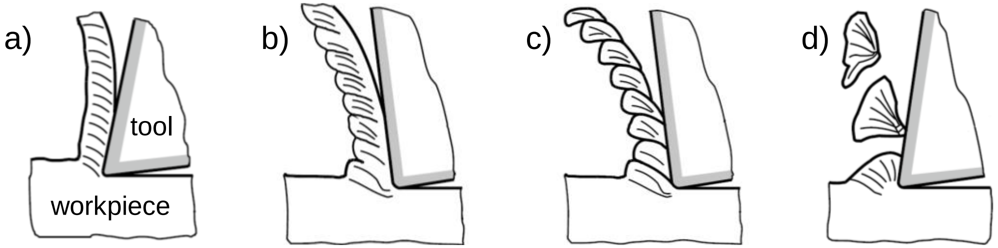
3: Separative zone

4: Rake face shear zone

5: Preliminary deformation zone

Different effective zones at the chip formation

© Denkena, Tönshoff: Spanen



Different types of chip formation; a) continuous chip; b) lamellar chip; c) segmented chip; d) discontinuous chip

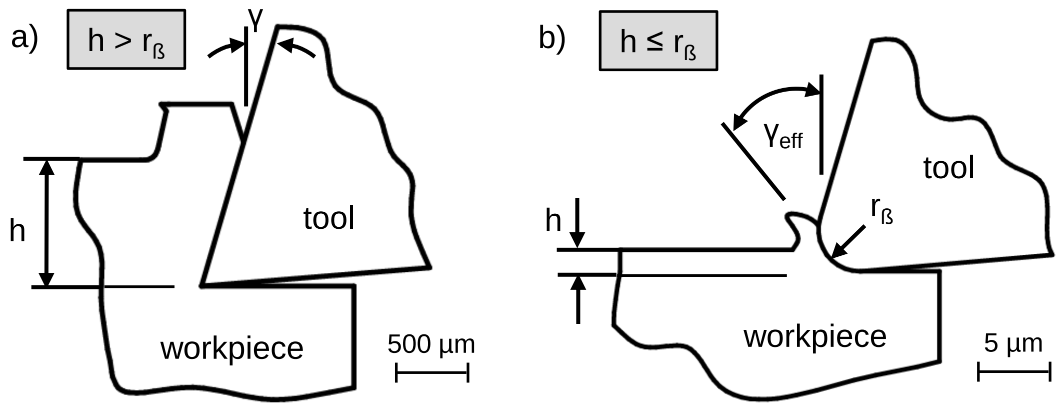
Chip Separation Model: Theory of Shear Planes

- Highly simplified assumptions
  - deformation only in a defined shear zone
  - Exclusively plastic material behavior
  - Constant friction between tool and workpiece
- Chip formation process
  - Cutting edge compresses the material

    ⇩
  - Plastic and elastic deformations leading to shear stresses τ

    ⇩
  - Chip separation after exceeding the materials shear strength τ_{max}
- Strong dependence of material behavior on load vector

Fundamentals of Machining Technology

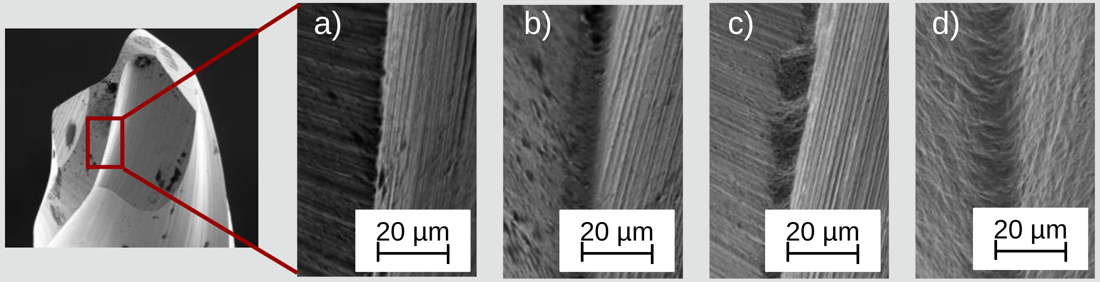


© M. Polte, IWF TU Berlin

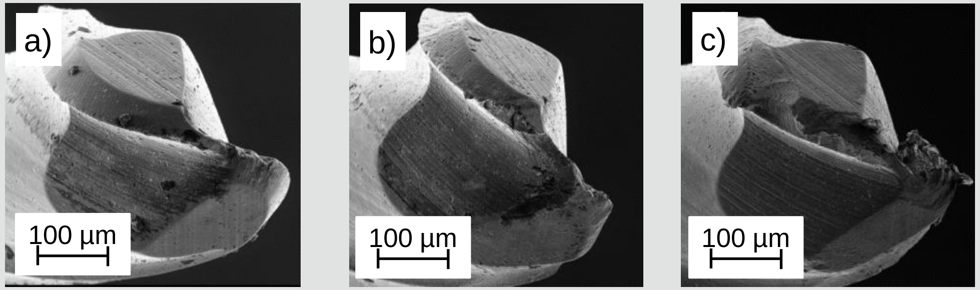
Tool engagement conditions within a) macro- and b) micro-machining

Macro- vs. micro-machining

- Micro-cutting: chip thickness $h < 10\ \mu m$
- Tool engagement conditions micro-cutting: $h \leq r_ß$
- Negative effective rake angle γ
- Resulting necessities:
  - Targeted cutting-edge preparation
  - Knowledge about the tool wear



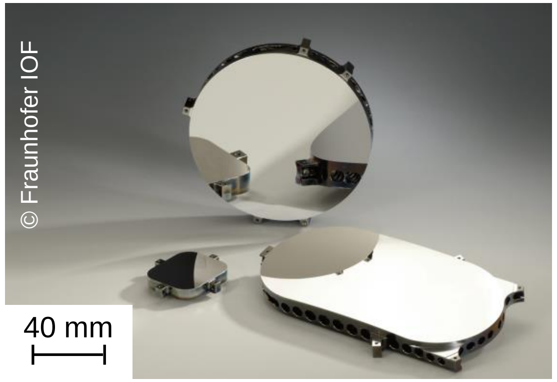
Comparison of different cutting-edge preparation methods; a) initial state; b) drag finishing; c) blasting with silicone-oxide particles; d) magnetic finishing



Influence of the rounded cutting edge radius $r_ß$ on the tool wear behavior after $l_c = 1.5$ m; a) $r_ß = 3\ \mu m$; b) $r_ß = 5\ \mu m$; c) $r_ß = 9\ \mu m$

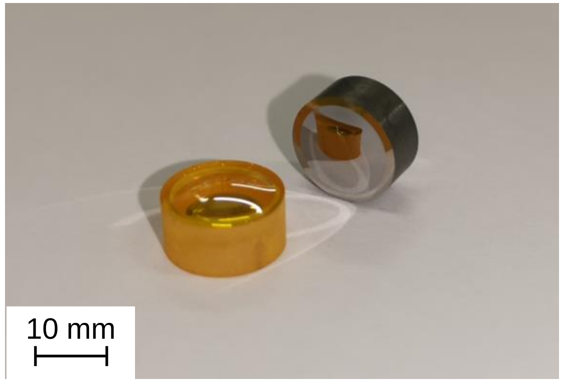
Motivation and Recent Challenges - Necessity to Increase Accuracy

Space applications

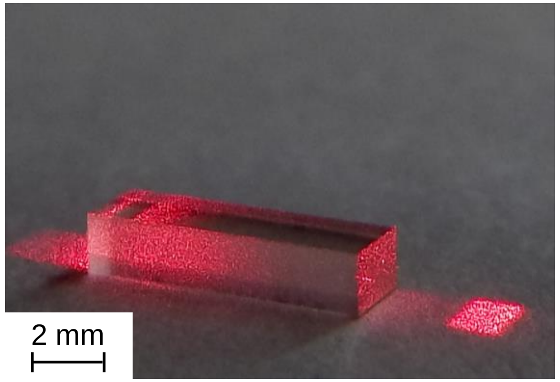


Sensor technology

IR-Sensor optics



Quantum technology

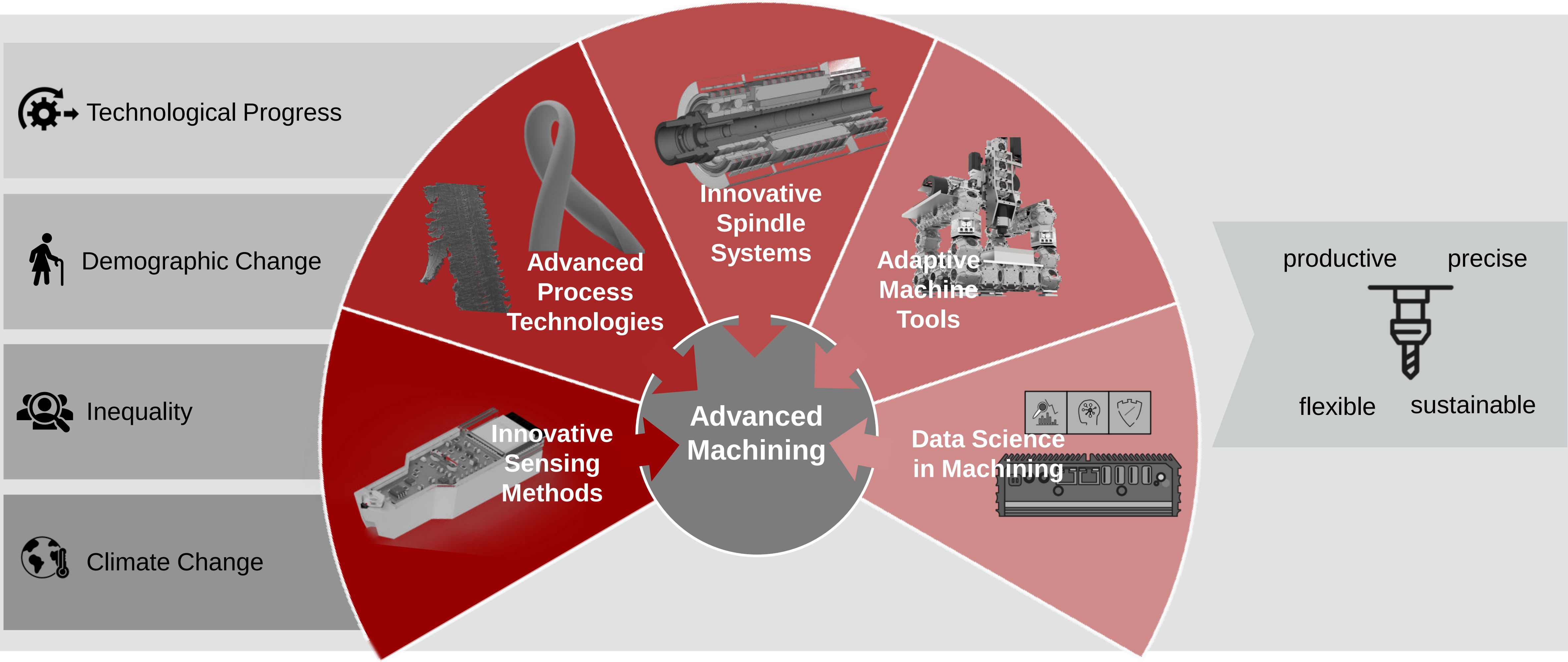


Optical applications in the field of ultra-precision machining

Requirements

- Enlargement of the material spectra
  - Brittle-hard materials for sensor optics
  - Glass ceramics for laser and space applications
- Increased requirements for industrial applications
  - Shape accuracy a_S
  - Surface roughness
  - Economic production
  - Sustainable manufacturing

Developments in Advanced Machining - Key Innovations in Recent Years



Technological Progress

Demographic Change

Inequality

Climate Change

productive precise

flexible sustainable

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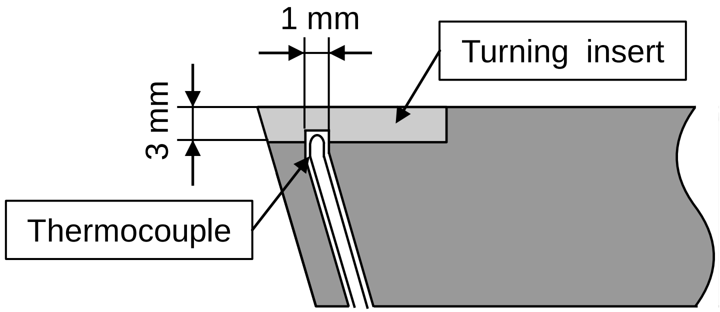
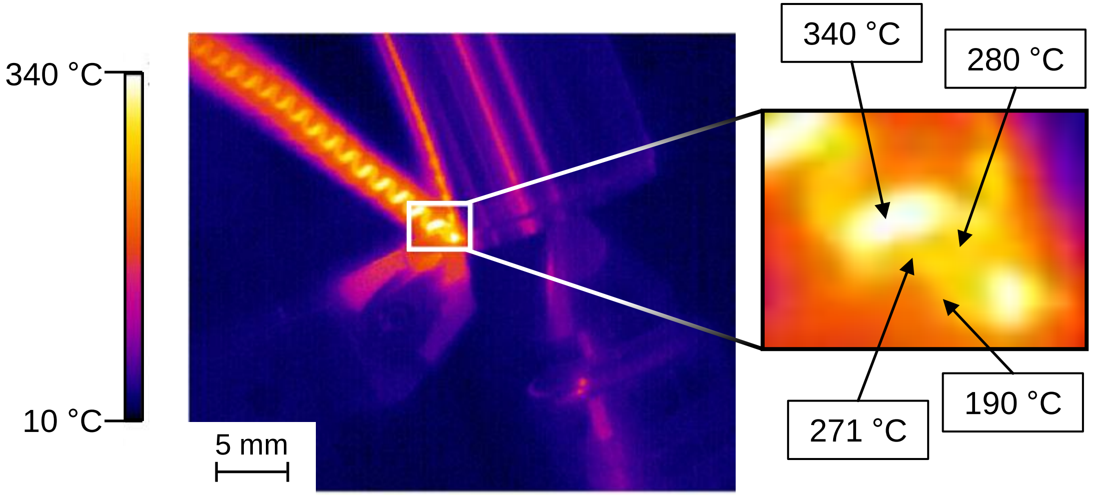
Innovative Sensing Methods – Highly Sensitive Temperature Measurement System



R. Shetty, Journal of Science, 2009.

Integrated thermocouple in cutting tool for the measurement of the cutting temperatures ϑ_C



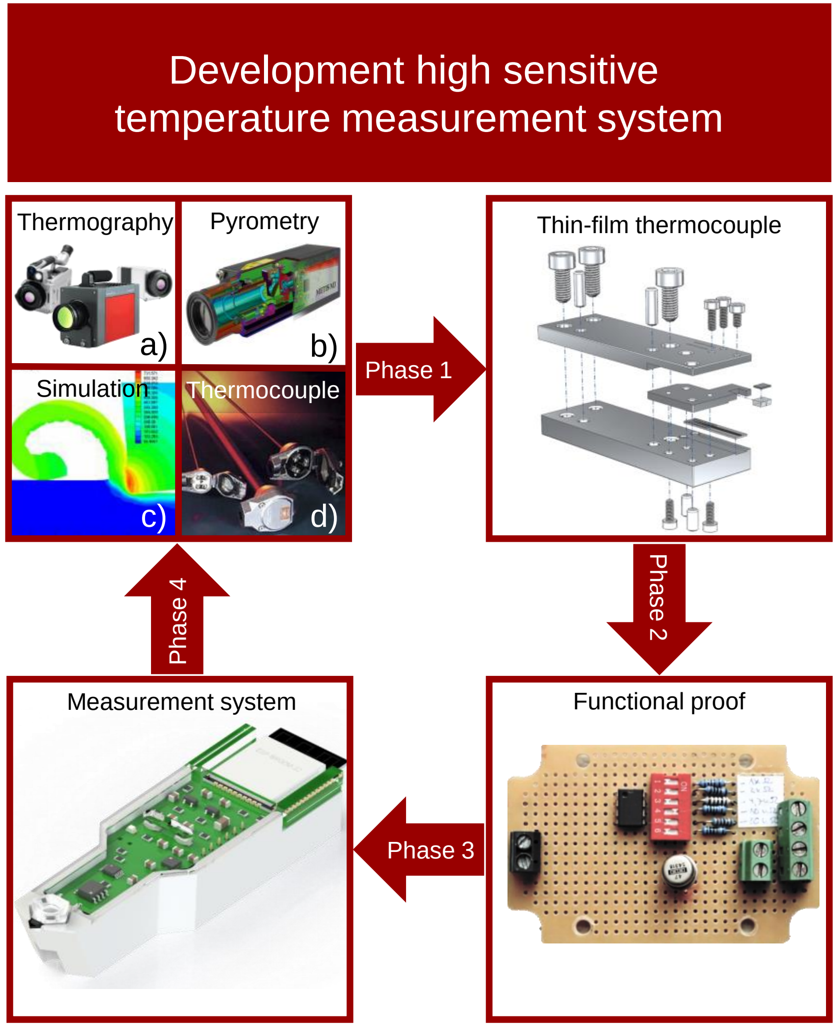
R.A. Rahman Rashid et. al., Precision Engineering, 2012.

Temperature determination in turning operation using thermal imaging camera

State-of-the-art ultra-precision machining

- undefined tool wear leads to deviations in form- and surface roughness
- ineffective use of maximum tool life
- tool wear depends mainly on cutting temperatures ϑ_C
- limitations of current methods of temperature measurement:
  - high response times t_R
  - reduced measurement accuracies a_M
  - differing thermal material properties

Innovative Sensing Methods - Highly Sensitive Temperature Measurement System



Development high sensitive
temperature measurement system

Thermography a)

Pyrometry b)

Simulation c)

Thermocouple d)

Phase 1

Thin-film thermocouple

Phase 2

Functional proof

Phase 3

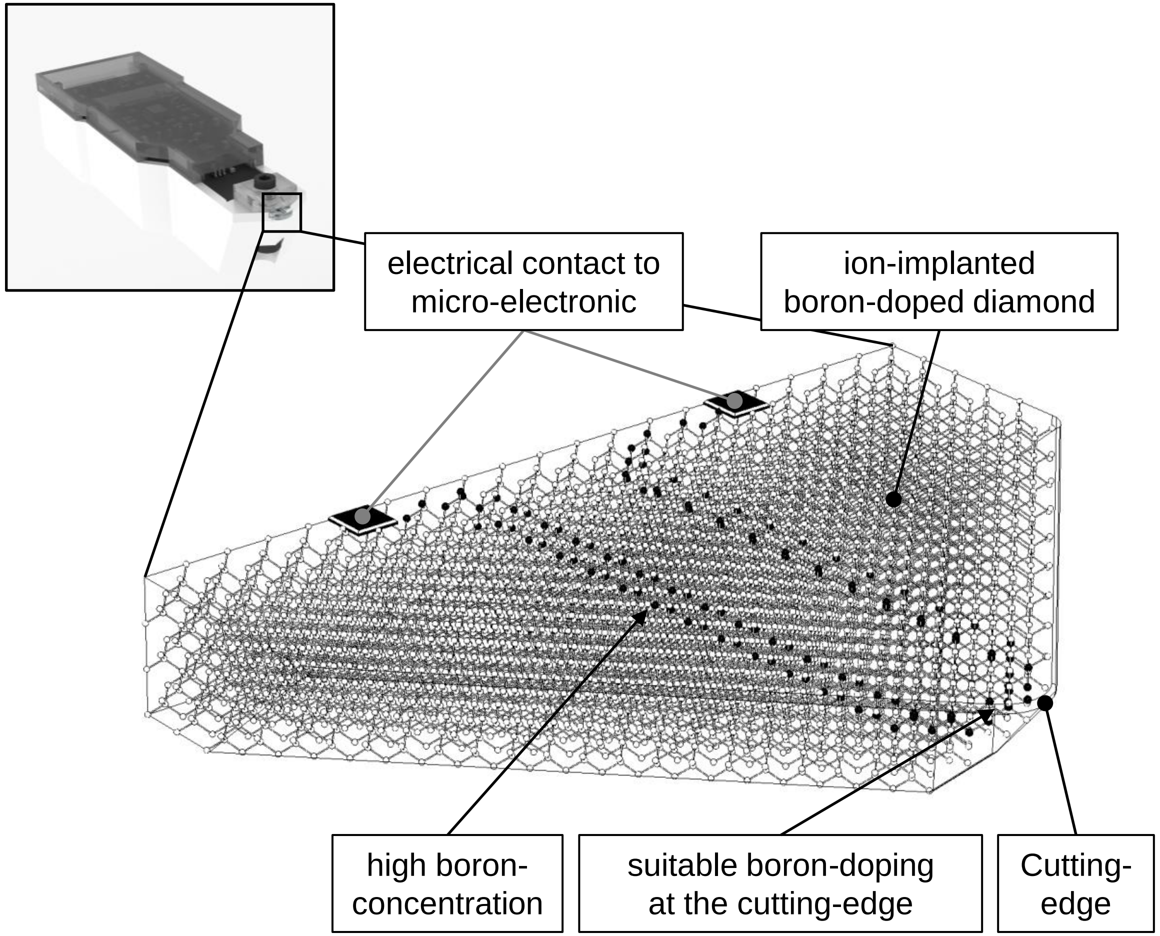
Measurement system

Phase 4

Development of an
innovative temperature measurement system

- direct and highly temperature measurements in the cutting zone of a SCD
- comprehensive knowledge about the interrelations in ultra-precision machining
- identification and characterization of tool wear using SCD
- feedback of the sensor data in real time t_{Re}
- adaptive process control based on the measured temperatures ϑ in the cutting zone

Innovative Sensing Methods - Highly Sensitive Temperature Measurement System


electrical contact to micro-electronic

ion-implanted boron-doped diamond

high boron-concentration

suitable boron-doping at the cutting-edge

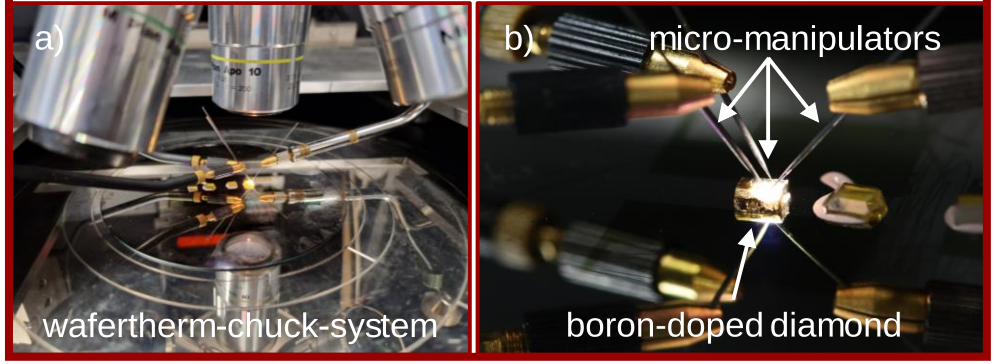
Cutting-edge

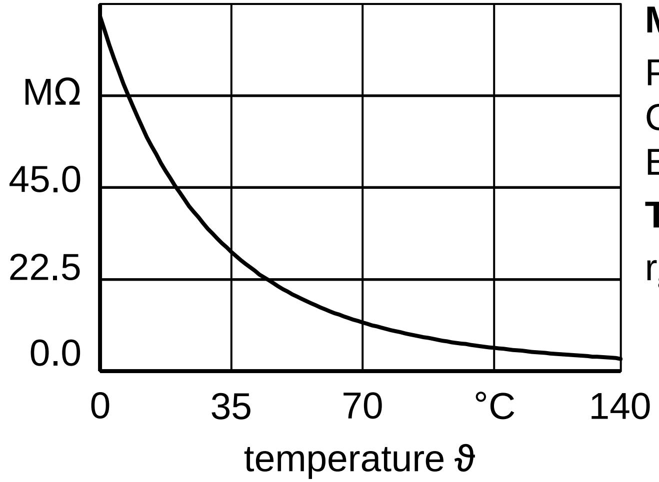
Solution Approach

- development of an improved temperature
  sensor based on ion-implanted boron-doped diamonds
- specific introduction of
  boron-atoms into crystal lattice and the cutting-edge
- avoid structural damages
  on the cutting-edge of the diamonds
- defined current flow at the cutting-edge
- increased sensitivity
  for a precise temperature measurement

Innovative Sensing Methods - Highly Sensitive Temperature Measurement System

Characterisation of ion-implanted boron-doped diamonds





Calibration curve of an ion-implanted boron-doped diamond

Measuring device:

PA 200, SUESS MICROTEC;
Chuck-System SP 74 A,
ERS ELEKTRONIC GMBH

Tool:

r_ε = 1.5 mm

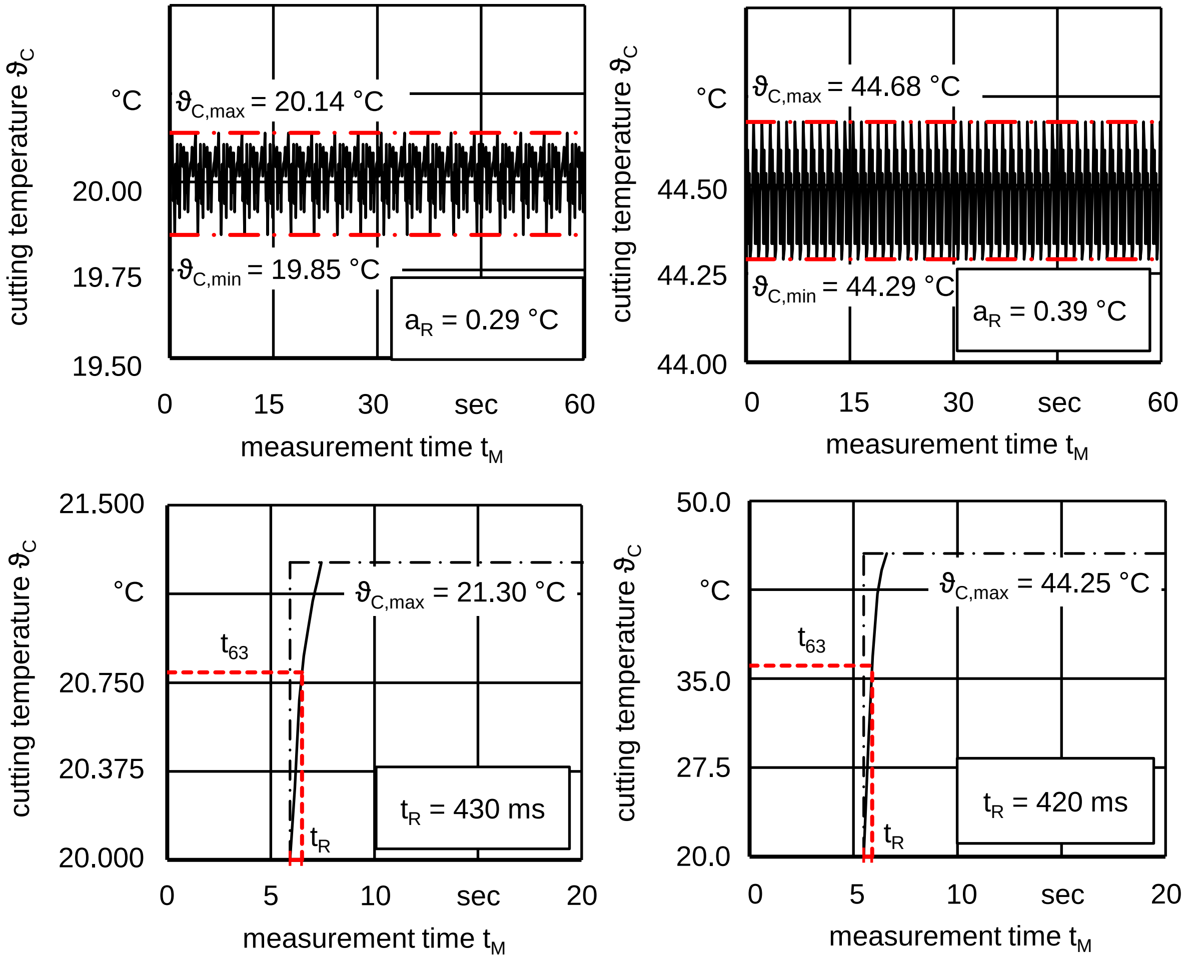
Sensor Calibration

- determination on the temperature-resistance relation
- highly accurate heating of the ion-implanted boron-doped diamonds with a Wafertherm®- chuck system
- electrical contacting using high-precision micro-manipulators
- measurement of electrical resistances R_{el} with temperature steps of $\Delta\vartheta = 1$ °C

Results

- successful ion-implantation resulting in suitable electrical conductivity κ
- identification of a suitable doping characteristic

Innovative Sensing Methods - Highly Sensitive Temperature Measurement System



Resolution accuracy a_R and
reaction time t_R using ion-implanted boron-doped diamonds

Resolution accuracy a_R

- resolution accuracy of $a_R \leq 0.39$ °C
  could be identified for different cutting temperatures ϑ_C
- slight increase at
  higher cutting temperatures ϑ_C due to physical effect

Reaction time t_R

- investigation of the
  reaction time t_R based on the guideline VDI/VDE 3522
- measurement system enables a response time of
  $t_R \leq 430$ ms independent of the cutting temperatures ϑ_C
- process-reliable temperature
  measurements can be realized using ion-implanted diamonds

Innovative Sensing Methods - Highly Sensitive Temperature Measurement System

Machine Tool:
Moore Nanotech 350 FG,
NANOTECHNOLOGY SYSTEMS

Measurement Device:
temperature measurement
system, IWF TU BERLIN

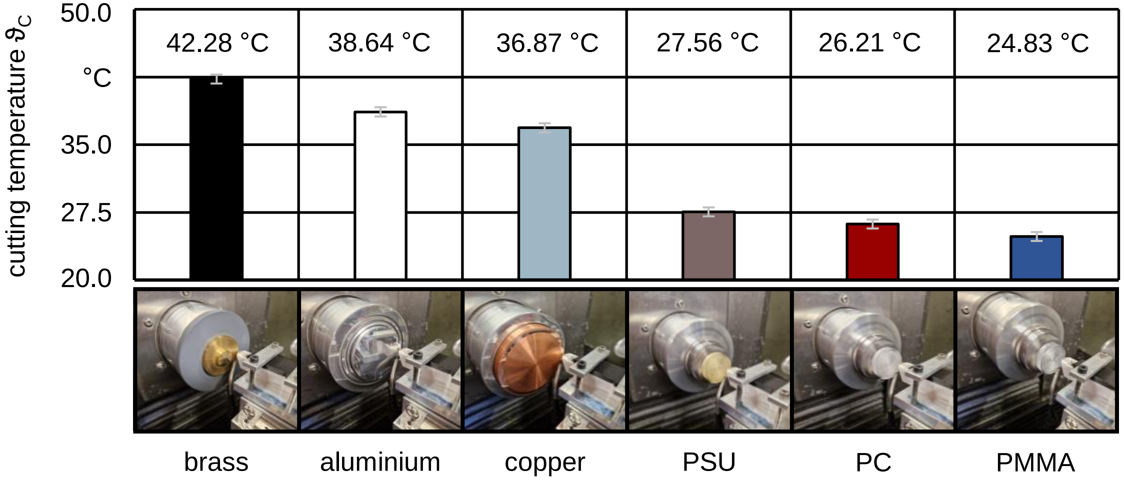
Process:
ultra-precision turning

Material:
ion-implanted
boron-doped diamond
r_ε = 1.5 mm

Doping-level:
d_{lev} = $4E^{15}$ - ions/cm^2

Doping-length:
d_{len} = 0.4 mm

Parameter:
cutting speed: v_c = 350 m/m
depth of cut: a_p = 5 µm
feed: f = 5 µm



Comparison of different
temperature levels between metallic and plastic-based materials

Temperature measurements using ion-implanted boron-doped diamonds as temperature sensor

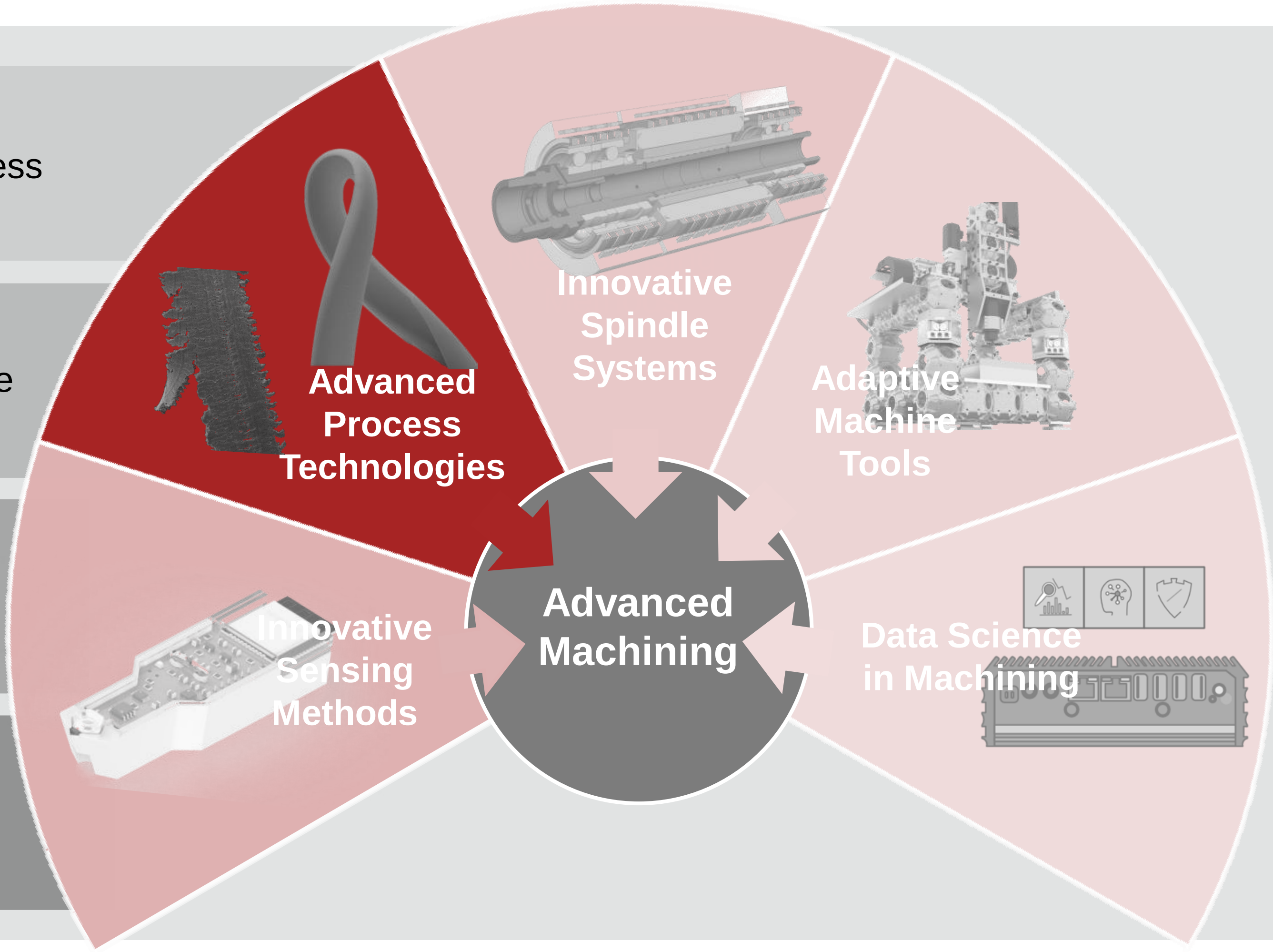
- higher cutting temperatures ϑ_C could be measured by the ultra-precision turning of metallic materials
- process-reliable machining of electrically conductive materials

Results

- measurements of high-precision temperatures ϑ with a reduced distance to the cutting-edge
- correlation of temperatures ϑ with tool wear, surface roughness and shape
- model-based self-optimisation of shape and surface roughness
- foundation for zero-waste production and potential for significant CO2-savings

Developments in Advanced Machining - Key Innovations in Recent Years

- Technological Progress
- Demographic Change
- Inequality
- Climate Change



Advanced Process Technologies

Innovative Spindle Systems

Adaptive Machine Tools

Innovative Sensing Methods

Data Science in Machining

Advanced Machining

productive precise

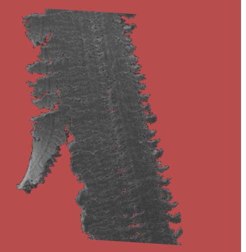
flexible sustainable

Advanced Process Technologies – Cutting Hard-Brittle Materials

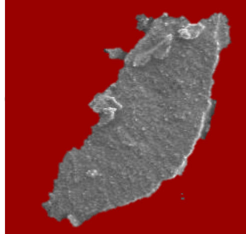
Initial Situation

- Ductile cutting mechanism with hard-brittle materials
  - Hydrostatic stress condition is required
  - Crack propagation due to material dislocations
  - Fractures can exceed machined surface
- Different possibilities to a achieve stress condition in cutting area

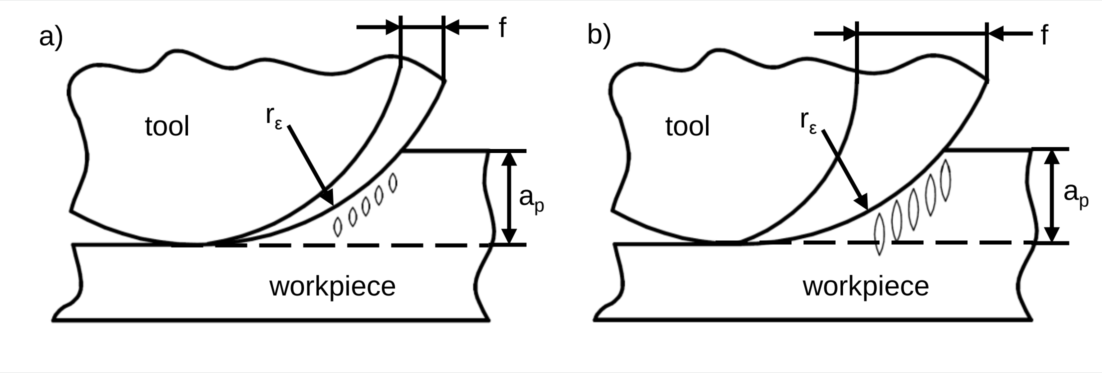
Ductile chip



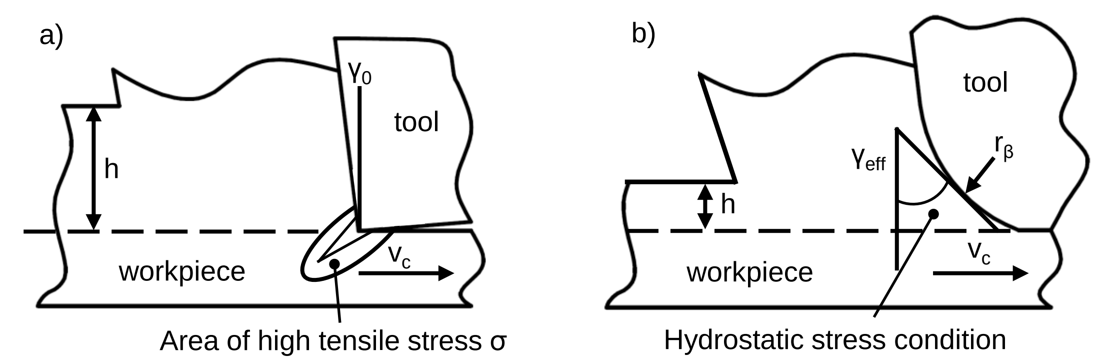
Transition area



Discontinuous chip



Dependence of crack propagation on feed f; a) dislocations above machined surface; b) cracks within machined surface



Creation of a hydrostatic stress condition with a) tool macro geometry and b) micro geometry

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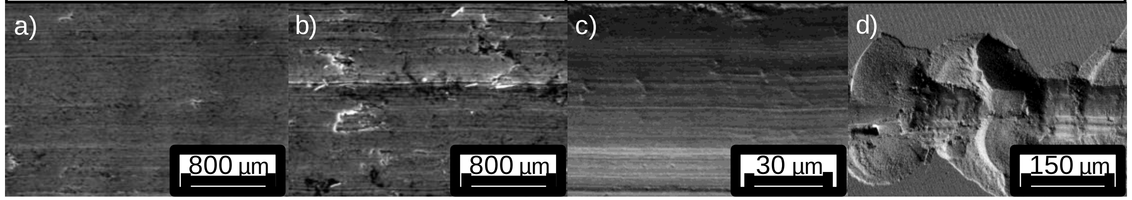
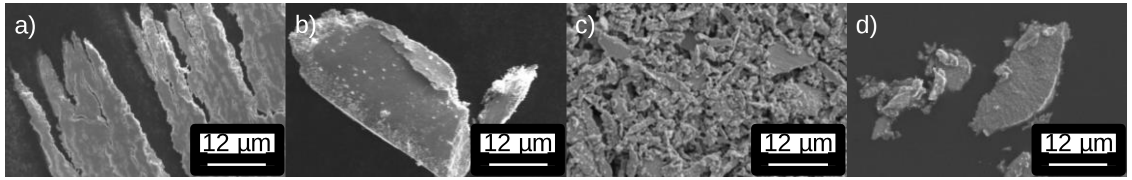
Advanced Process Technologies – Cutting Hard-Brittle Materials

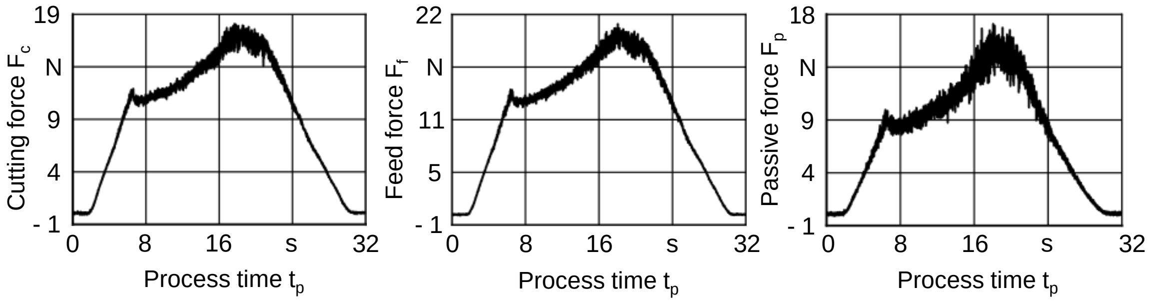
Conventional cemented carbide cobalt portion = 12.0 %	Binderless cemented carbide cobalt portion = 0.8 %



Surface topology of the workpiece, a), c) ductile cutting,
b) transition to ductile-brittle material behaviour, d) brittle cutting



SEM-Images of the different chip formations

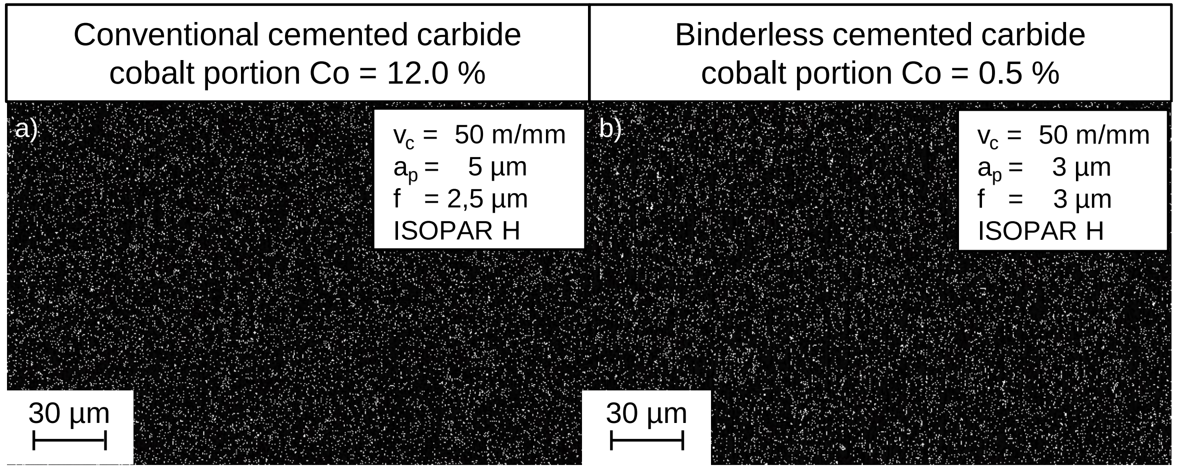


Force curve for scratch tests with conventional carbide

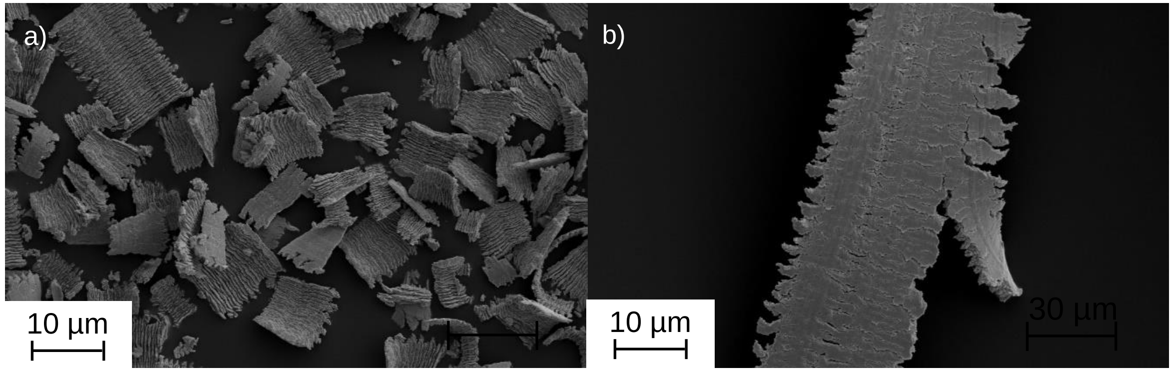
Experimental Investigation

- Scratch tests were conducted to identify suitable cutting parameters
  - Ductile material behaviour
  - Brittle material behaviour
- Variation of the cutting depth ap and feed f in a range from 0 µm ≤ a_p / f ≤ 35 µm
- Process cooling: ISOPAR^{TM} H / dry machining
- Analysis of the resulting surface quality, tool wear, chip formation and process forces

Advanced Process Technologies – Cutting Hard-Brittle Materials



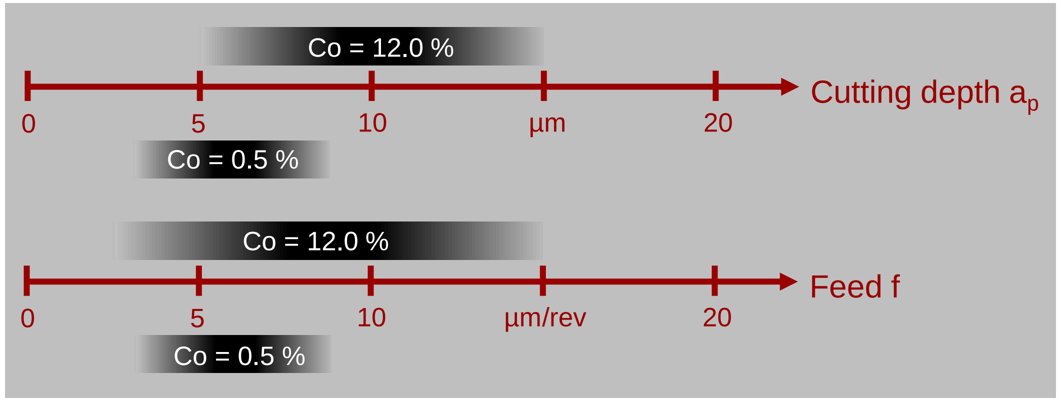
SEM-Images of surface textures ; a) conventional carbide and b) binderless carbide



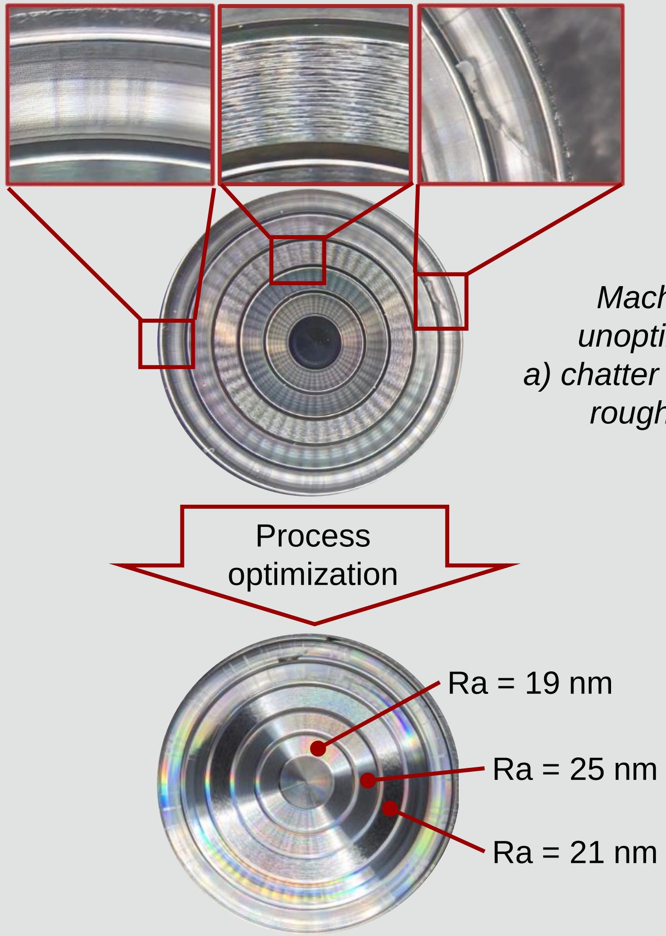
Resulting chips; a) finishing cut and b) roughing cut

Results

- Extensive experimental investigations were conducted
- Relevant parameters:
  - Cutting depth a_p
  - Feed f
- Identified process window for ductile cutting



Advanced Process Technologies – Cutting Hard-Brittle Materials



Machining results with unoptimized parameters; a) chatter marks, b) high surface roughness, c) breakout

Industrial Significance

- Delivery of optimized process parameters do achieve ductile cutting behavior
- Possibility to manufacture complex components from hard brittle material:
  - Injection molds
  - Cutting tools
  - Injection nozzles
  - Stamping tools

Further Research Fields

- Implementation of ultrasonic assisted machining
- Investigation of ultrasonic-related effects

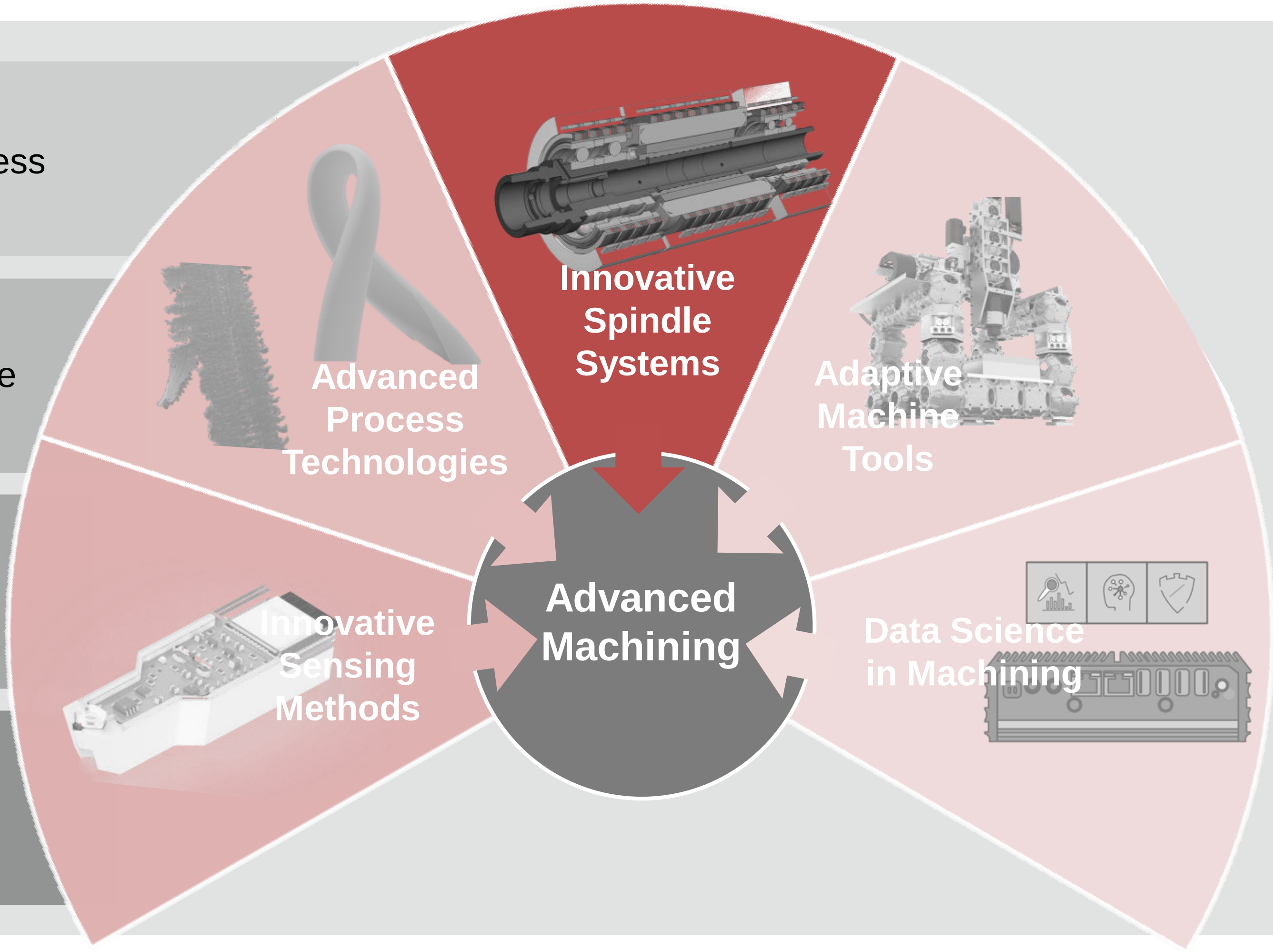
Developments in Advanced Machining - Key Innovations in Recent Years

Technological Progress

Demographic Change

Inequality

Climate Change



Innovative Spindle Systems

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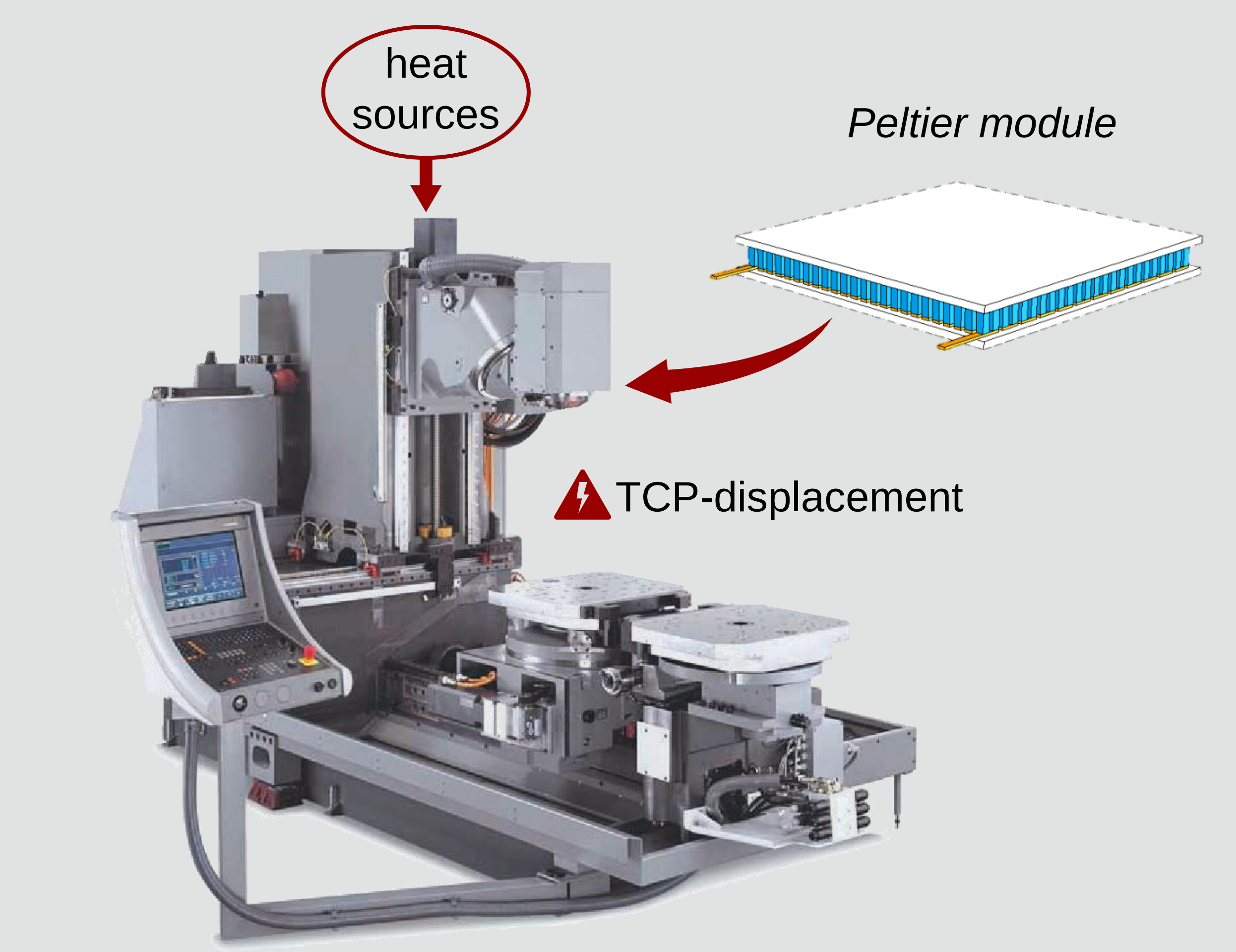
Advanced Spindle Systems – Integrated Thermoelectric Control



Machine tool

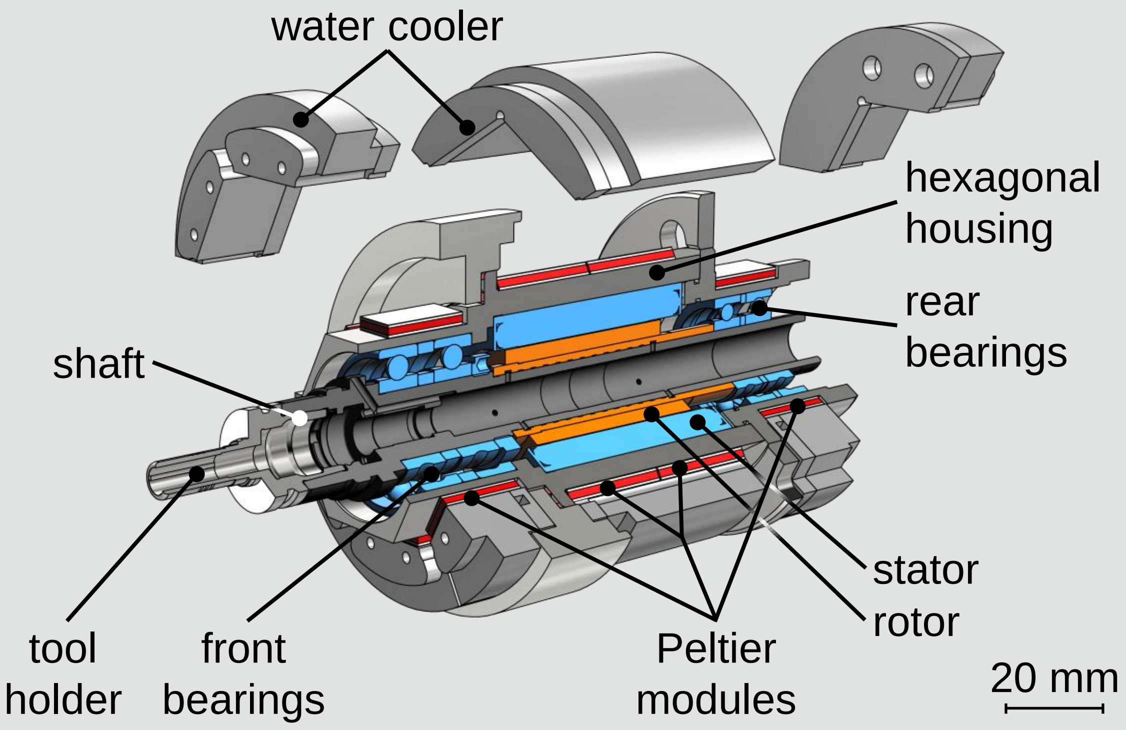
Challenge

- Significant proportion of geometrical errors is caused by thermal behavior of machine tools
- Axial displacement of tool center point (TCP) due to thermal deformation of motorized spindles
- Temperature variations due to process-related load changes in bearings and motors
- Long warm-up periods to reach thermal steady states are necessary for high-precision machining

Approach

- Reduction of thermally induced displacements by integration of Peltier modules

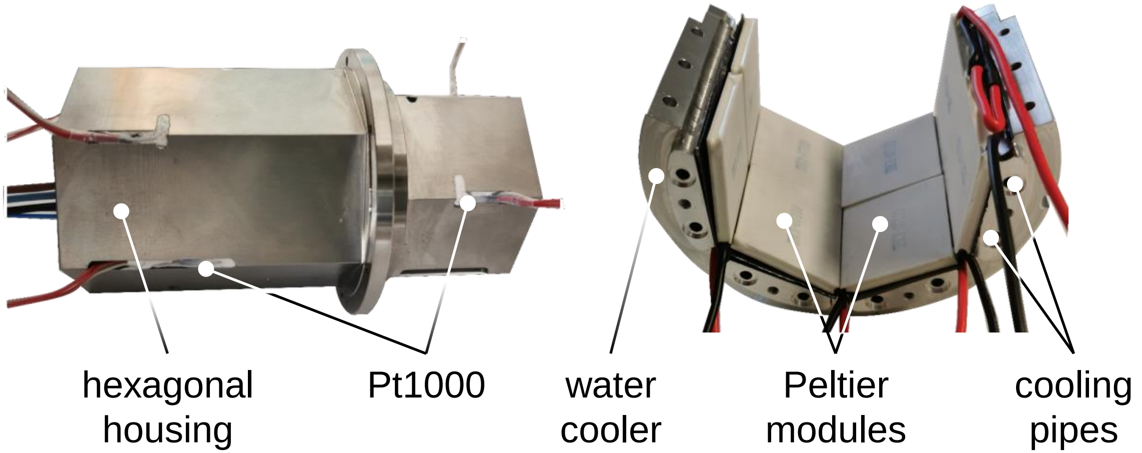
Advanced Spindle Systems – Integrated Thermoelectric Control



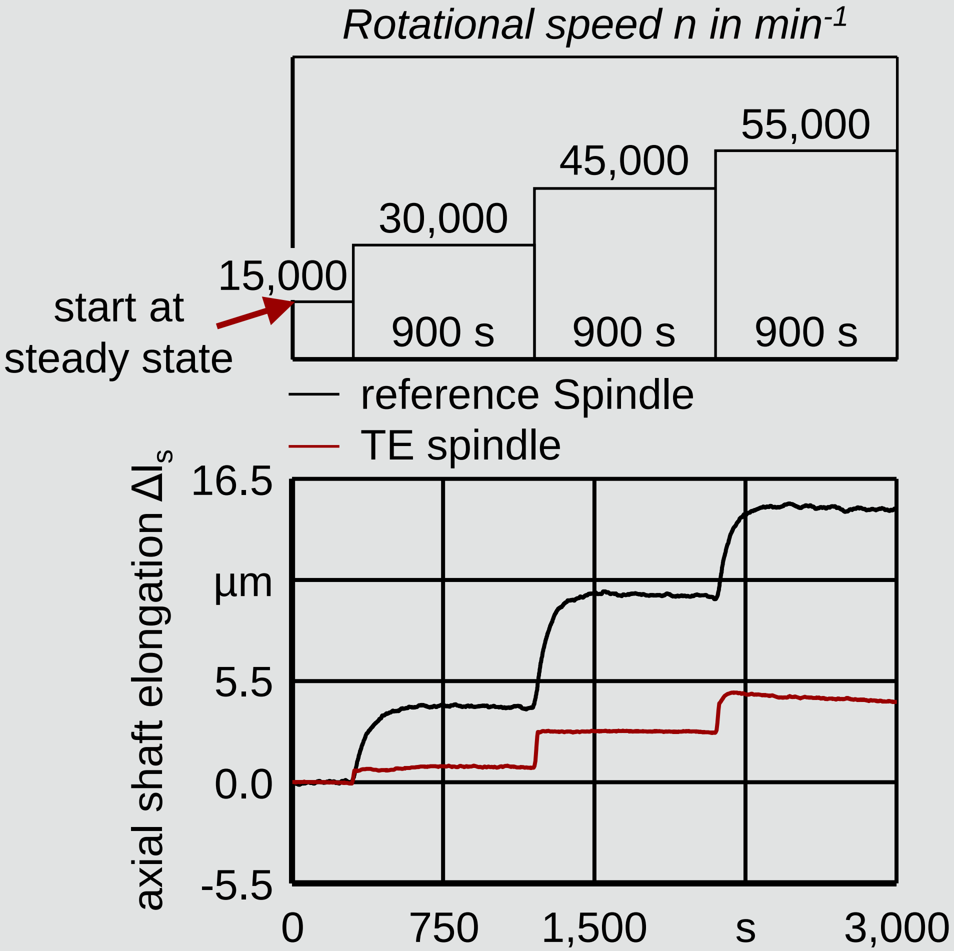
Model of a thermoelectrically tempered motorized milling spindle (TE spindle)

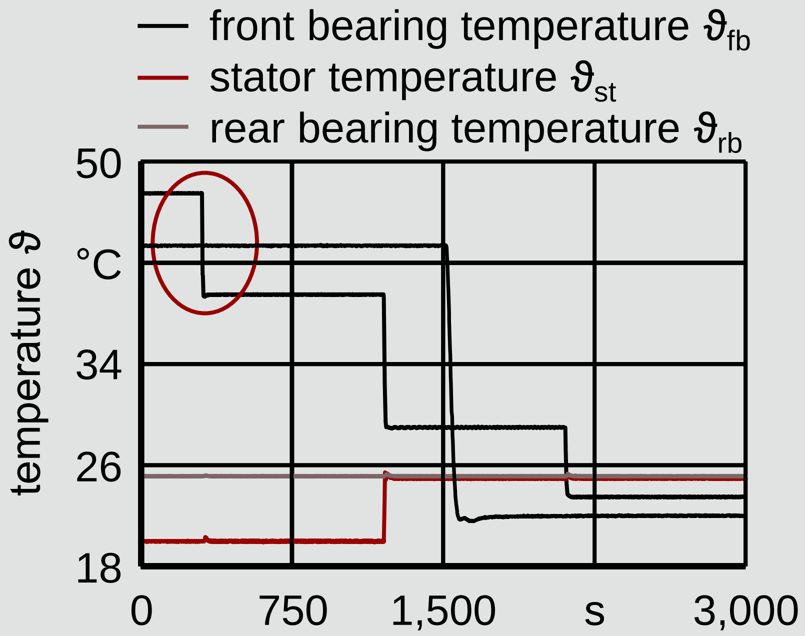
System structure

- Design of thermoelectrically tempered spindle based on Spindle Z62 by Alfred Jäger GmbH
- Hexagonal housing and water cooler allows integration of 24 prismatic Peltier modules
- Heat sources: motor, front and rear bearings

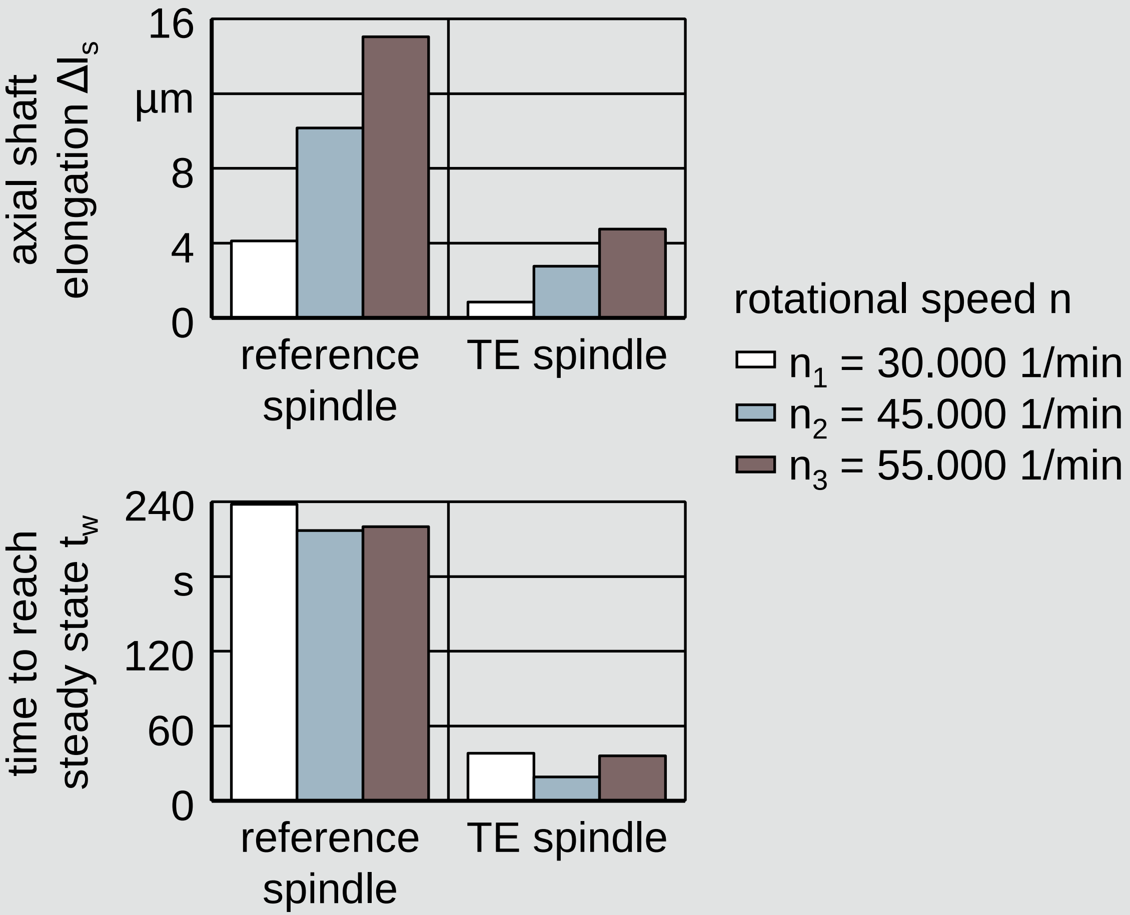


Advanced Spindle Systems – Integrated Thermoelectric Control





Advanced Spindle Systems – Integrated Thermoelectric Control



Results

- Precise and fast temperature control of spindle components
- Potential to influence axial shaft elongation under changing induced heat flow rates
- 68 % reduction of axial shaft elongation Δl_s for rotational speed 15,000 $\text{min}^{-1} \leq n \leq$ 55,000 min^{-1}
- 86 % reduction of time to reach steady state Δt_w

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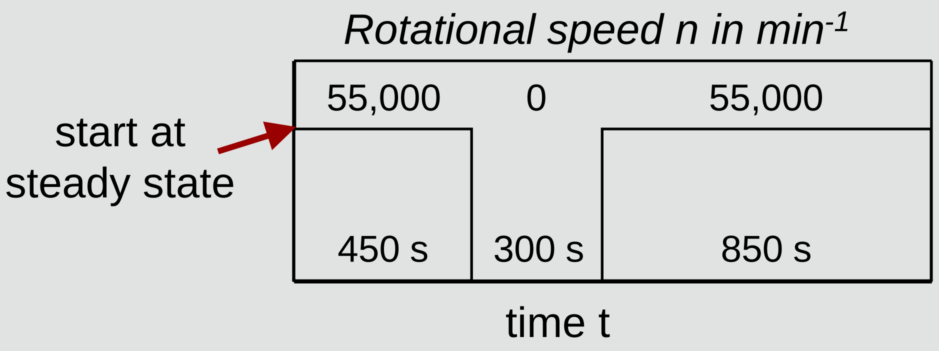
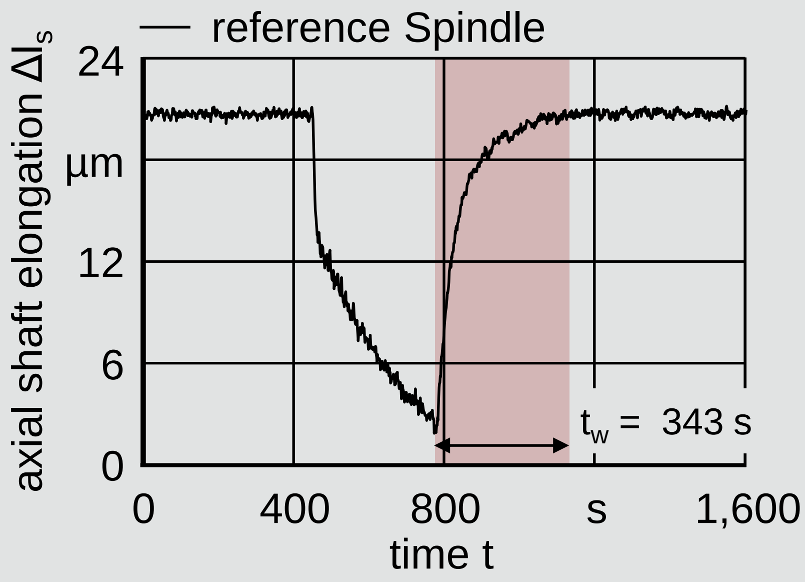
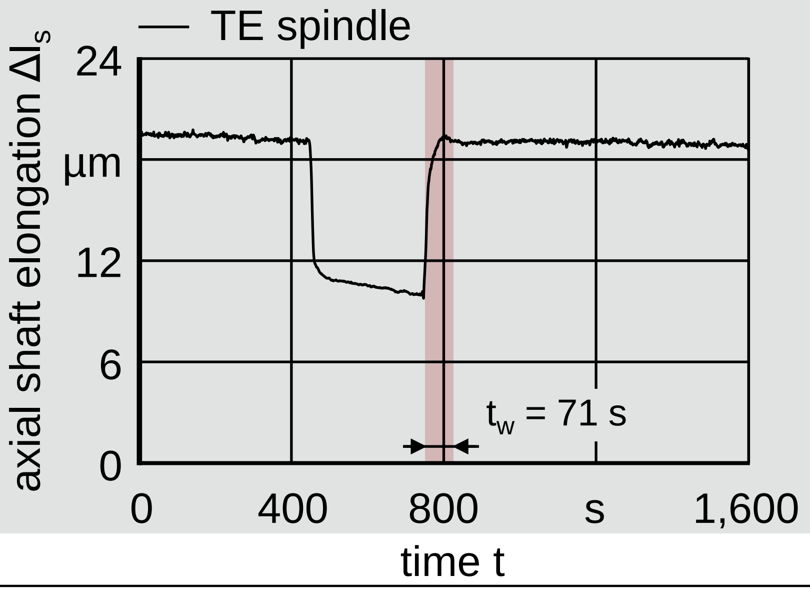
Advanced Spindle Systems – Integrated Thermoelectric Control



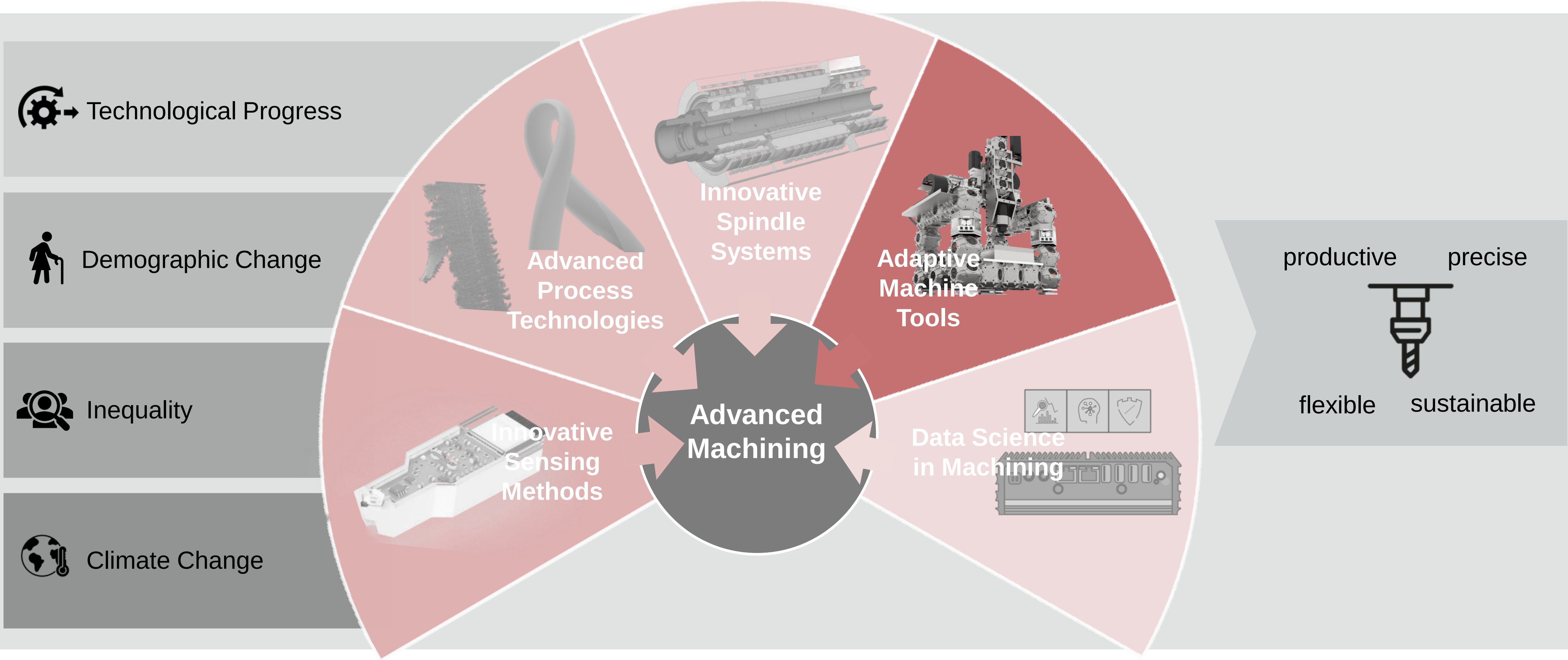


Economic Significance

- Reduction of non-productive times due to shorter warm-up processes
- Tests showed a reduction in energy consumption by 45 %



Developments in Advanced Machining - Key Innovations in Recent Years



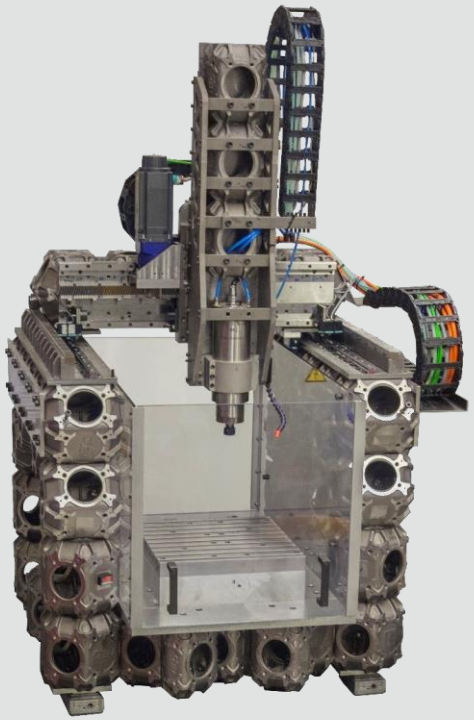
Technological Progress

Demographic Change

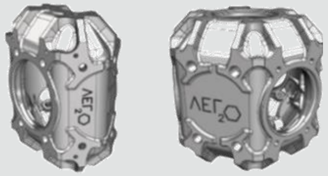
Inequality

Climate Change

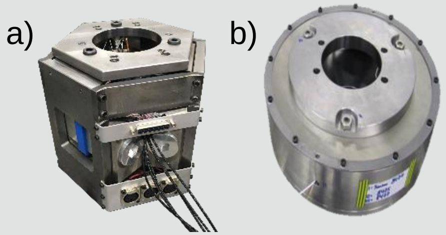
Adaptive Machine Tools – Modular Machine Structure



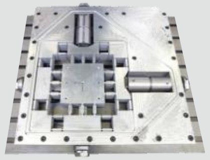
Modularized milling machine as a portal-configuration



Different shaped structural modules



Active modules; a) thermo-static compensation; b) active damping module



Workpiece fixture with build-in static-dynamic compensation

Initial Situation

- Monolithic machine structures have several disadvantages
  - Lack of adaptability to different workpieces
  - High production costs at small batch sizes
  - Limited possibility to retrofit various components

Motivation for Modularization

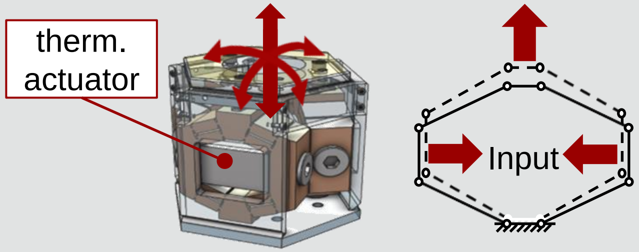
- Scalable, flexible and reusable machine tool structure
- Compensation of modularization deficits through active modules
- Automated methods and tools to shorten the planning and design phase

Adaptive Machine Tools – Modular Machine Structure

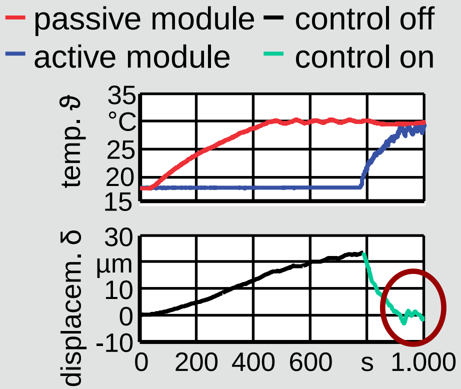
Results

- Active components enable increases in accuracy and performance

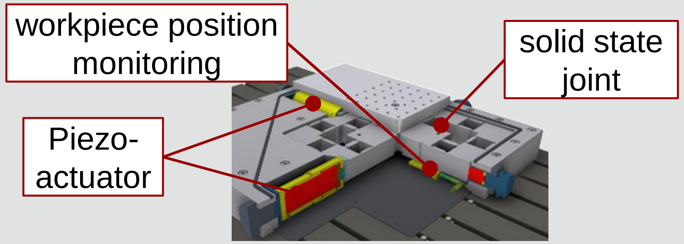
Thermo-static compensation



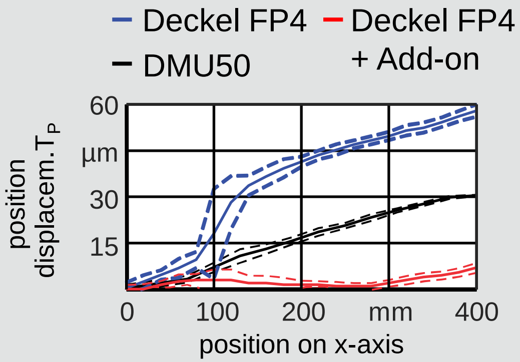
Active component for compensating thermally induced displacement



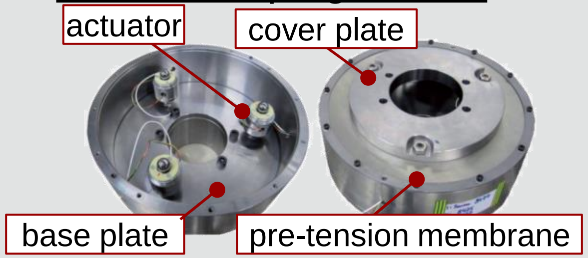
Static-dynamic compensation



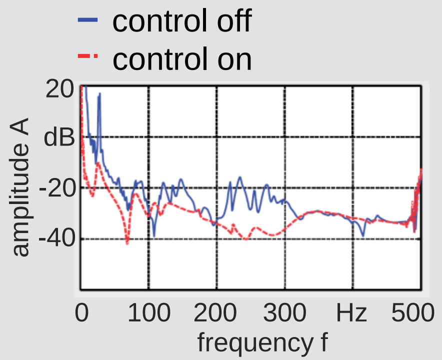
Active component for compensating position accuracy



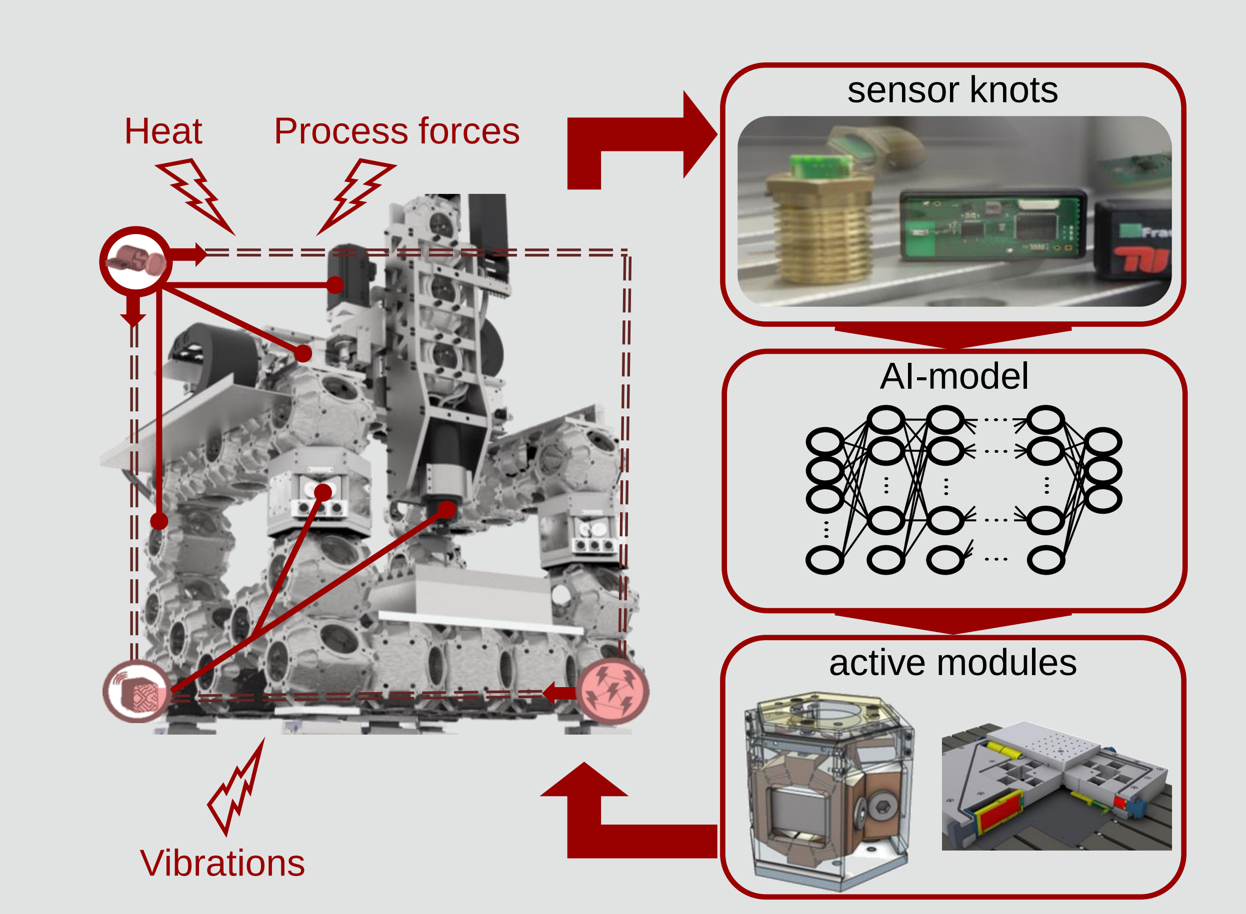
Active damping control



Active component for compensating the dynamically induced displacement



Adaptive Machine Tools – Modular Machine Structure



Self-optimization through AI models and active components

Challenges

- Heat, process forces and vibrations are limiting the machining results

Target

- Increased performance and accuracy through self-optimization of the machine tool

Solution approach

- Self-sufficient sensor nodes for disturbance variable detection
- AI models for forecasting and deriving needs-based compensation strategies
- Modular system with active components for performing compensatory actuating movements

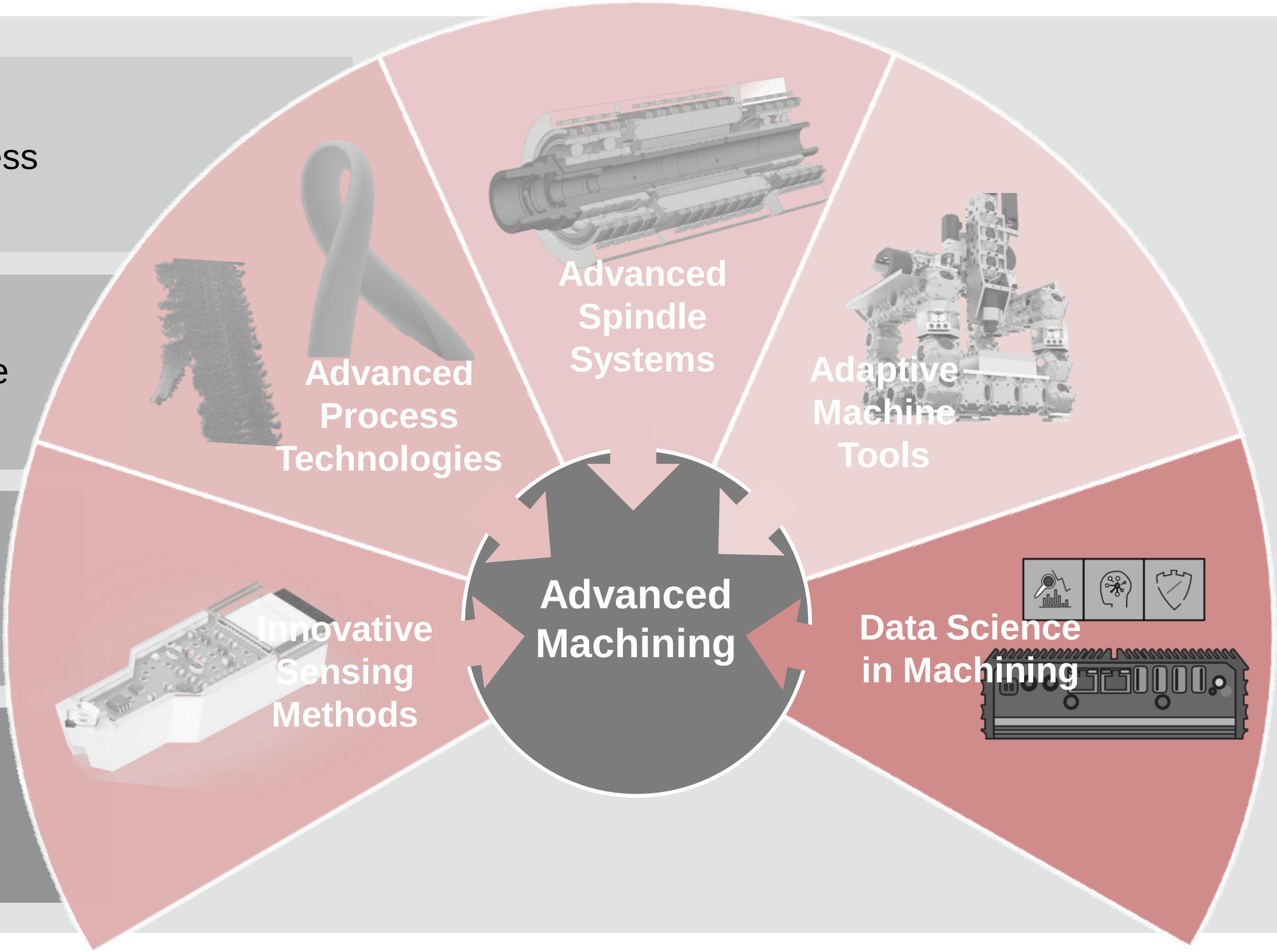
Developments in Advanced Machining - Key Innovations in Recent Years

Technological Progress

Demographic Change

Inequality

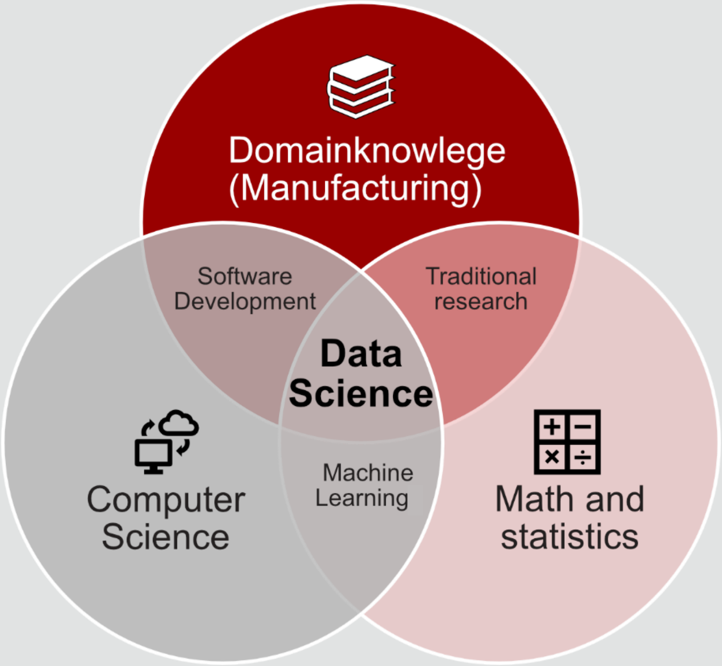
Climate Change



productive precise

flexible sustainable

Data Science in Machining – Implementation of Edge Devices



Data Science as venn-diagram

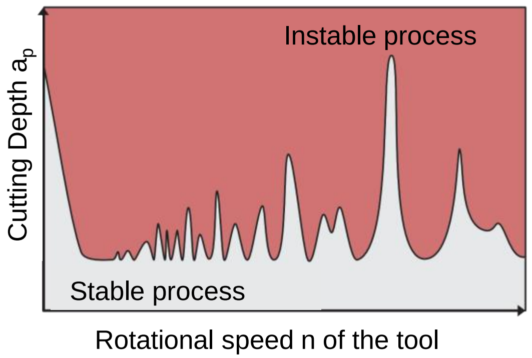
Basics of Data Science

- Interdisciplinary scientific approach
- Main goal: extracting desired information from a large mass of available information
- Combine specific expertise with extracted data to gain knowledge

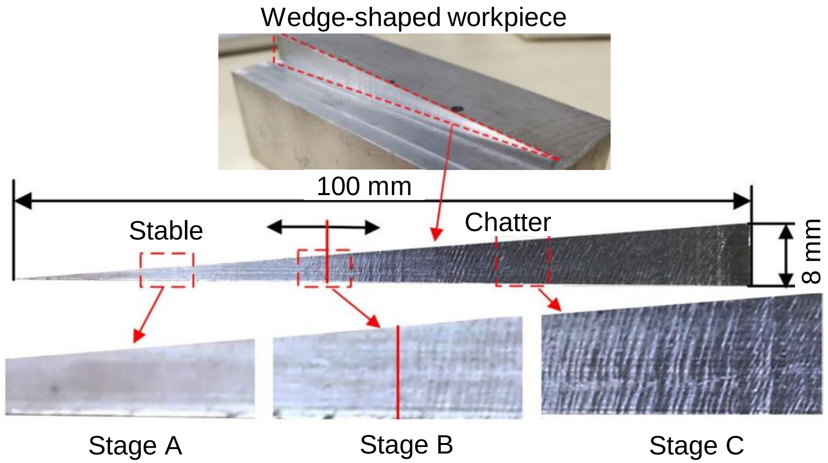
Typical Workflow

- Data acquisition with sensor systems (e.g. IoT)
- Saving and pre-processing
- Data analysis to identify main effects and major correlations
- Visualization to exceed comprehensibility

Data Science in Machining – Implementation of Edge Devices



Schematic representation of the process stability

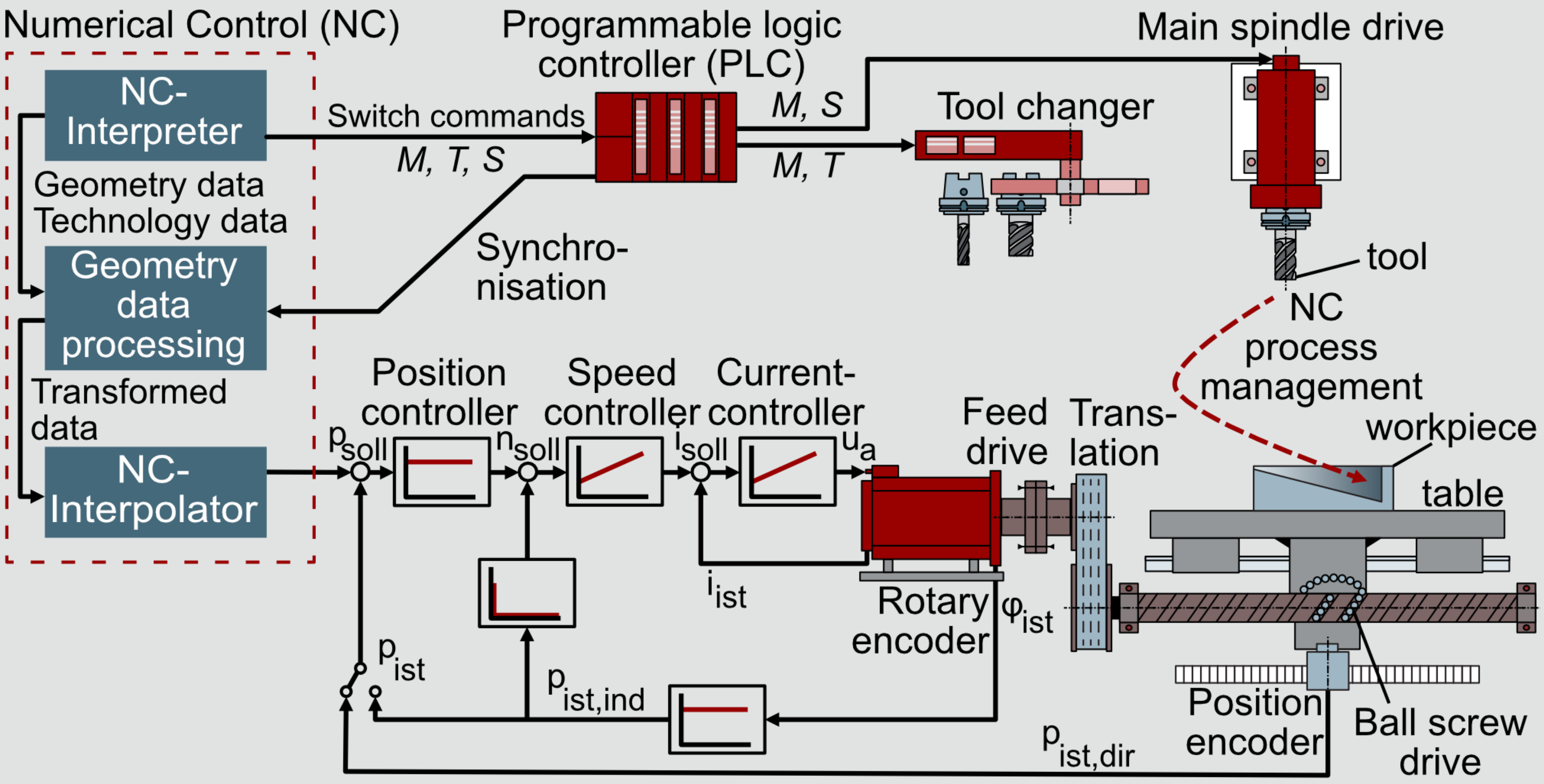


Influence of the cutting depth a_p on the chatter behavior

Application Case for Machine Data: Chatter Reduction

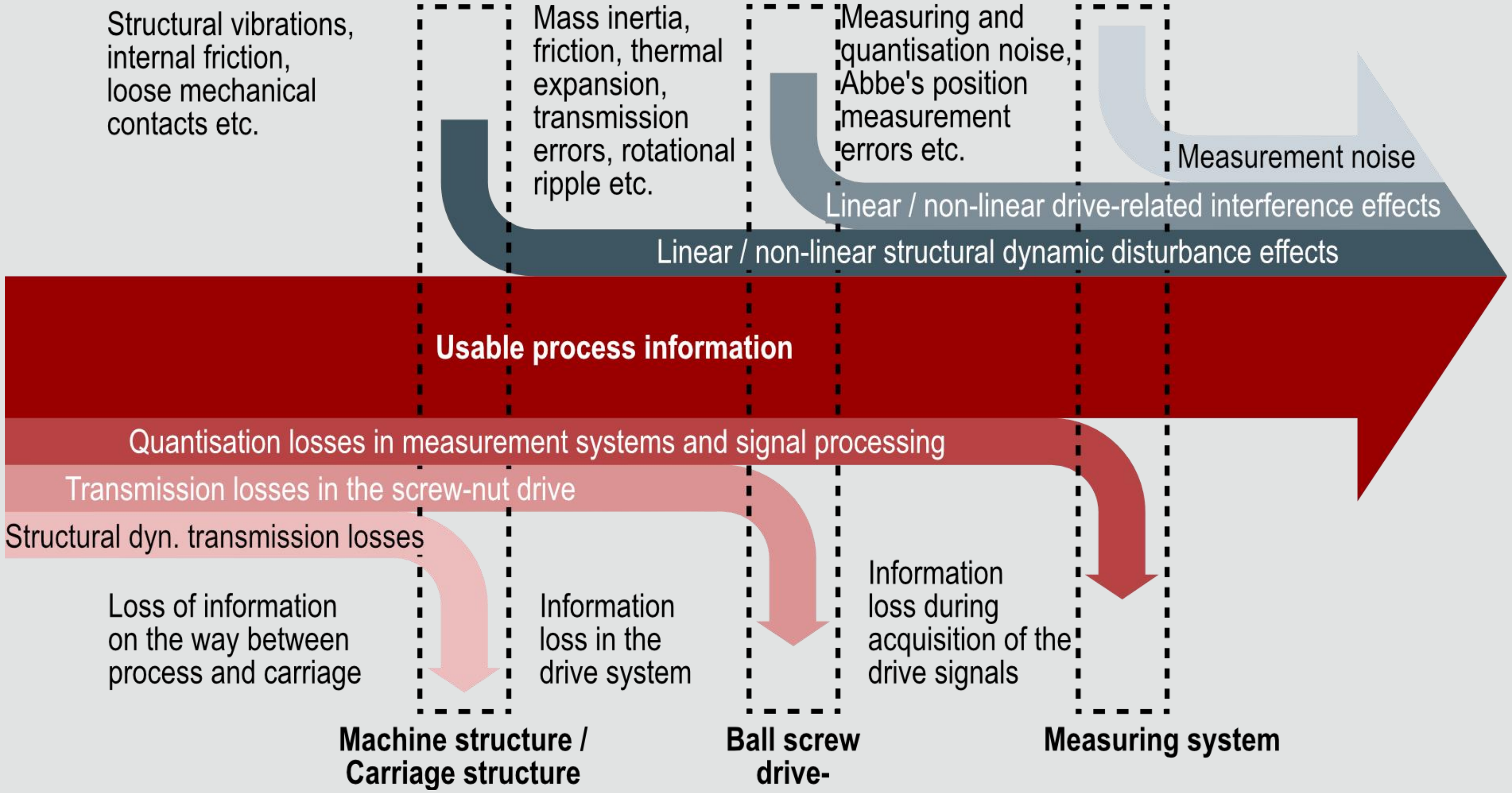
- Machine-related influencing parameters
  - Foundations, mounting conditions
  - Slide and machine table movement
  - Spindle speed
- Tool- or workpiece-related influencing parameters
  - Workpiece compliance
  - Workpiece clamping condition
  - Tool mass
- Process-related influencing parameters
  - Cutting edge geometry
  - Tool wear
  - Feed, Cutting speed

Data Science in Machining – Implementation of Edge Devices



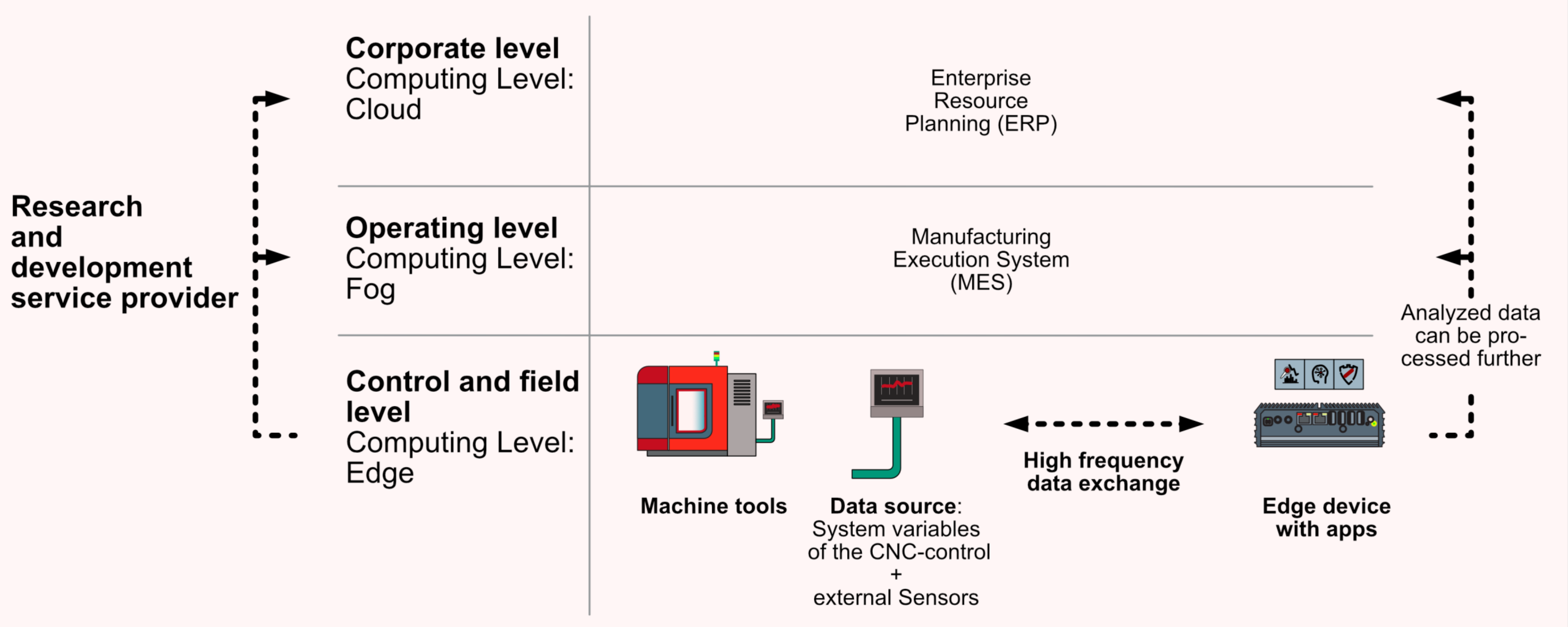
Signal flow in a control unit within a typical CNC-machine

Data Science in Machining – Implementation of Edge Devices



Machine tool as a data source: Breakdown and composition of all available process information

Data Science in Machining – Implementation of Edge Devices



Research and development service provider

Corporate level
Computing Level: Cloud

Enterprise Resource Planning (ERP)

Operating level
Computing Level: Fog

Manufacturing Execution System (MES)

Control and field level
Computing Level: Edge

Machine tools

Data source: System variables of the CNC-control + external Sensors

High frequency data exchange

Edge device with apps

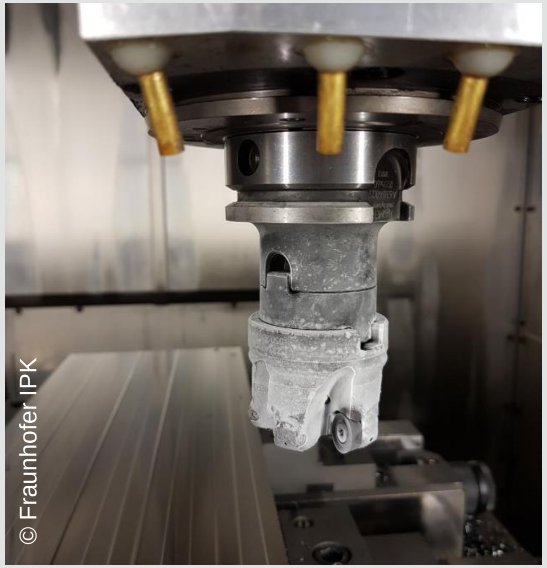
Analyzed data can be processed further

Future of Applied Information Technology in Machining

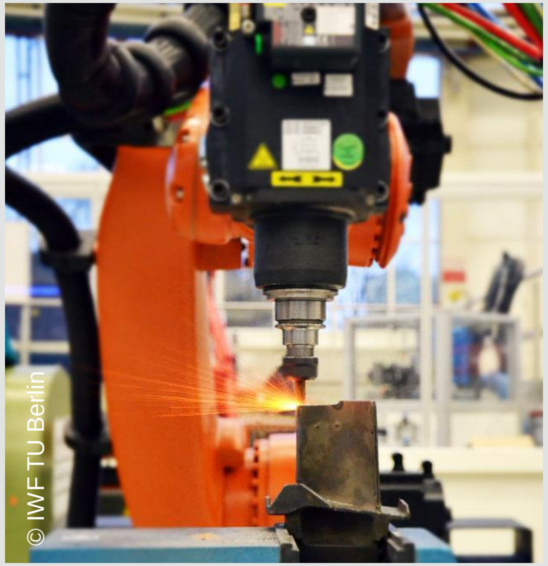
Institute for Machine Tools and Factory Management

Manufacturing Technology

Automatization of manufacturing processes



Development of cryogenic cooling concepts for machining advanced materials



Machining of large structures with a high grade of geometric flexibility using six-axes industrial robots

Development and optimization of process technologies for hard to machine materials

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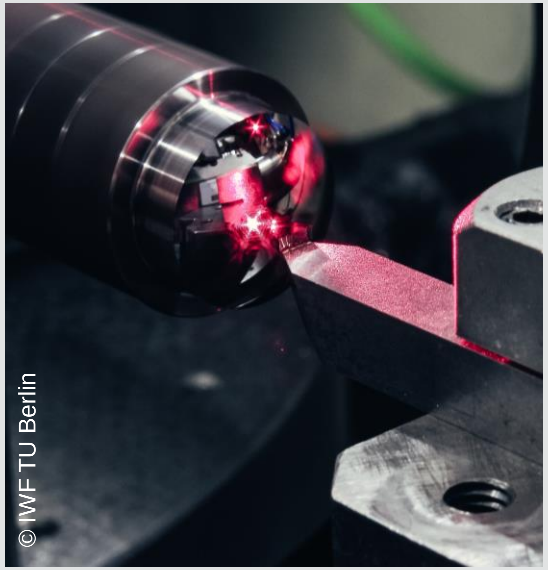
High- and Ultra-Precision Machining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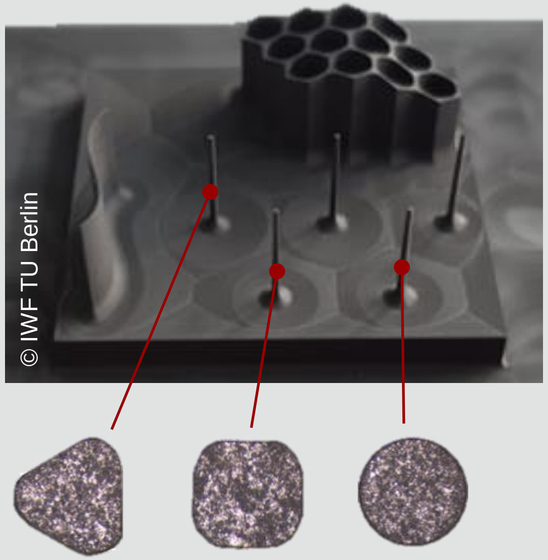
UP-Turning of optical components with surface qualities Ra < 10 nm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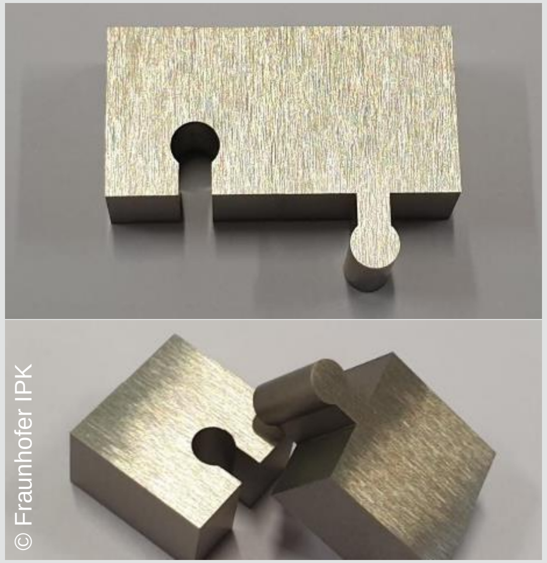
Micro-Milling of complex structure made from graphite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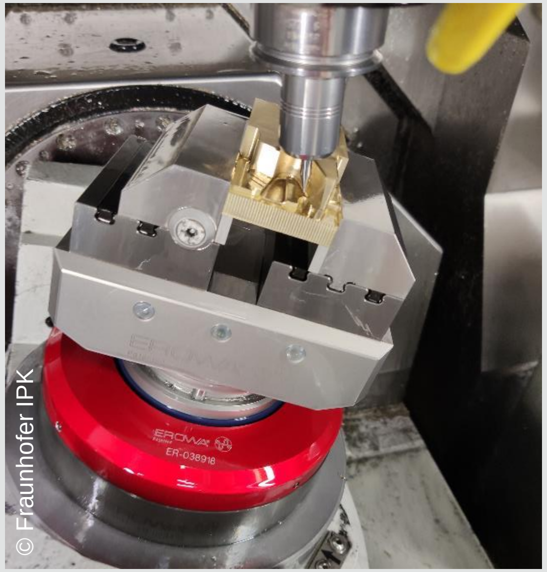
Manufacturing of high precision steel parts with micro-EDM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Process optimization of 5-axis milling operations

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Development of Advanced Machine Components

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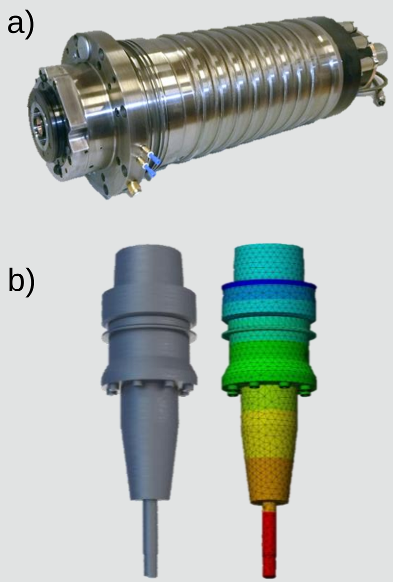
Ultrasonic system for ultra-precision turning processes

<u>Ultrasonic system for</u> <u>**turning** applications</u>

- Superimposition of the tool movement with a 1-dimensional oscillation
- Reduction of the temperature ϑ in the cutting zone
- Possibility to machine steel materials with monocrystalline diamond tools

- Frequency f up to 100 kHz
- Amplitude A up to 3 µm



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Ultrasonic oscillation system; a) milling spindle; b) toolholder with integrated ultrasonic actuator

<u>Ultrasonic system for</u> <u>**milling** applications</u>

- High precision milling spindle
- Integrated current transfer system
- Utilization of the smallest tools

- Spindle speed n up to 40.000 rpm
- Frequency f up to 65 kHz
- Amplitude A up to 2.5 µm

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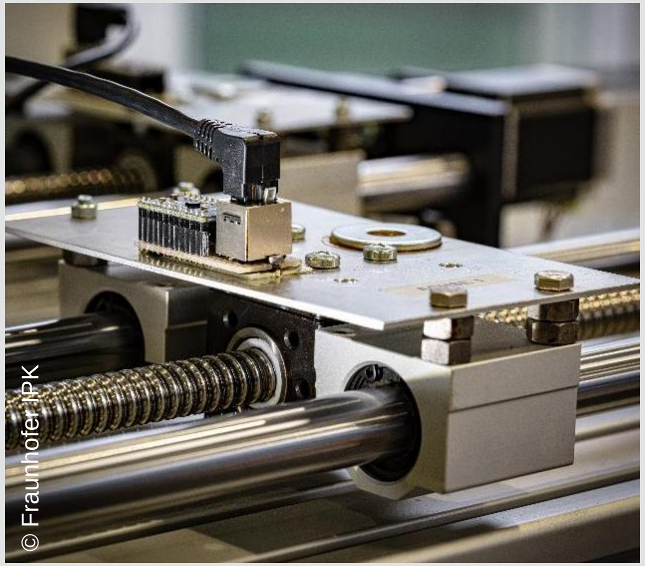
Data-based Optimization on Manufacturing Processes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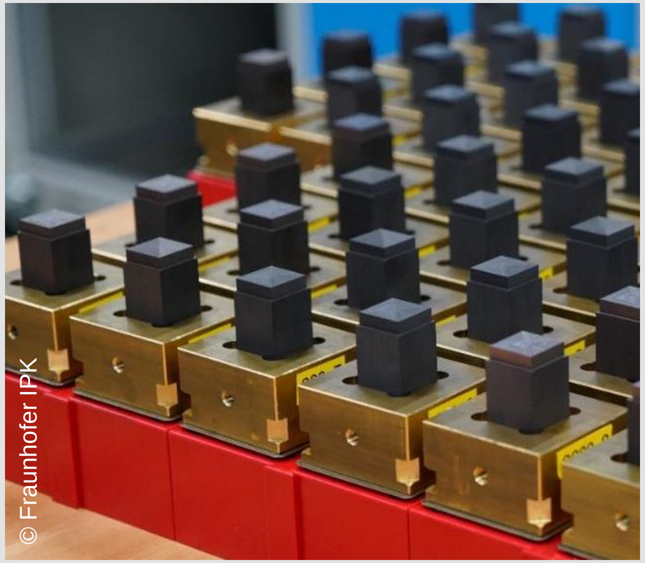
Implentation of IoT-based systems to enhance productivity and recognize machine failures at an early stage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Optimization of stochastic processes using evolutionary algorithms

Development and validation of IoT-architectures and data-pipelines to combine multiple data sources

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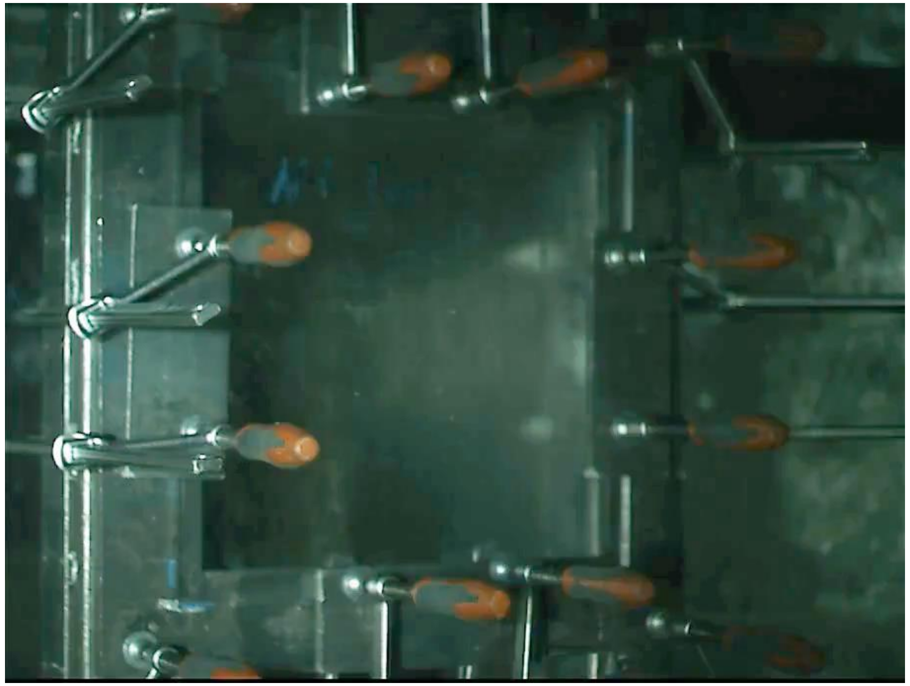
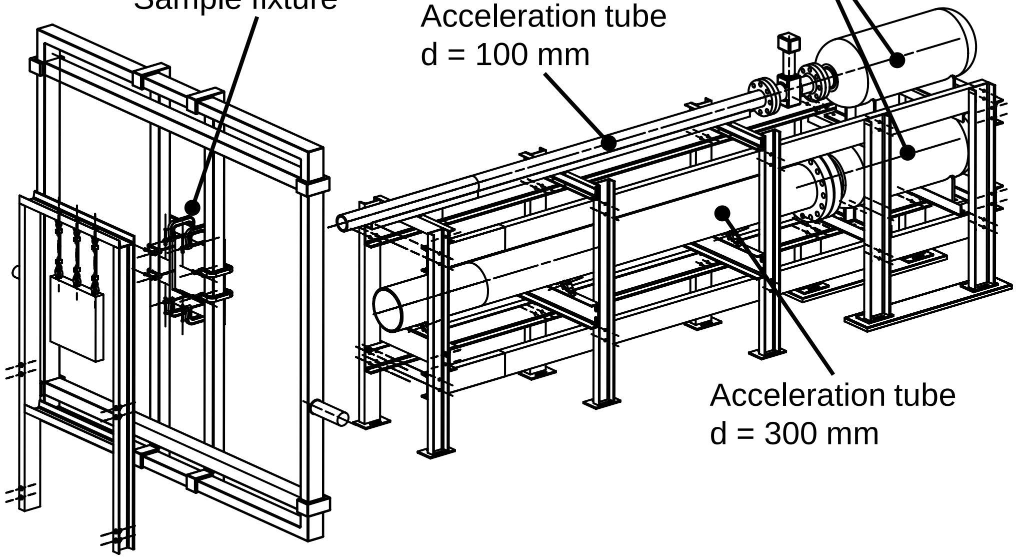
Particle Accelerator of a different kind



High speed footage of an impact test with a tool fragment



Test facility to investigate the impact resistance of safety glass on machine tools

Thank you for your interest

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