ipt INSTITUTO DE PESQUISAS TECNOLÓGICAS

## COMUNICAÇÃO TÉCNICA

**Nº 176488**

# Micro-O micro milling process optimization

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# Micro-O
# Micro Milling Process Optimization

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# Content

- Market demand
- Micro-machining
- Micro-O project
- Development of the virtual machine tool
- Application transfer

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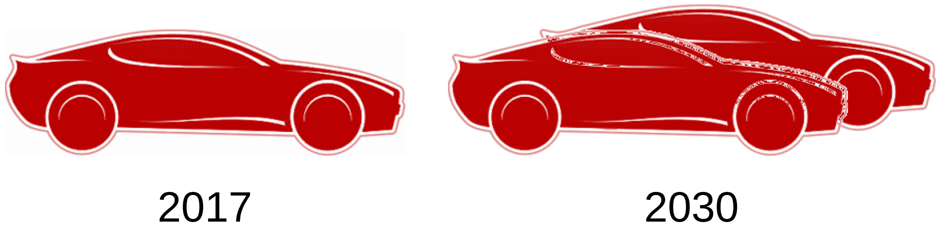
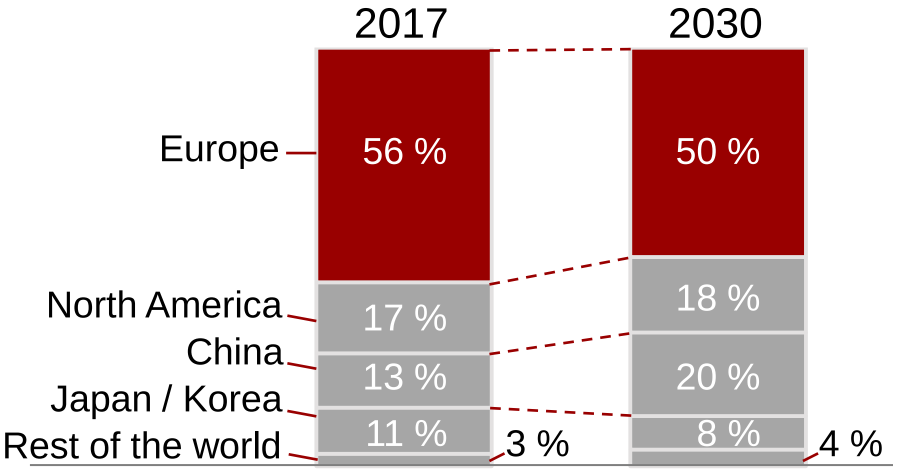
# Market demand
## The need to increase productivity

By 2030, vehicle production will **increase** by **30 % to 123 million** units worldwide




*Change in the share of value added in automotive engineering*

By 2030, Europe's share of value added in the automotive industry will **fall** from **56 % to 50 %.**

**The global market is changing**

Future Automotive Industry Stock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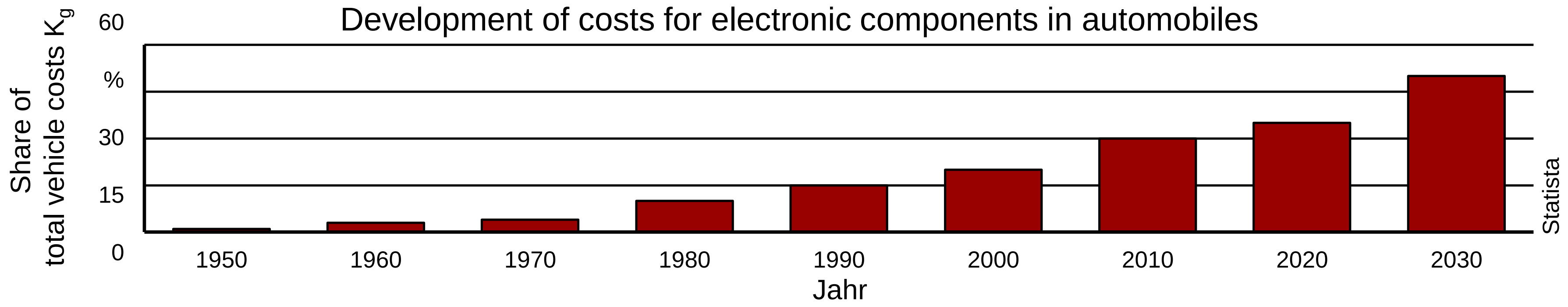
# Market demand

## The need to increase accuracy

| 1980 | 2018 | Concept |
| --- | --- | --- |


- Analoge display
- Analoge control panel

- Fully digitized systems
- Eyetracking and voicecontrol
- Personalizable and cloud-based



# Market demand
## The need to increase accuracy

**Digital wing**

www.profil-marketing.com

**Head-up-display**

www.kogan.com

www.audi-mediacenter.com

Geometrical accuracy of the lence
**0,5 µm ≤ T ≤ 5,0 µm**

Arithmetic average of the roughness profile
**2 nm ≤ Ra ≤ 5 nm**

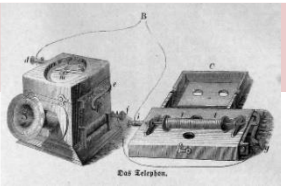
Geometrical accuracy
of the windshield **T = 5 µm**

# Market demand

## Need to increase accuracy

**Telephony**

Philipp Reis (1863)



schi.org

Fuld & co (1930)

C. Vittoratos

Nokia 3210 (1999)


Nokia

**Computer Technology**

Zuse Z1 (1938)

kawala.de

Amiga 600 (1992)

A. Jones

Lenovo Ideapad (2015)

Lenovo

**Photography**

Coated Tin Plate (1826)

R. A. Moss

AGFA Box 50 (1949)

M. Reisner

Leica AF-C1 (1990)


CC BY-SA 4.0

Smartphone Galaxy S9 (2018)

**Phone:**
Micro-joining

**Camera lens:**
UP-turning
**Injection moulding**
*Tolerance T < 1 µm*

**Board:**
Functional coating
Soldering

**Display:**
Functional coating


Samsung


*147.7 mm*

*68.7 mm*

**Speaker & Microphone:**
EDM-drilling
*Tolerance T < 5 µm*

**Housing:**
**Micro-milling**
Die-sinking EDM
Injection moulding
*Tolerance T < 5 µm*

*Source: Samsung*

# Content

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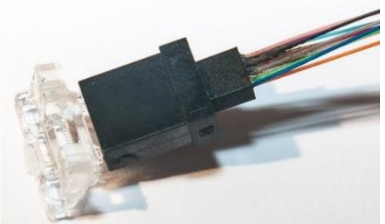
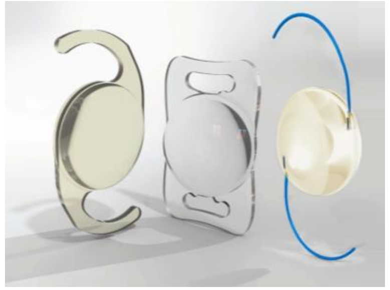
# Micro-machining
## Where does micro-machining start?

### Fiber coupler



- Lens diameter $d_{lens}$ = 220 µm
- Geometrical accuracy $T_{Lens} \leq 5$ µm

### Intraocular lens



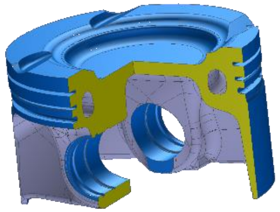
www.aumedo.de

- Length of lens $l_{lens}$ = 30 mm
- Geometrical accuracy $T_{lens} \leq 3$ µm

**Micro-machining?**

### Engine piston

- Drill hole diameter $d_{drill}$ = 25 mm
- Geometrical accuracy $T_{drill} \leq 5$ µm



MAHLE

### Marine diesel engine

- Cylinder drill hole diameter $d_{drill}$ = 695 mm
- Geometrical accuracy $T_{drill} \leq 30$ µm

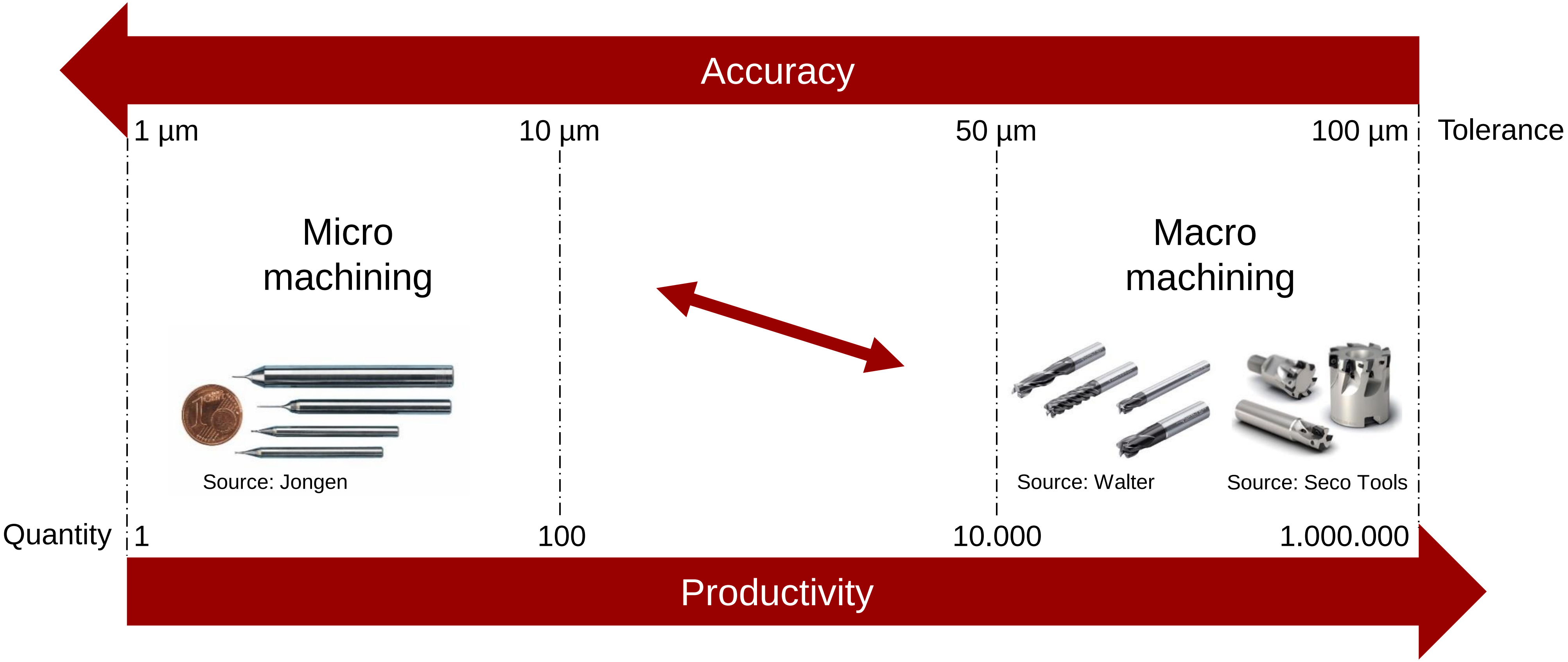
MAN Energy Solutions

# Micro-machining
## Definition of micro-production engineering

- (…) too small to be machined easily. (…) 1 µm to 500 µm was adopted as the range for this keynote paper.
  *Masuzawa, 2000, State-of-the-art Micro-machining*
- (…) functional features or at least one dimension are in the order of µm.
  *Alting et al., 2003, Micro Engineering*
- Dimensional micro metrology is (…) defined (…) considering at least one critical dimension or functional feature in the micrometer range.
  *Hansen et al., 2006, Dimensional Micro and Nano Metrology*
- (…) micro-scale production is defined as the production of goods with at least one critical dimension or at least one function-critical tolerance in the range of single micrometers.
  Uhlmann et al., 2016,
  *Process Chains for High-Precision Components with Micro-Scale Features*

# Micro-machining

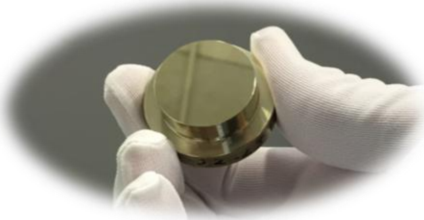
## Challenges | Classic consideration of accuracy and productivity



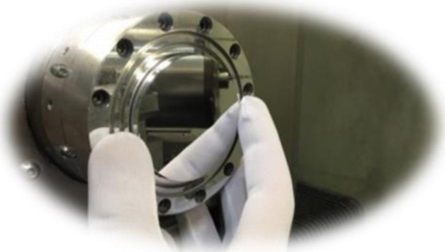
# Micro-machining
## Challenges | Micro-production engineering

Feature sizes in micrometer or nanometer range

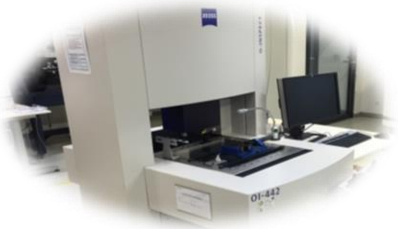
Manufacturing of reference surface



Realignment of workpieces



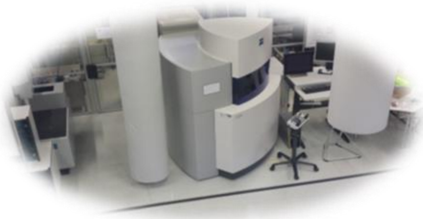
Intermediate metrology steps



**Micro-machining**

Process monitoring and automation


Environmental conditions

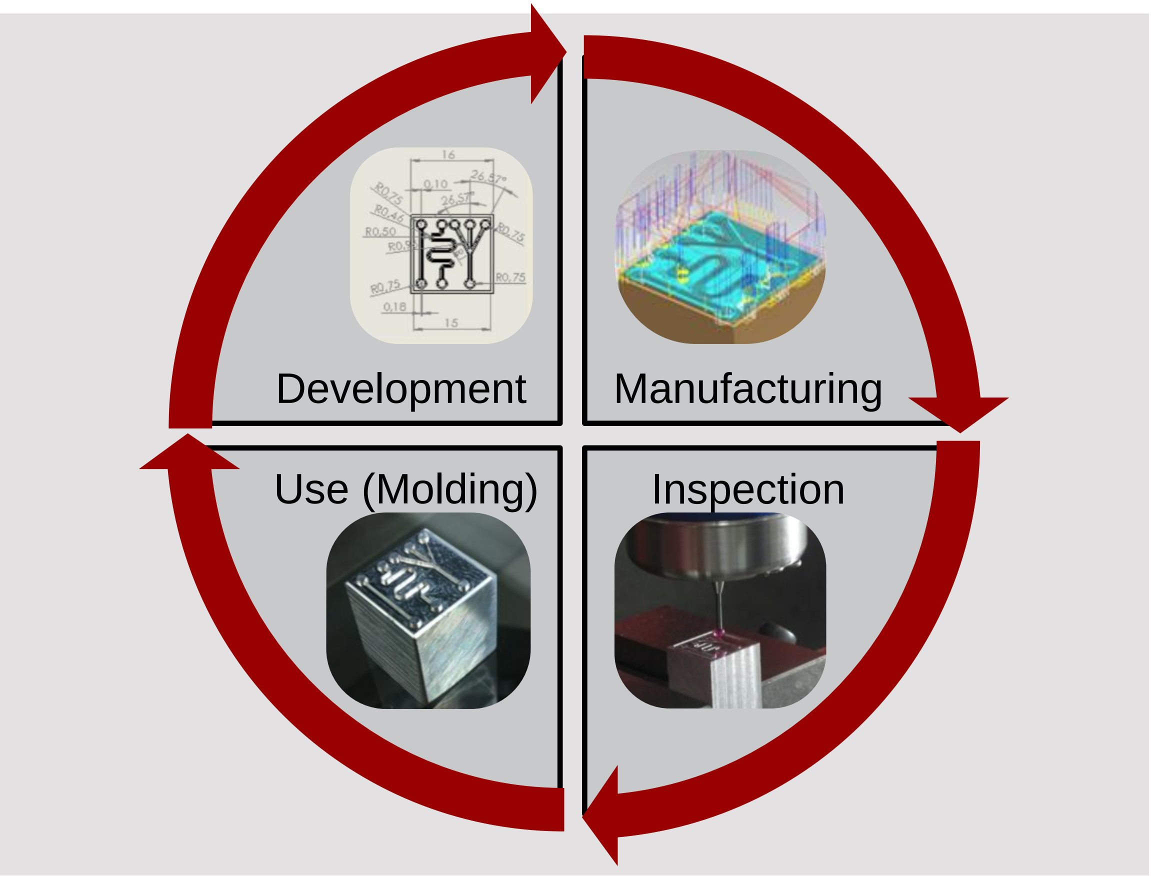


Machine tool systems

# Content

- Market demand
- Micro-machining
- Micro-O project
- Development of the virtual machine tool
- Application transfer

# Micro-O project
## Motivation

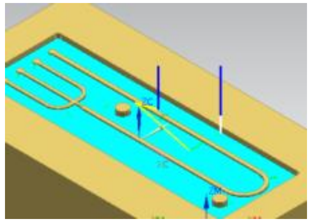



- Increasing demand for micro-structured parts and products requires enhancing the productivity
- Increased pressure on highly developed industry due to strong competition and low labor cost
- Focus on high quality and improvement of innovative, reliable, advanced technologies
- Integrate the experience and data from the entire manufacturing chain:
  - Product development
  - Manufacturing
  - Inspection
  - Use (Molding)

Source: IWF, IPT, UFABC, SCPM

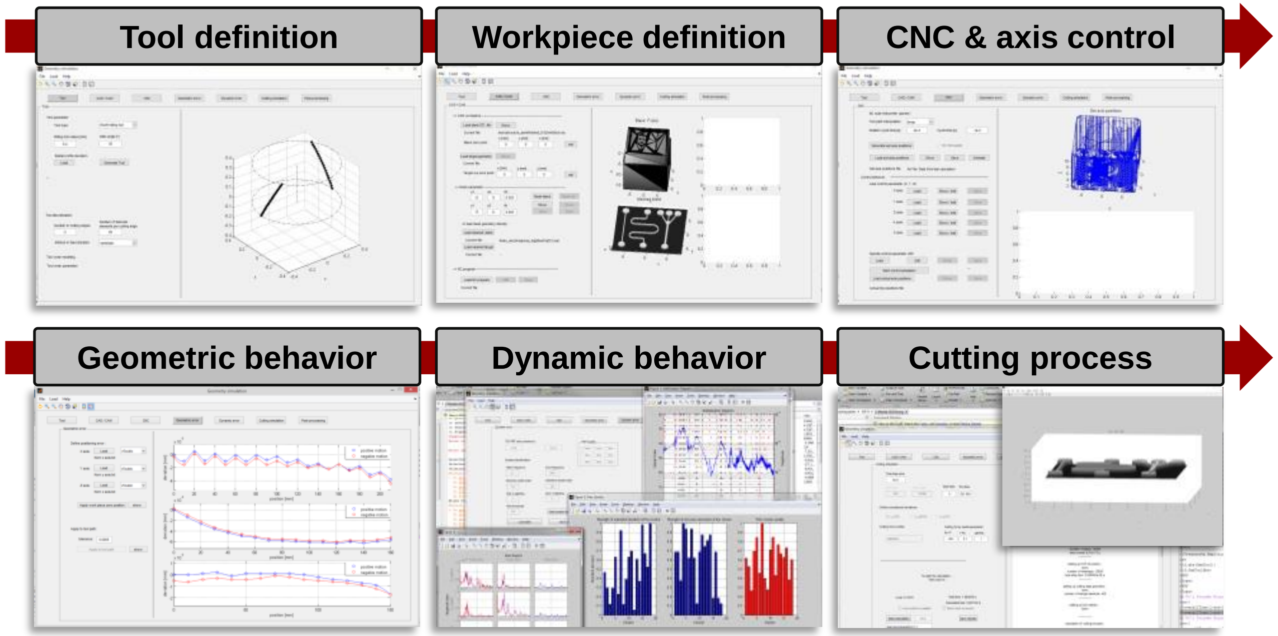
# Micro-O project
## Basic approach

Development of a virtual machine as a digital twin of the Kern EVO machine tool:

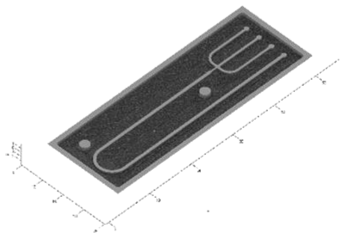


- **Tool form**
- **Part model**
- **NC program**

Virtual machine input




Virtual machine tool interface



- **Surface topography**
- **Process forces**

Virtual machine output

# Content

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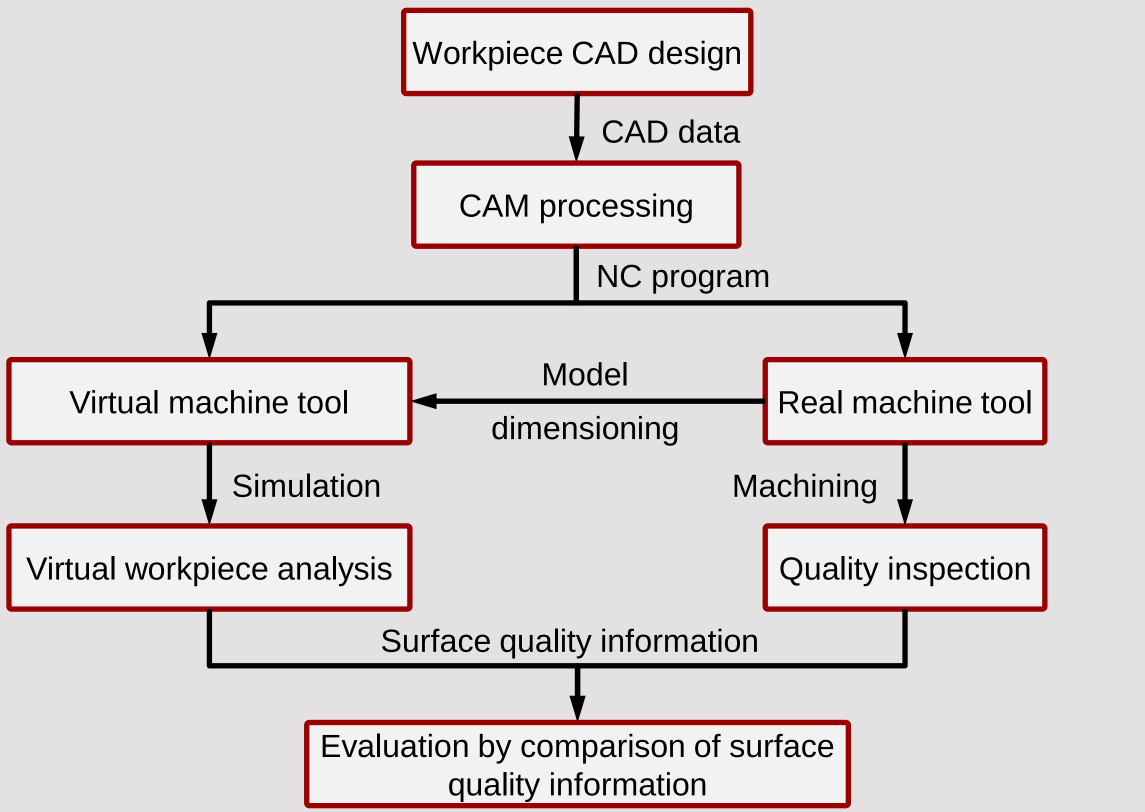
# Development of the virtual machine tool
## Approach



Evaluation procedure

- CAM programs are able to handle micro-milling processes and derive NC programs with tool path
- Conduction of experimental tests to determine
  - related cutting forces,
  - surface roughness,
  - machine tool behavior
  - and adjust the virtual machine tool models
- Parallel machining and simulation to derive virtual and real workpiece with micro-features
- Comparison of topography and surface roughness of the workpieces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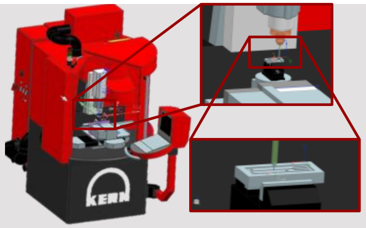
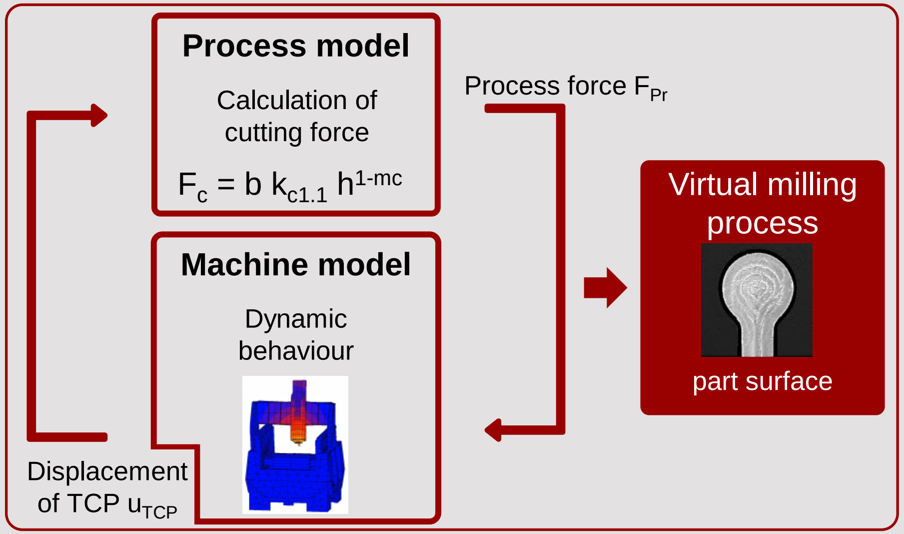
# Development of the virtual machine tool
## Approach



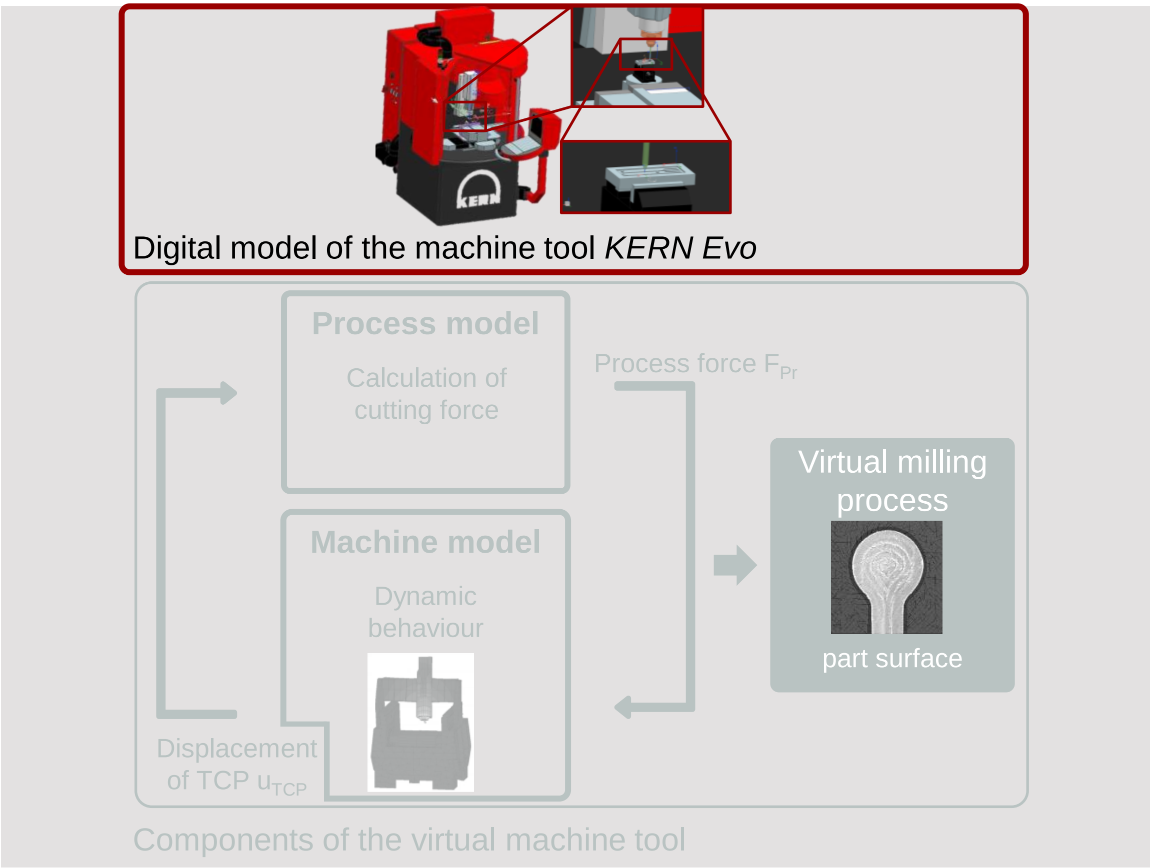
Digital model of the machine tool *KERN Evo*




Components of the virtual machine tool

- Development of a virtual machine as digital twin of the machine tool *KERN EVO*
- Coupling of process and machine model
  - Cutting force calculation according to Kienzle
  - Consideration of dynamic machine behavior
  - Simulation of the part surface
- Surface topography and process forces as output of the virtual milling process

# Development of a virtual machine tool
## Digital model




### Digital model

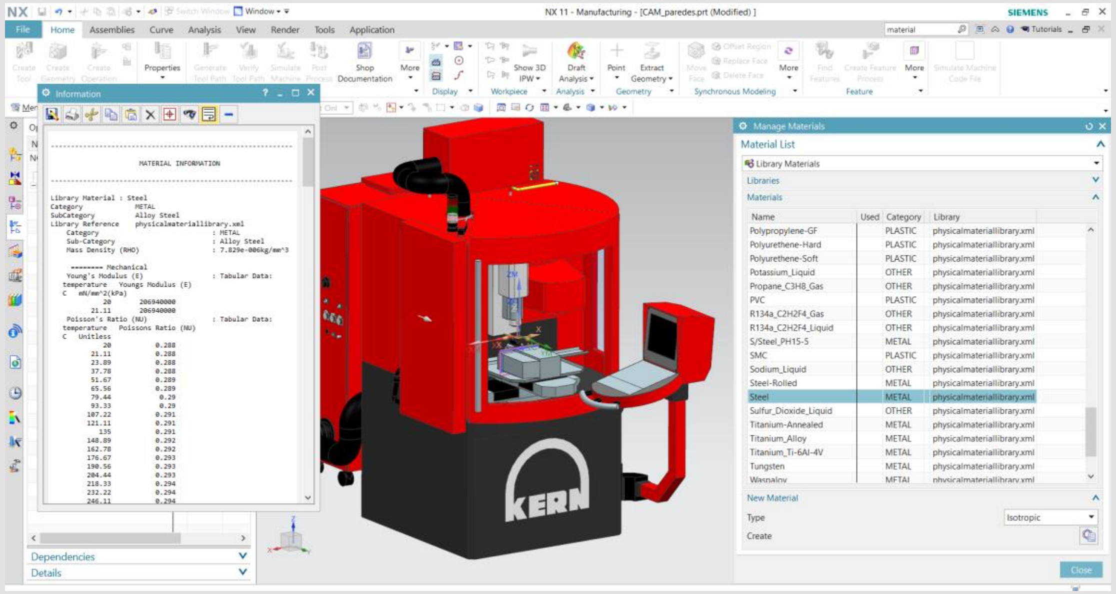
- Real machine elements (body, spindle, tool changer, axes, fixture, accessories, etc…) modeled
- All geometries connected with position frames and kinematic chains to simulate all moving elements
- Use of a virtual numeric control kernel identical to the real machine to control all motions

### Main subject

- Process planning

# Development of the virtual machine tool

## Digital model | Process planning




Process library and digital model integrated in NX10

- Simulate the process for optimizations, safety check and to reduce machining costs and try outs
- Integrate the whole product information, from development, manufacturing, inspection until use
- Creation of a live and updated library integrated in CAD/CAM system with:
  - Cutting strategies and parameters, materials, tools and best practices from project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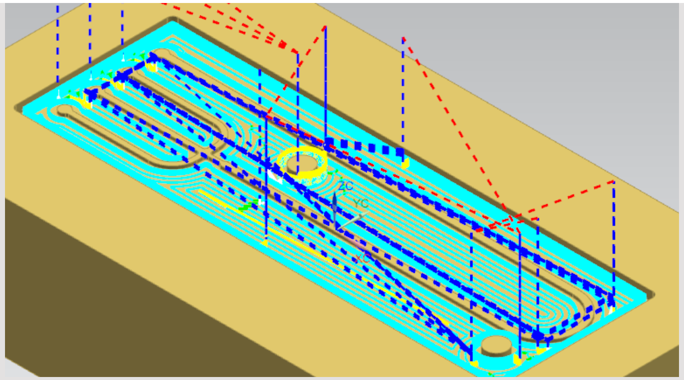
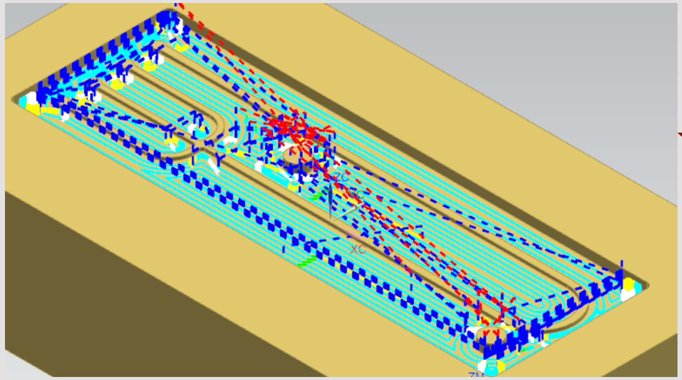
# Development of the virtual machine tool
## Digital model | Process planing



NX10: 8th generation CAM program - machining time: 2:00:06



NX10: 9th generation CAM program - machining time: 1:40:23

**Reduction of time only in this step:**

**16.4 %**

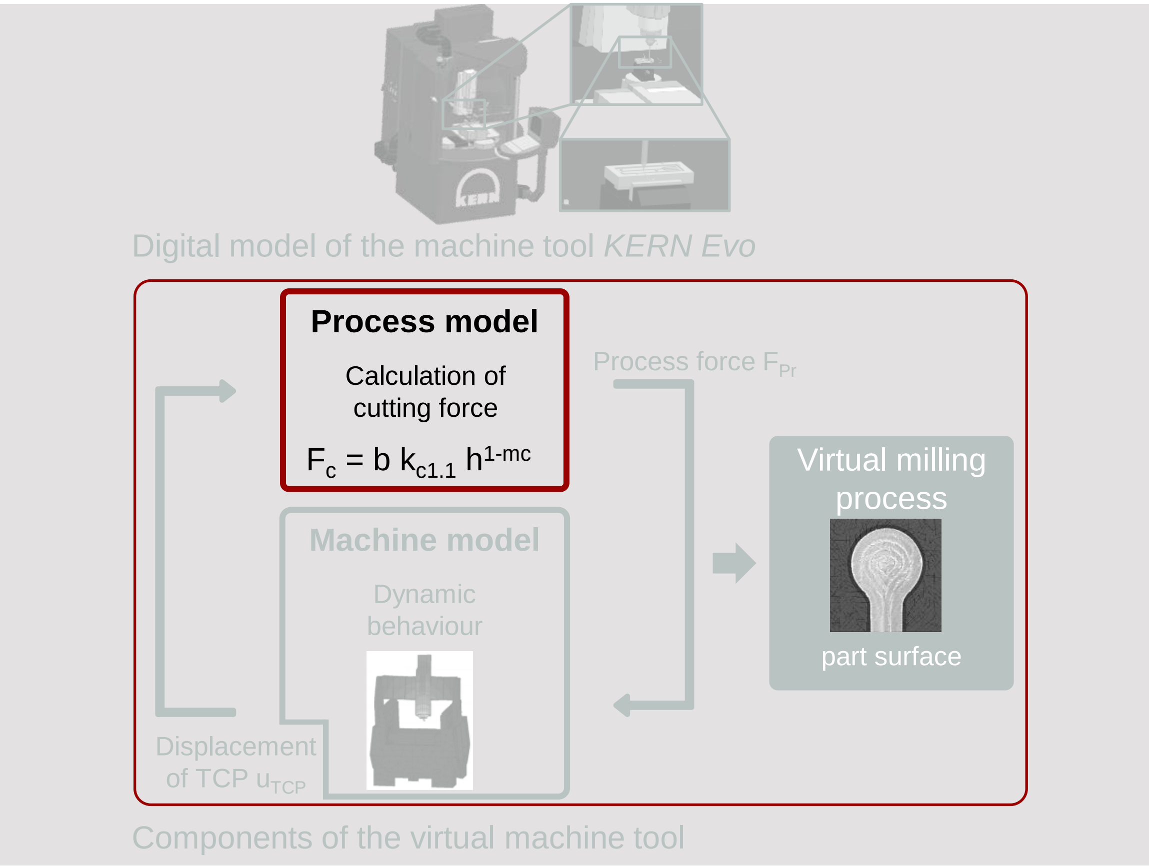
### Achievement

- Virtual model emulates real machine’s axis speed, acceleration, jerk and control specific behavior
- Model used to detect collisions, improve cutting moves and study material left for optimizations
- Improved cutting strategies, methods, parameters and engage/retract strategies added to library

### Enhancement

- Reduction of try outs and machining time
- Experience transfer by best practices library

# Development of the virtual machine tool
## Process model




### Process model

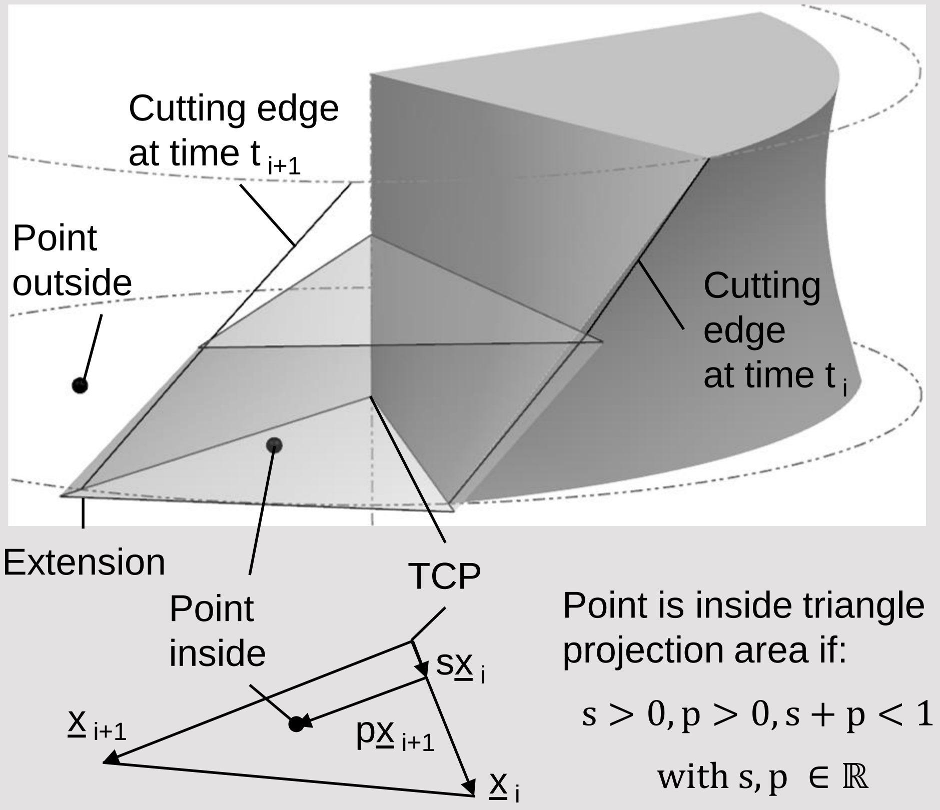
- Cutting force model is based on Kienzle equation
- Added the relation between radial and tangential cutting force to generate the direction vector
- Efficient Cutting force model with realistic cutting force mapping

### Main subjects

- Geometric cutting model
- Cutting parameter
- Tool wear analysis

# Development of the virtual machine tool

## Process model | Geometric cutting model



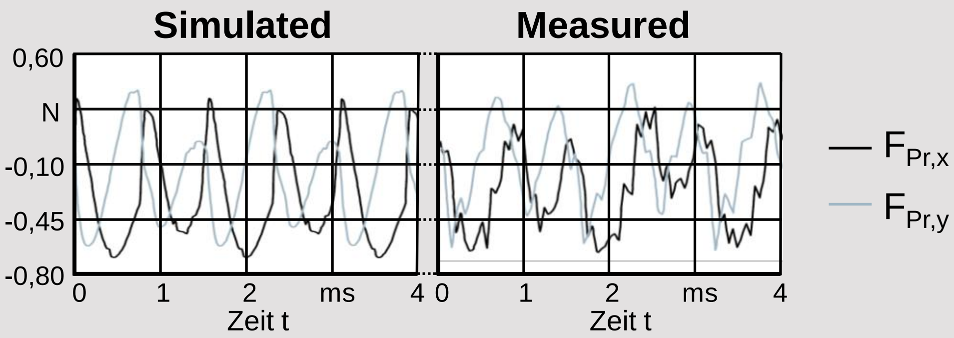

Basic idea of proposed discretized cutting procedure

- Simple and calculation efficient geometric detection
- Determination
  if a point lies within or outside a triangle
- ‘Hit box’ volume is described by
  movement of cutting edge and the
  discretized points in direction of the cutting edge
- Usage of triangle implies independent description of cutting edges (radius, form etc) and can be applied to radius as well as shaft milling tools

# Development of the virtual machine tool

## Process model | Geometric cutting model

| | | | process parameter |
|---|---|---|---|
| Machine tool: | Kern Evo | | $a_p$ = 10 µm |
| Tool: | Diameter | d = 0,4 mm | $a_e$ = 400 µm |
| | Blades | z = 2 | $f_z$ = 10 µm |
| Workpiece material: | X40CrMoV5-1 | | n = 40.000 1/min |




Comparison of the virtual machine tool and the process result

### Achievement

- Realistic mapping of process forces $F_{Pr}$
- Average deviation between simulated and measured process forces **$\Delta F_{Pr}$ < 11 %**

### Enhancement

- Main-time parallel and model-based process design
- Optimized machining process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# Development of the virtual machine tool

## Process model | Cutting parameter

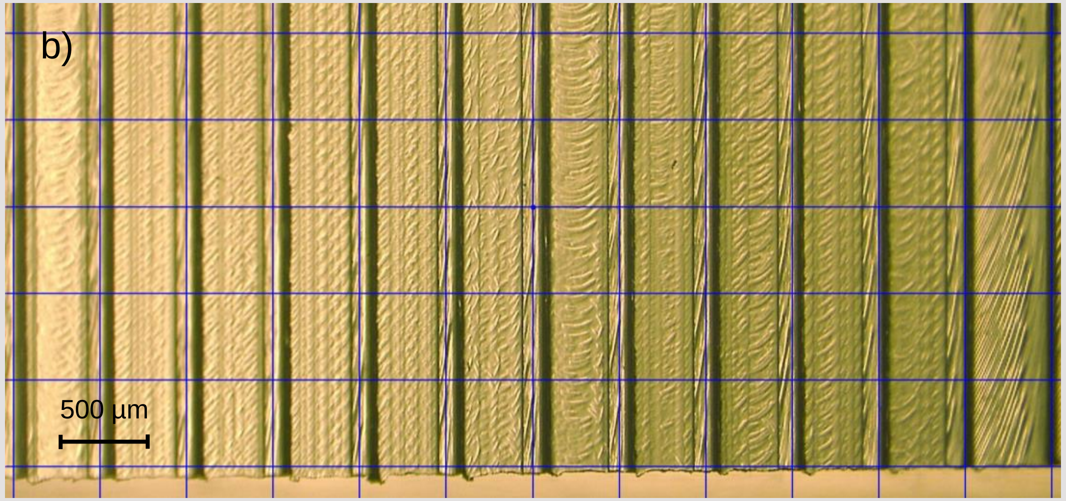
a)

**Lowest roughness achieved:**

Ra: 0.013 µm

**Experimental setup**

| | |
|---|---|
| Material: | X40CrMoV5-1 (H13) |
| Tool: | end mill d = 0.4 mm |
| $a_p$: | 4, 10, 20 µm |
| $a_e$: | 20, 40 µm |
| $f_z$: | 4, 10, 20 µm |
| n: | 30, 50 krpm |




Steps Experiment: a) Test piece, b) Steps surface

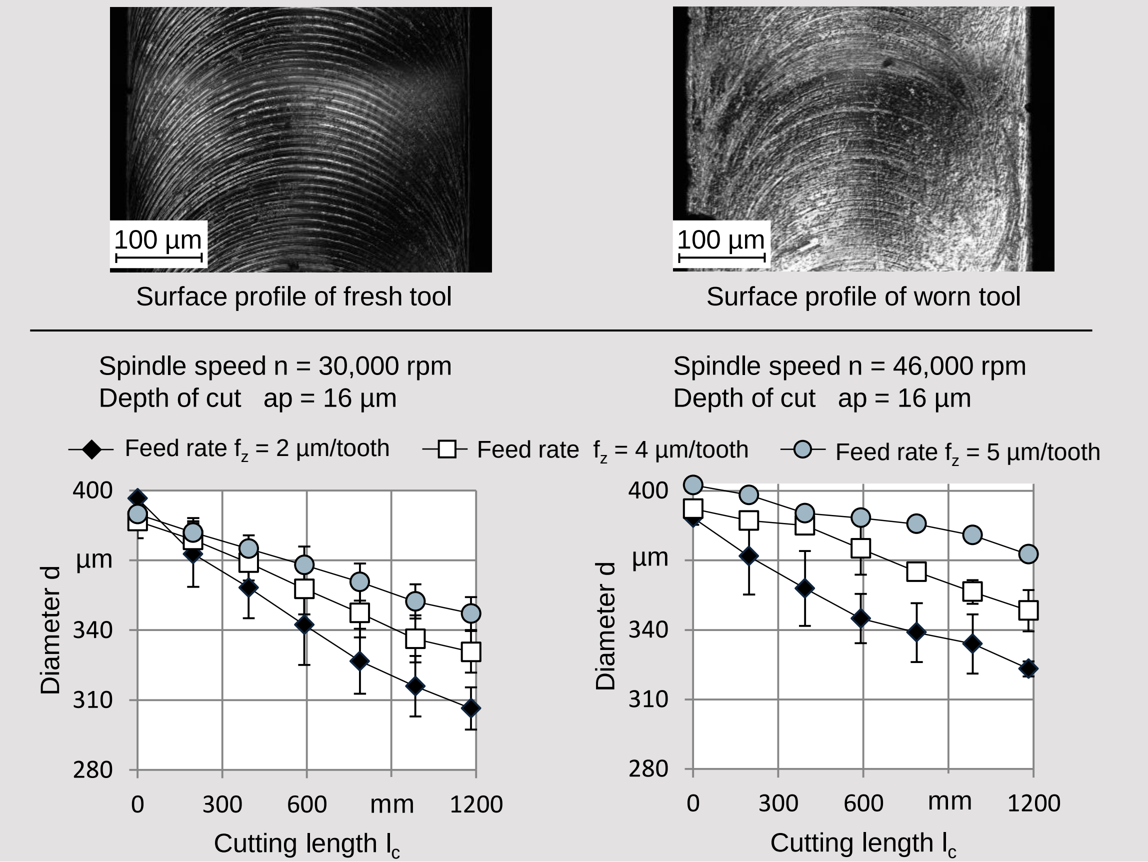
- Analysis of the effects of cutting parameters on roughness
- Knowledge integration into the virtual machine tool

### Achievement

- Balance between lower process times and required surface roughness, optimizing the milling process
- Milling process surface roughness similar to polishing, grinding and lapping, dismissing further finishing processes

# Development of the virtual machine tool

## Process model | Tool wear




- Tool wear affects the finish surface quality
- Gradual tool wear causes loss of cutting geometry, efficiency and leads to wear acceleration
- Study of tool wear
  in relation to cutting conditions and surface quality

### Achievement

- Tool diameter reduction model
- Provides a reliable simulation-based proposal for the tool change strategy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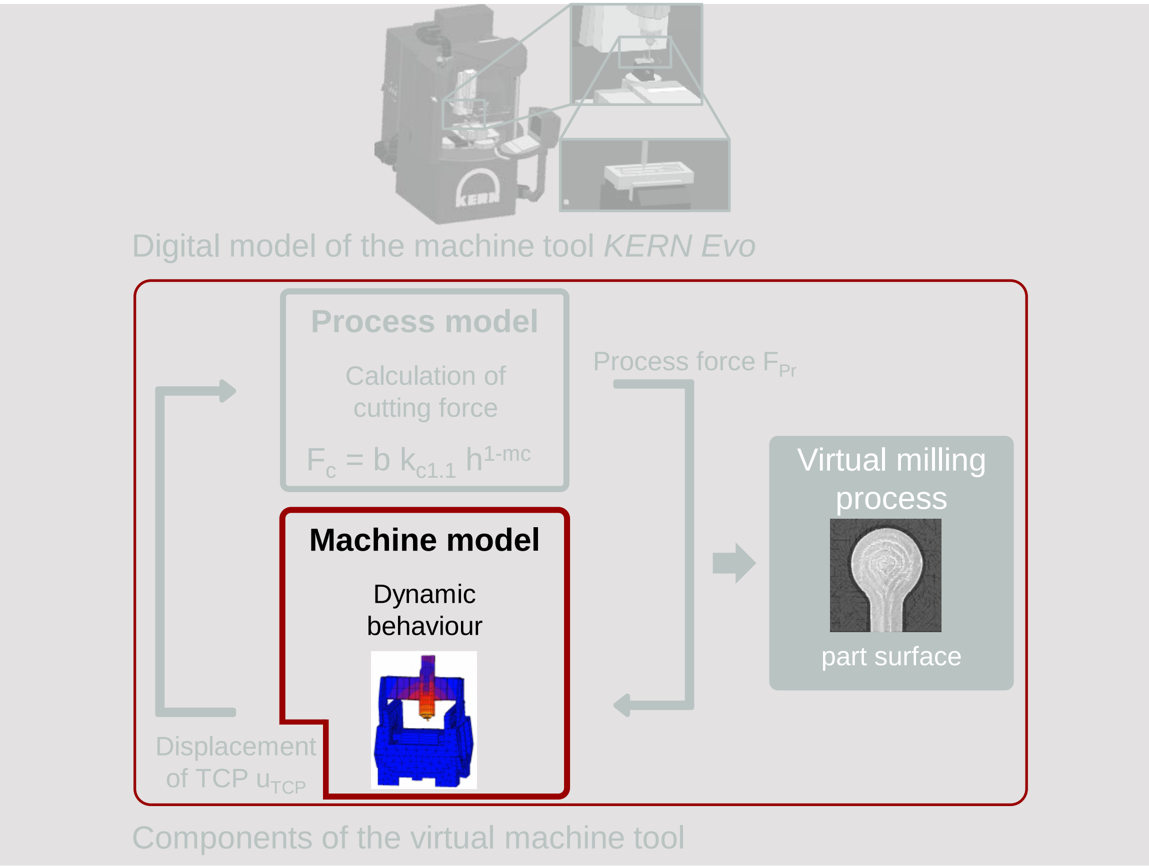
# Development of the virtual machine tool
## Machine model



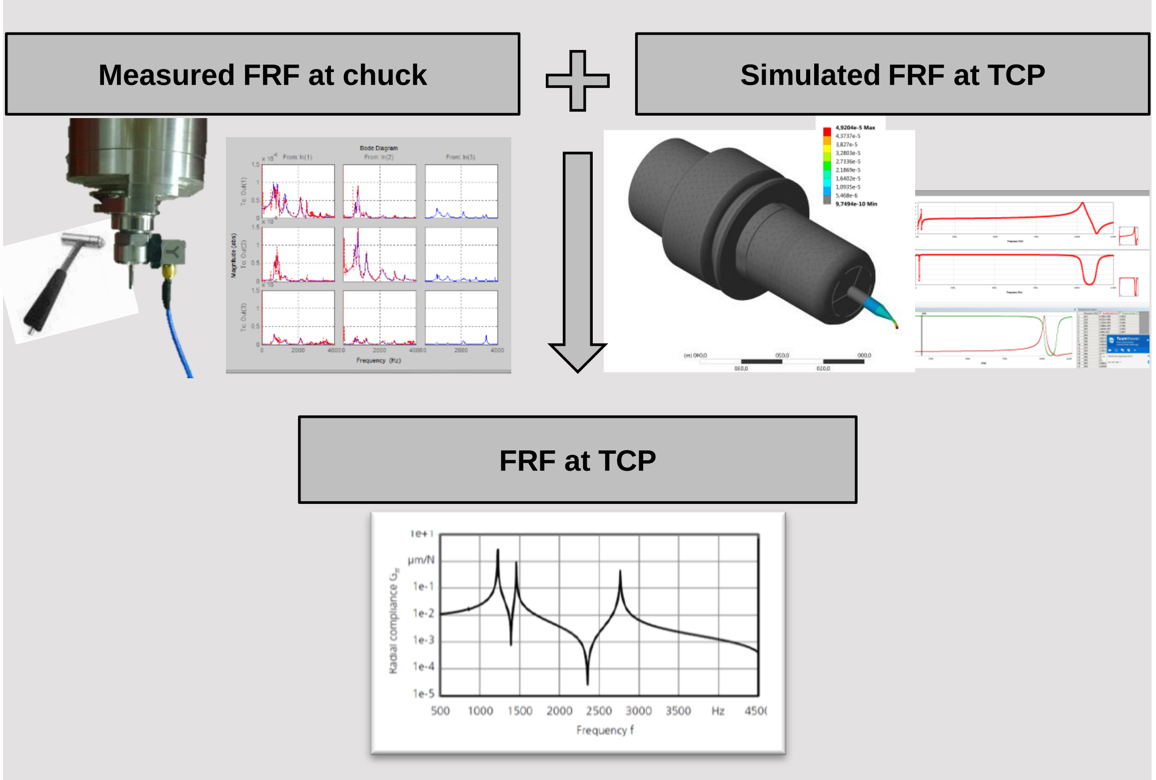

### Machine model

- Representation of machine behavior during process
- Emulates the real machine compliance when subjected to cutting forces and internal elements motion dynamics

### Main subjects

- Dynamic behavior
- Geometric behavior

# Development of the virtual machine tool
## Machine model | Dynamic behavior



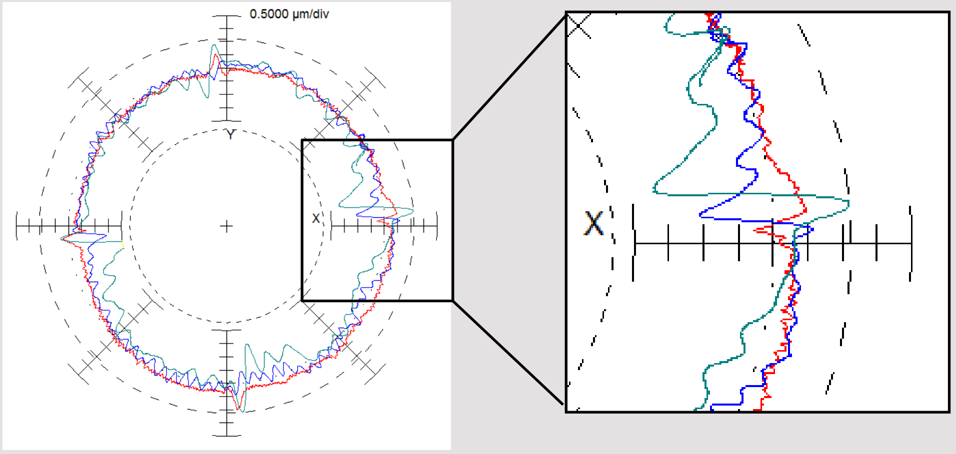

Procedure to determine FRF at TCP with support of FE simulation

- Challenge to measure the frequency response function (FRF) at tool center point (TCP) of a small tool (d < 1mm)
- FRF measurement at chuck extended by finite element (FE) simulation of chuck and tool

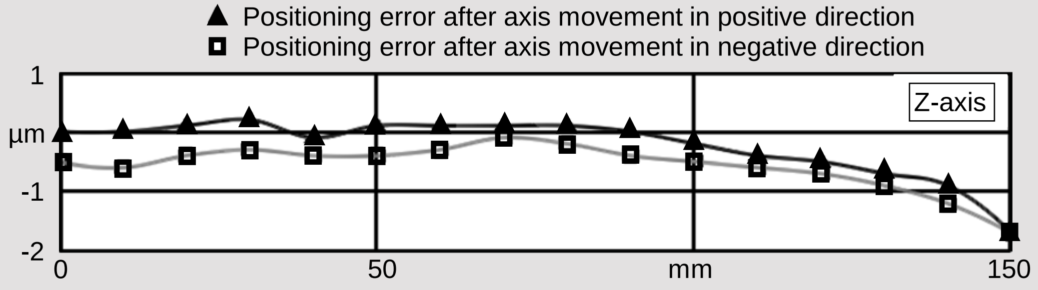
### Achievement

- Impact of damping, cantilever length, end mill form and clamping device was considered in the model
- For micro-milling, tool dynamics (1st and 2nd eigenfrequency) dominate the compliance at TCP

# Development of the virtual machine tool
## Machine model | Geometric behavior




Results of circular tests in form of radial deviation



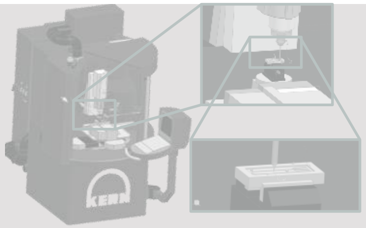

Measured positioning error of Z

- Positioning errors and backlash are minimal in ultra precision machines, but affect the part's geometry
- Measurement and modelling of the positioning errors

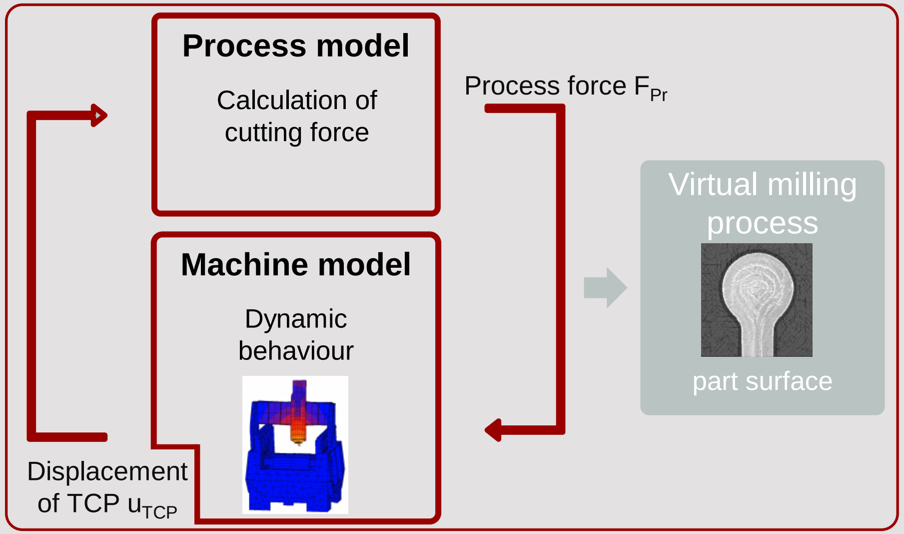
### Achievement

- Grid encoder and laser interferometer used for circular and linear tests
- Positioning errors measured and added to machine model

# Development of the virtual machine tool
## Machine model and process model



Digital model of the machine tool *KERN Evo*




Components of the virtual machine tool

### Machine model and process model

- Process model interacts with machine model on each time step
- The updated forces and tool center point (TCP) displacement are used on the consecutive time step
- Method allows simulation of “chatter” phenomena

### Main subject

- Process stability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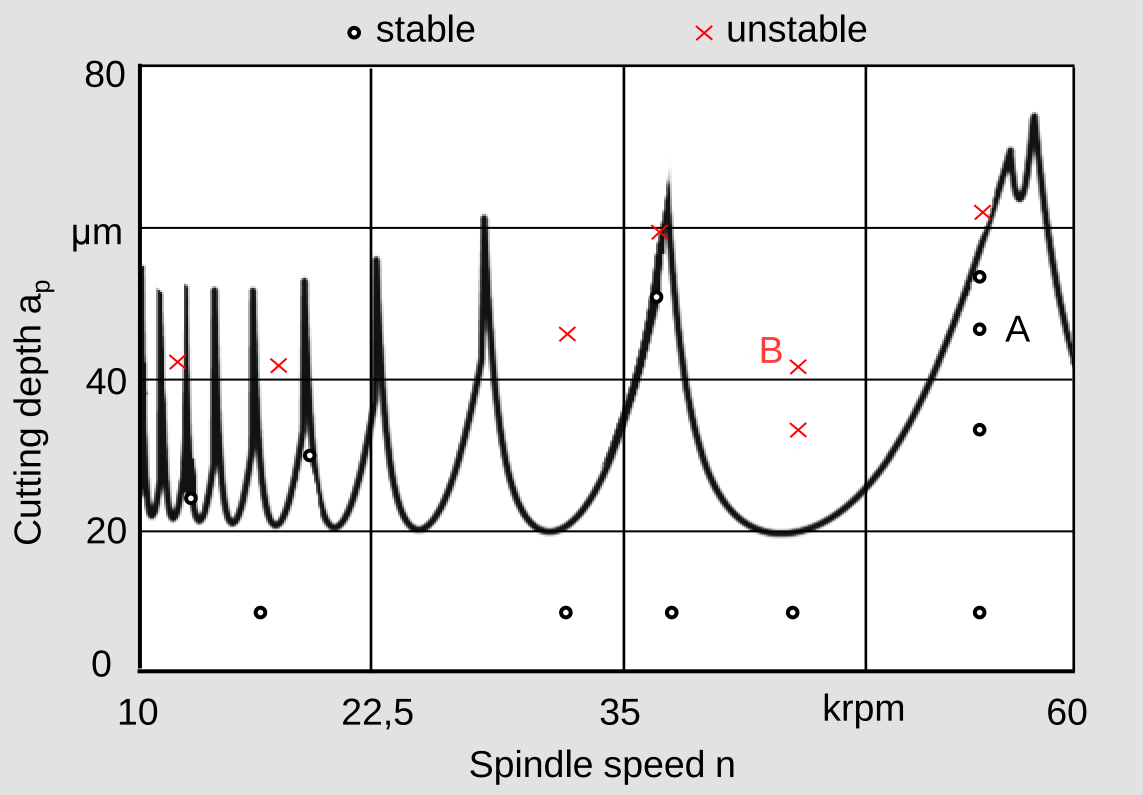
# Development of the virtual machine tool
## Machine model and process model | Process stability




Stability lobe diagram [JIN13]

- Process stability analysis
- Process stability strongly influences surface quality
- Stability also affects tool life and process safety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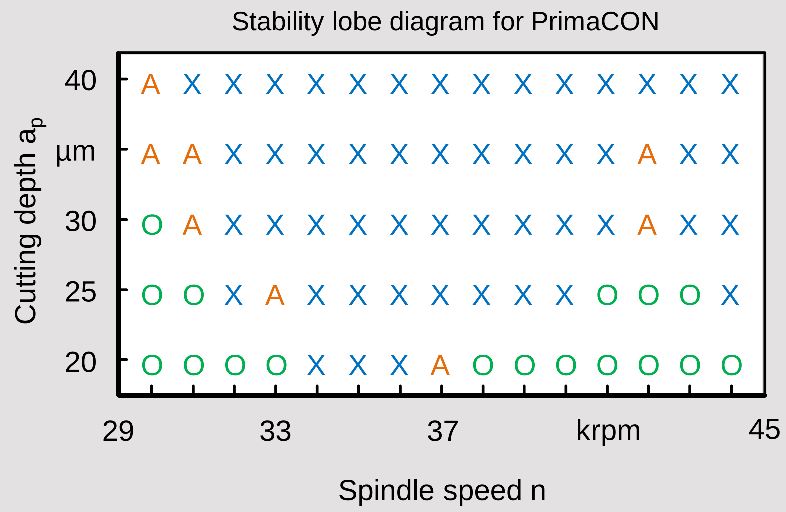
# Development of a virtual machine tool

## Machine model and process model | Process stability



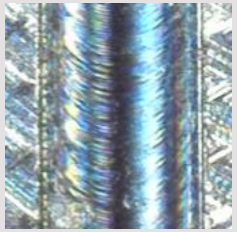

**Experimental setup**

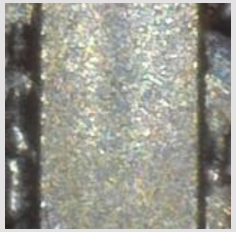
Material:X40CrMoV5-1 (H13)

Tool: end mill d = 0.4 mm z = 2

| | | |
|---|---|---|
| $a_p$: | 20 to 40 | µm |
| n: | 29 to 45 | krpm |
| $a_e$: | 400 | µm |
| $f_z$: | 4 | µm |

O stable process
A uncertain state
X unstable process


O Stable process


A Uncertain state


X Unstable process

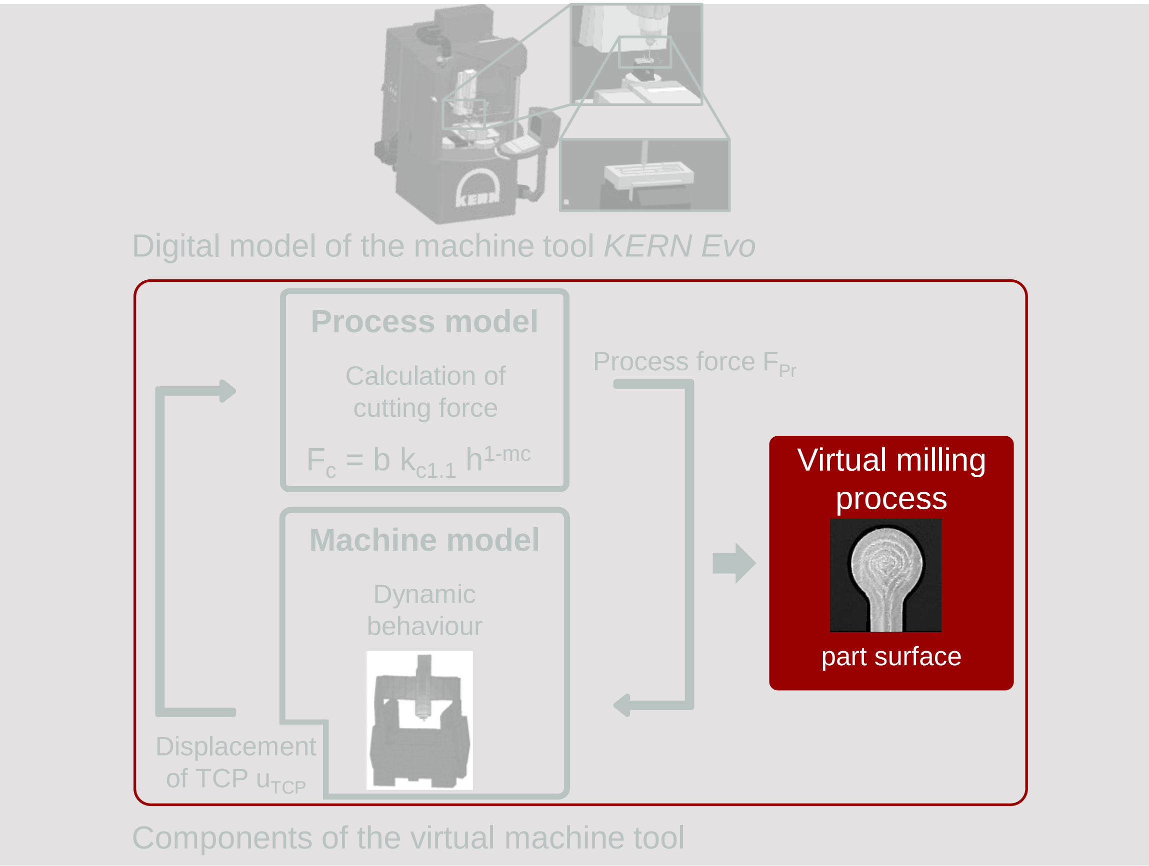
## Achievement

- PrimaCON: a clear stability limit could be observed
- Kern Evo: chatter difficult to be observed due to machine enhanced structure, new tests ongoing
- Comparison with virtual machine and fine-tuning

## Enhancement

- Higher material removal Inside stable regions
- Higher surface and part geometry quality on optimal sets of parameters
- Unstable spindle speeds can be avoided, preserving tool life and product quality

# Development of the virtual machine tool
## Virtual milling process



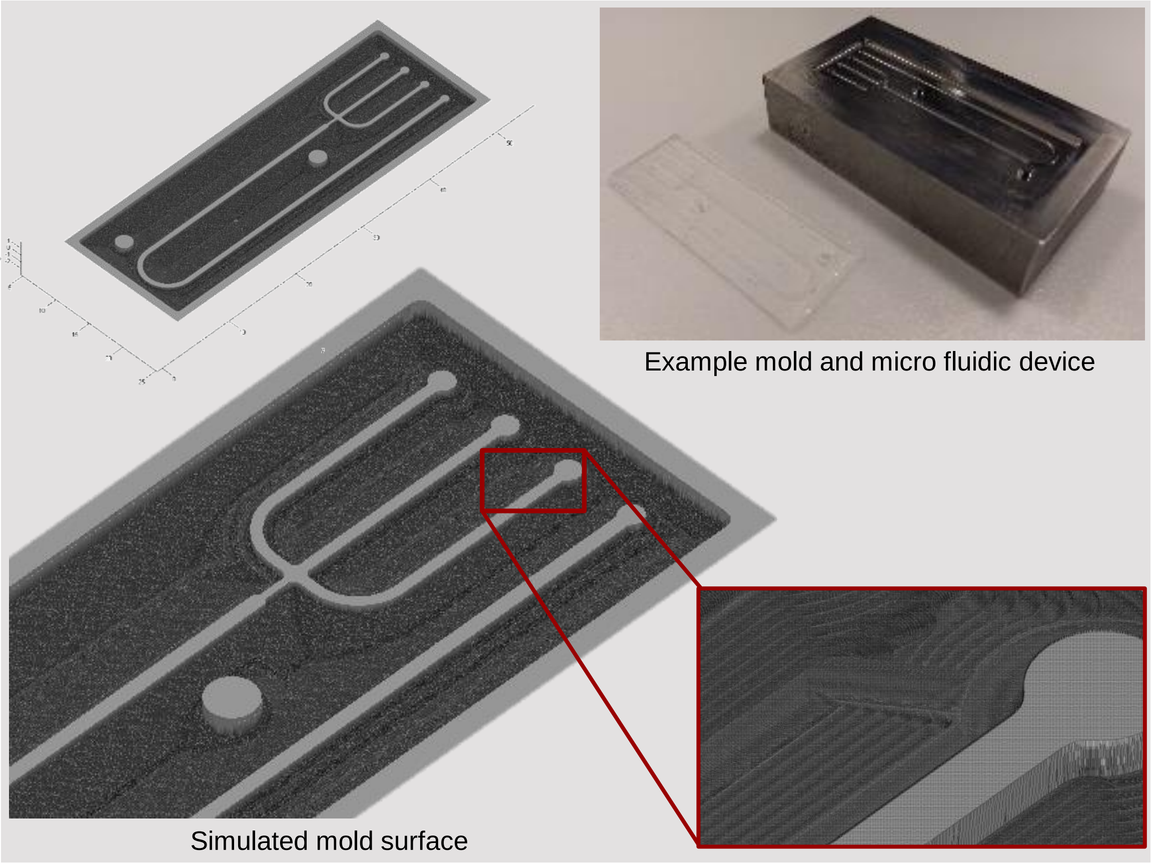

### Virtual milling process

- Integrate data from other models and adjust behavior to emulate the real machine process

### Main subject

- Roughness analysis and comparison of the surface

# Development of the virtual machine tool
## Virtual milling process | Roughness comparison surface



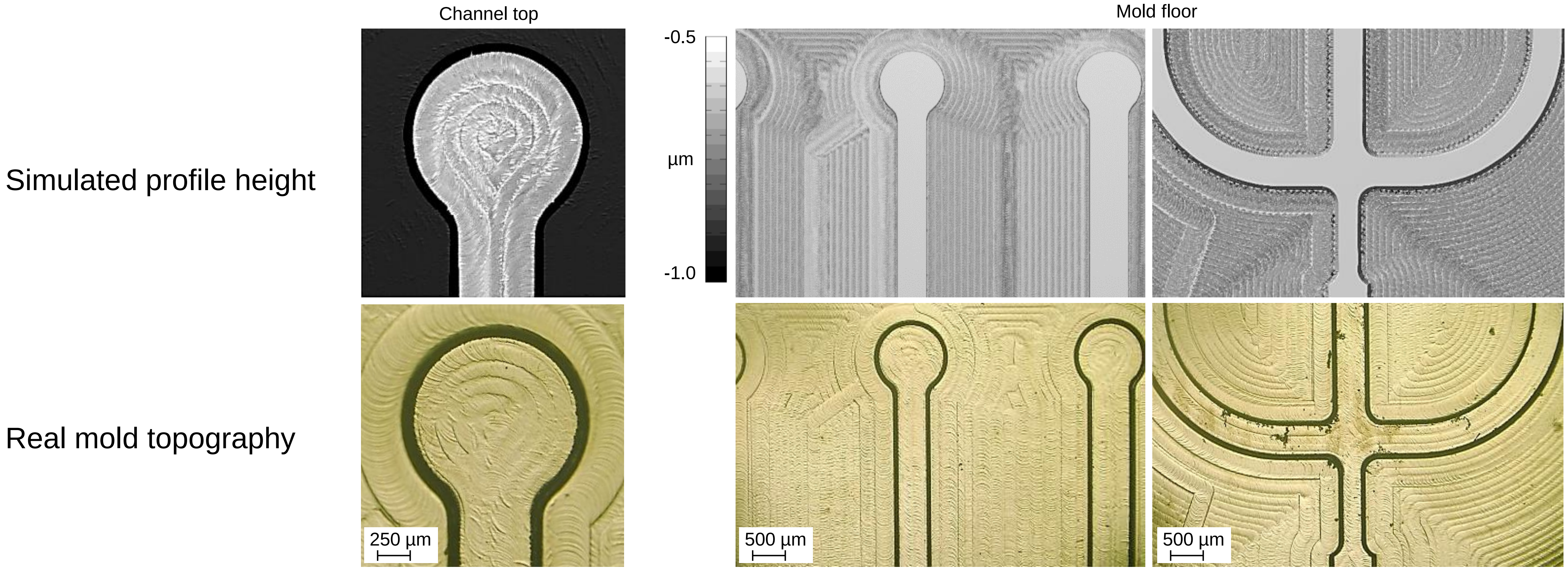
Example mold and micro fluidic device

Simulated mold surface

- Predict the resulting surface quality to enhance quality control efficiency (measure only critical areas from simulation)
- Individual evaluation of different impacts on local machining error (geometric, dynamic, control, tool geometry)

# Development of the virtual machine tool

## Virtual milling process | Roughness comparison surface



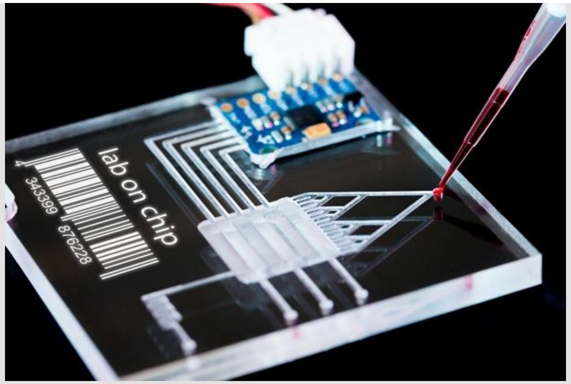

# Content

- Market demand
- Micro-machining
- Micro-O project
- Development of the virtual machine tool
- Application transfer

# Application transfer
## Scope of application

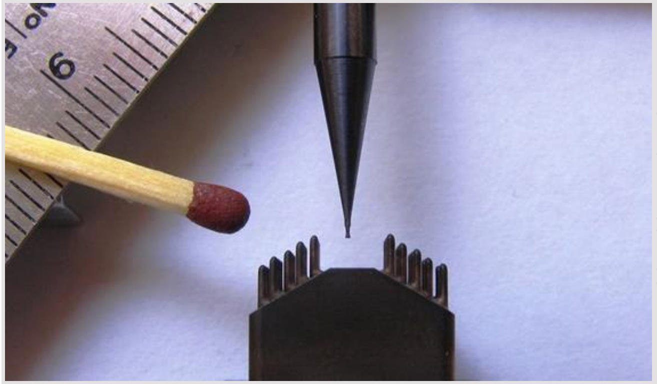

www.kugler-precision.com

Functional surface - Electrode for optical

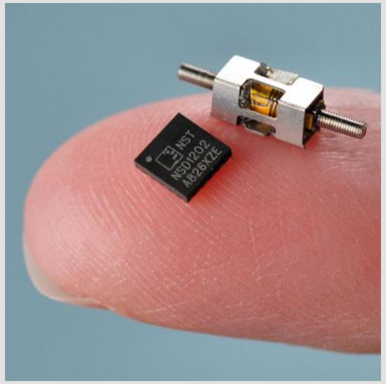


www.news-medical.net

Bio and medical application - Lab on a chip


www.moldmakingtechnology.com

Tooling fabrication - graphite electrode


www.ecnmag.com

Micro-part - Piezo Motor

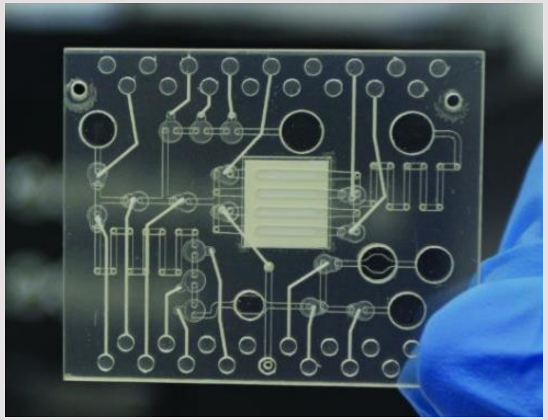
### Functional surfaces
- Surface finish and geometry precision are key characteristics
- Manufacturing time and costs are secondary

### Bio and medical applications
- Components are mostly disposable,
- Manufacturing time and costs are important

### Tooling fabrication
- Geometries impose limitations for later finishing processes, such as polishing and lapping
- Requires optimal surface quality

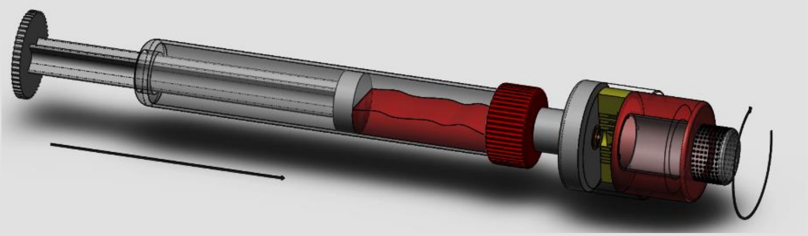
### Micro-parts
- Realignment of workpieces between manufacturing steps

# Application transfer
## Micro-injection molding of high-precision micro-fluidic systems



*Lab-On-Chip © ALine Ldt.*

*Lab-on-Disk-Device © Hahn-Schickard*



*Concept design of a disposable system for the separation of blood-plasma for molecular genetic diagnostic methods © Fraunhofer IPK*

### Challenge

- Time-consuming blood analysis
- Stationary laboratory equipment
- Manufacturing and replication of micro-structures

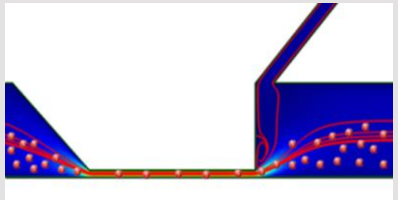
### Approach

- Transfer of diagnostics into micro-fluidic based point-of-care systems
- Micro-injection molding of disposable systems for the reduction of production costs

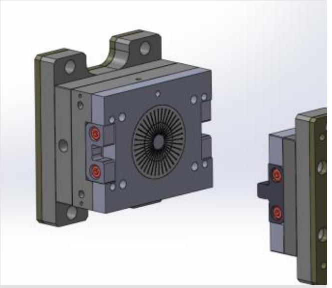
# Application transfer
## Micro-injection molding of high-precision micro-fluidic systems

Ultra-precision milling of mold insert

Flow-mechanical working principle of plasma-separation

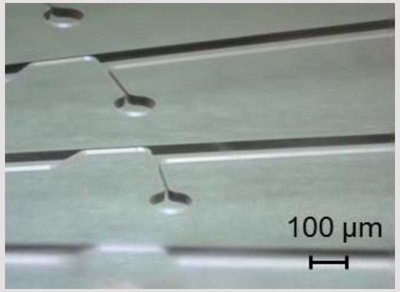


High-precision mold manufacturing

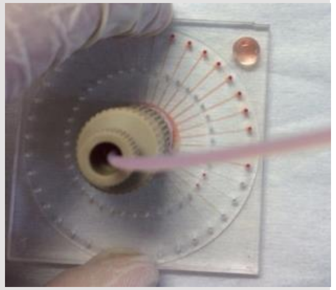


Functional micro-structures with dim. s ≤ 15 µm

Replication of the micro-fluidic functional structure




Experimental trial and integration into analytical system



*High-precision process chain for manufacturing of the blood plasma-separator © Fraunhofer IPK*

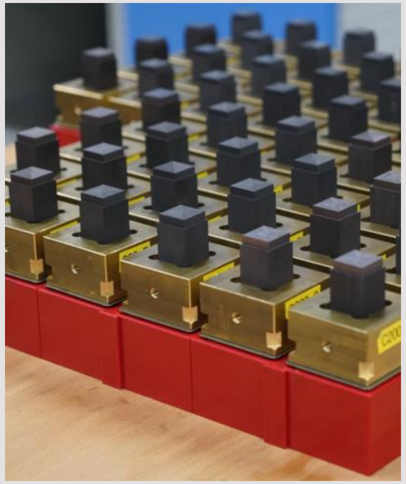
### Results

- Cost-effective replication of micro-fluidic blood-plasma separator structure
- Point-of-care blood-plasma separation device with a separating capacity of $\mathbf{V_{Sep} = 0.5}$ **ml/min**

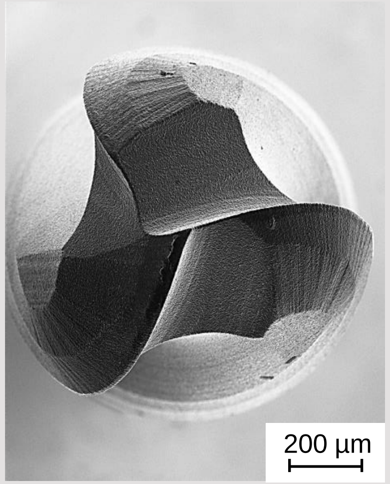
### Enhancement

- Replication of smallest functional structures with **s ≤ 15 µm** against 100 µm of conventional Lab-On-Chip structures
- Replication accuracy $\mathbf{a_R < 1}$ **µm**

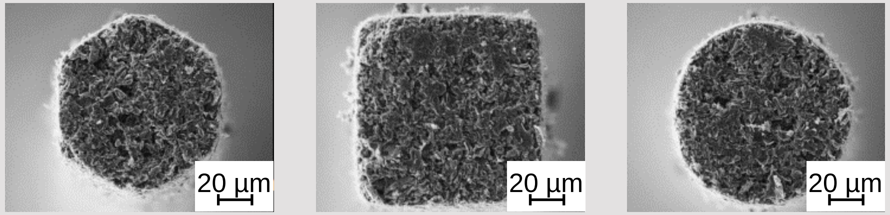
# Application transfer
## Increased accuracy in tool and mold making



Electrodes for spark-eroding sinking




Milling tool for graphite machining




Milled pin electrodes

### Challenges

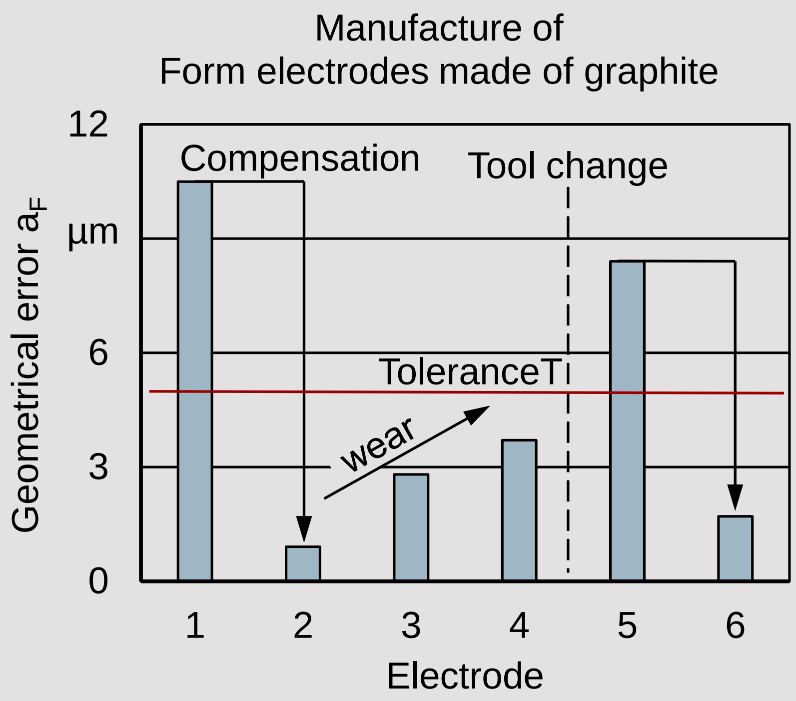
- Increasing demands on precision and economic efficiency
- Further development of the machine tool, tool and process results in inadequate increase in production accuracy

### Approach

- Process-integrated, automated compensation of tool geometry errors

# Application transfer

## Increased accuracy in tool and mold making




Geometrical error $a_F$ of milled electrodes for spark-eroding sinking

### Enhancement

- Precision manufacturing
despite inaccurate tools and machines
- Process-integrated compensation
without measuring the tool radius r
- Economical production with
standard tools and low waste
- Key technology for
optimized precision in tool and mold making


DFG CAPES IWF ipt SCPM CECS

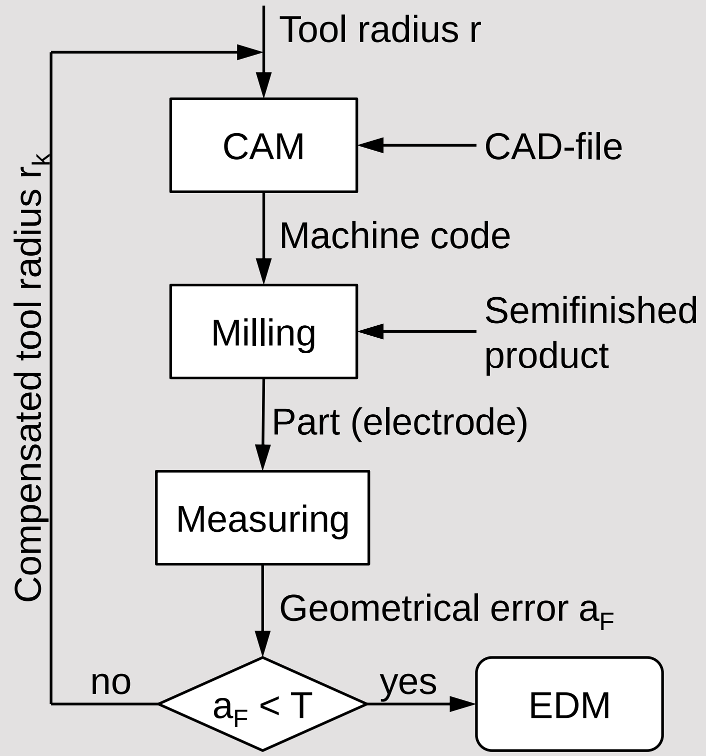
**Thank you for your attention!**

# References


- MET13 Metwally, K.; Gauthier-Manuel, B.; Barriere, T.; Khan-Malek, C.: Replication of micronic and submicronic structured surfaces using micro-injection and micro-injection compression moulding. 8th International Conference on MicroManufactoring, Victoria, BC, Canada, 25.03.2013 - 28.03.2013.
- JIN13 JIN, X.; ALTINTAS, Y. Chatter Stability Model of Micro-Milling With Process Damping. Journal of Manufacturing Science and Engineering, v. 135, 2013.
- SCH18 Schützer, K., da Silva de Luca Ramos, L.W., Mewis, J., Tamborlin, M.O., Baldo, C.R.: Simulation tool for prediction of cutting forces and surface quality of micro-milling processes. International Jornal of Advanced Manufacturing Technology, v. 99, pp 225–232 2018.

# Application transfer

## Increased accuracy in tool and mold making




Compensation of the milling tool radius r

### Technological innovation

- Inline-capable CAM adaptation
- Measurement of relevant component geometries (electrode) integrated in process chain
- From geometrical error $a_F$ conclusion on real milling tool radius $r_k$

### Objective

- Machine-integrated, automated workpiece measurement
- Automated milling tool radius compensation in the CAM system