Cutting Edge Preparation of Micro Milling Tools

POVRCHOVÁ INTEGRITA

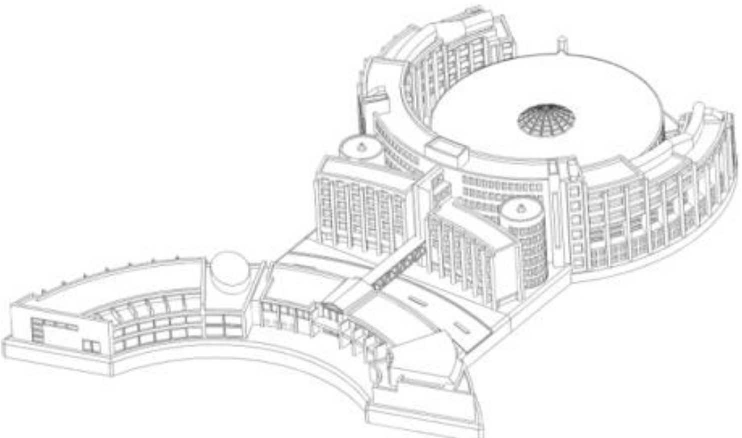
15.10.2014

Dr.-Ing. Armin Löwenstein

Fraunhofer
IPK
INSTITUTE
PRODUCTION SYSTEMS AND
DESIGN TECHNOLOGY

IWF
INSTITUTE FOR MACHINE TOOLS
AND FACTORY MANAGEMENT
TECHNISCHE UNIVERSITÄT BERLIN

Cutting Edge Preparation of Micro Milling Tools



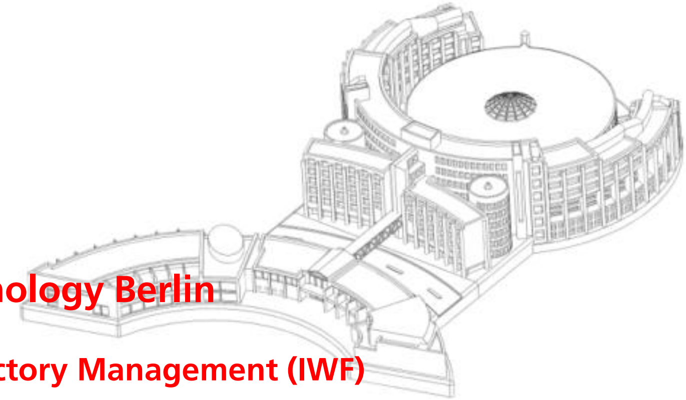
- Introduction
- Measurement of Cutting Edge Geometries
- Cutting Edge Preparation Process
- Micro Milling with Different Cutting Edge Geometries
  - Tool Wear
  - Workpiece Quality
  - Active Force
- Conclusion

Production Technology Center Berlin

Fraunhofer-Gesellschaft Institute for Production Systems and Design Technology (IPK)	Technische Universität Berlin Institute for Machine Tools and Factory Management (IWF)
▪ Budget 2011: € 18.2m ▪ Employees: 260	▪ Budget 2011: € 12.1m ▪ Employees: 257

More than 70 test areas and 7 special laboratories on about 7 100 m²

Production Technology Center



Fraunhofer-Gesellschaft
Institute for
Production Systems and Design Technology (IPK)

Corporate Management
Prof. Dr.-Ing. K. Mertins

Virtual Product Creation
Prof. Dr.-Ing. R. Stark

Production Systems
Prof. Dr. h. c. Dr.-Ing. E. Uhlmann

Automation Technology
Prof. Dr.-Ing. J. Krüger

Joining and Coating Technology
Prof. Dr.-Ing. Michael Rethmeier

Quality Management
Prof. Dr.-Ing. R. Jochem

Medical Technology
Prof. Dr.-Ing. E. Keeve

University of Technology Berlin
Institute for
Machine Tools and Factory Management (IWF)

Assembly Technology and Factory Management
Prof. Dr.-Ing. G. Seliger

Industrial Information Technology
Prof. Dr.-Ing. R. Stark

Machine Tools and Manufacturing Technology
Prof. Dr. h. c. Dr.-Ing. E. Uhlmann

Industrial Automation Technology
Prof. Dr.-Ing. J. Krüger

Joining and Coating Technology
Temporary Administration: Prof. Dr.-Ing. R. Stark

Quality Science
Prof. Dr.-Ing. R. Jochem

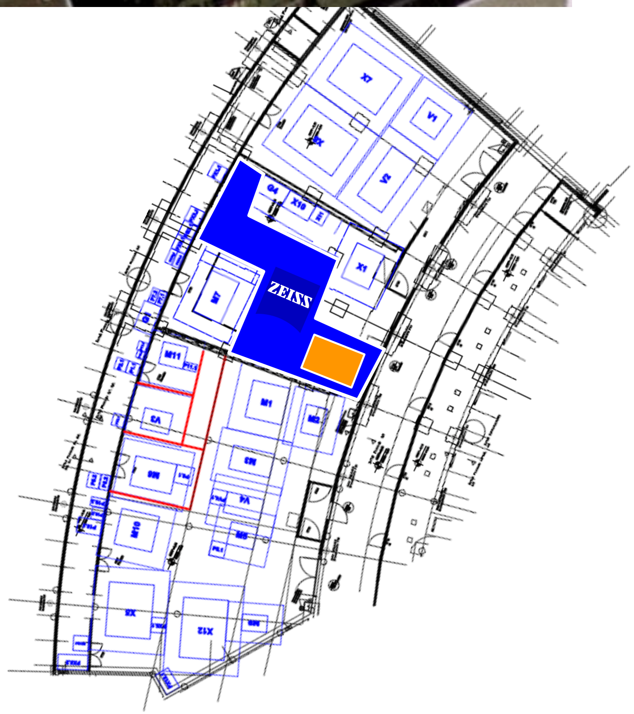
Micro Production Technology
Prof. Dr. h. c. Dr.-Ing. E. Uhlmann

Fraunhofer
IPK
INSTITUTE
PRODUCTION SYSTEMS AND
DESIGN TECHNOLOGY

INSTITUTE FOR MACHINE TOOLS
AND FACTORY MANAGEMENT
TECHNISCHE UNIVERSITÄT BERLIN

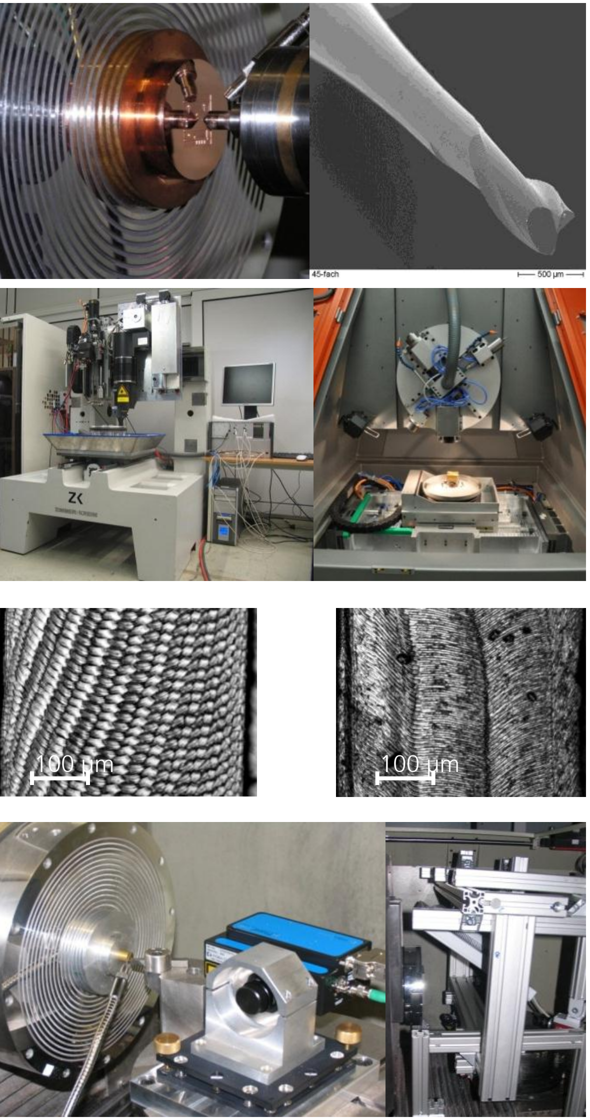
Micro Production Technology

- Since November located in the Application Center for Micro Production Technology
- 20 scientific staff, 2 technicians
- 50 - 60 student assistants
- 11 machine tools for micro-manufacturing
- 10 measurement devices for micro-manufacturing applications



Application Center for Micro Production Technology

- High precision laboratory (20°C ±0,5°C)
  - HP-machining (micro milling and micro grinding)
  - Electro-discharge machining (EDM)
  - Laser ablation
- Ultra-precision laboratory (20°C ±0,1°C)
  - UP-machining
  - Zeiss application center
  - measurement devices for micro production
- Process development laboratory
  - Coating technologies
  - Development and assembly of prototypes
  - small test stands

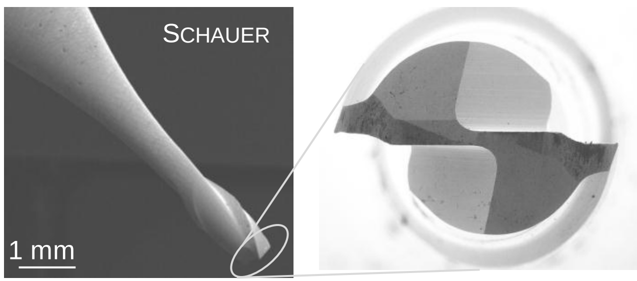


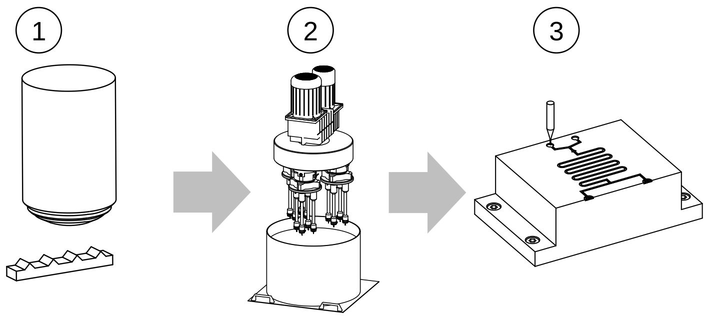
Micro Production Technology

- Development and investigation of micro-manufacturing processes
  - Micro milling
  - EDM
  - Ultra precision drilling and milling
- Development and improvement of tools
- Development of new machine tool concepts for micro-manufacturing processes
- Optimization of micro production processes and development of process chains
- Integration of measurement devices in machine tools for micro-manufacturing processes

Fraunhofer
IPK
INSTITUTE
PRODUCTION SYSTEMS AND
DESIGN TECHNOLOGY

INSTITUTE FOR MACHINE TOOLS
AND FACTORY MANAGEMENT
TECHNISCHE UNIVERSITÄT BERLIN





SCHAUER, K.: Entwicklung von Hartmetallwerkzeugen für die Mikrozerspanung mit definierter Schneide. Berichte aus dem Produktionstechnischen Zentrum Berlin. Hrsg.: UHLMANN, E. Stuttgart: Fraunhofer IRB, 2006.

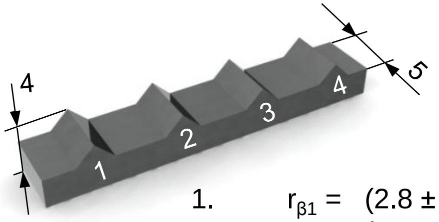
RISSE, K.: Einflüsse von Werkzeugdurchmesser und Schneidkantenverrundung beim Bohren mit Wendelbohrern in Stahl. Berichte aus der Produktionstechnik Hrsg.: KLOCKE , F. Aachen: Shaker Verlag, 2006.

Cutting Edge Preparation of Micro Milling Tools

- Micro milling with tool diameters of D ≤ 1 mm can be used for the production of precision components e.g. for die and mould fabrication.
- After the optimization of the tool geometry by SCHAUER tool wear is usually the main reason for the failure of cemented carbide micro end mills.
- The wear behavior leads to unpredictable tool life and quality of the workpieces.
- An approach to improve the tool wear performance is a defined cutting edge preparation as shown by RISSE with small drilling tools (D = 1 mm).
- For the optimization of micro milling tools knowledge in the following areas is necessary:
  (1) Measurement of cutting edge geometries
  (2) Influence of the parameters and lapping media in the preparation pro.
  (3) Influence of the cutting edge geometrie in the milling process

Fraunhofer
IPK
INSTITUTE
PRODUCTION SYSTEMS AND
DESIGN TECHNOLOGY

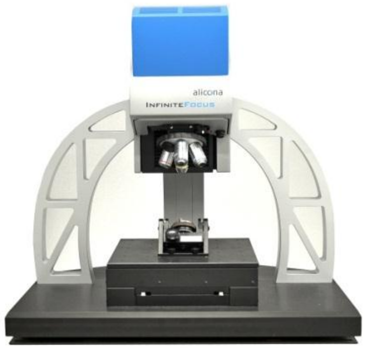
IWF
INSTITUTE FOR MACHINE TOOLS
AND FACTORY MANAGEMENT
TECHNISCHE UNIVERSITÄT BERLIN

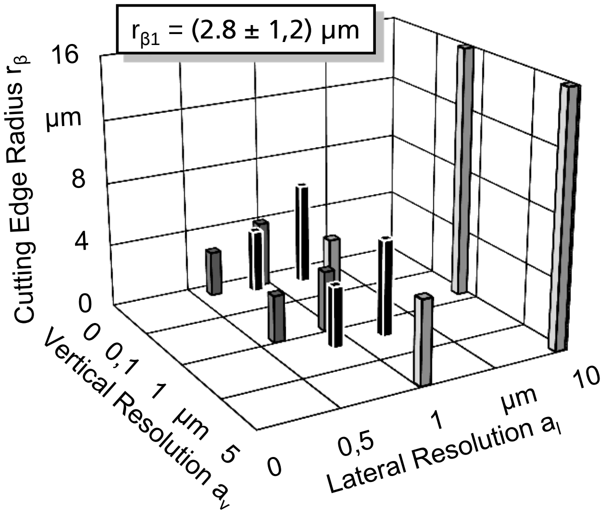


1. $r_{\beta 1} = (2.8 \pm 1.2)\ \mu m$
2. $r_{\beta 2} = (9.6 \pm 0.6)\ \mu m$
3. $r_{\beta 3} = (21.3 \pm 0.5)\ \mu m$
4. $r_{\beta 4} = (33.6 \pm 0.5)\ \mu m$

Settings:
Exposure H: 500 lx µs
Contrast K: 0,3
Light Source: 100 %
Gain: 100 %
Polarization: off

Edges Measuring Module:
Number of Profiles: 20
Measurement Range: 100 %



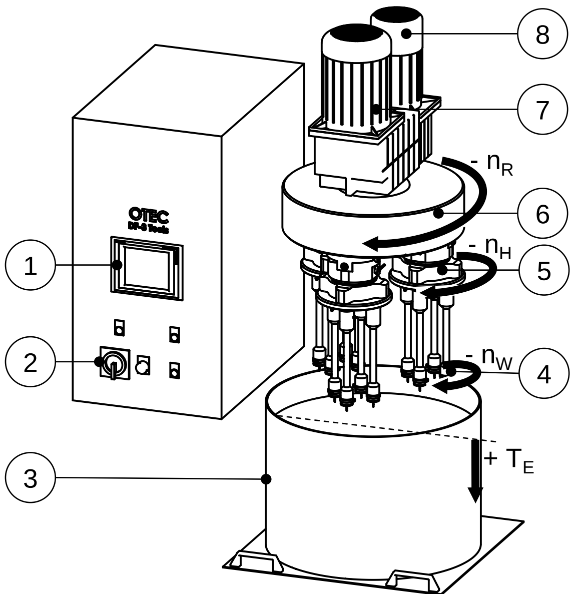


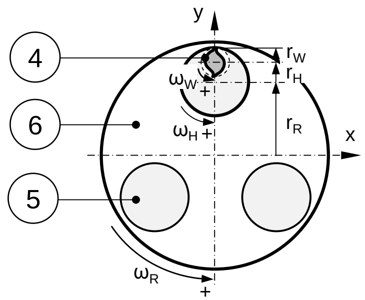
Measurement of Cutting Edge Geometries

- Production (IPK) and calibration (METAS) of a test standard.
- Based on a comparison of measuring devices, the system InfinitFocus of the company Alicona was selected:
  - Small systematic errors and measurement uncertainty even at radii $r_\beta < 10\ \mu m$.
  - Short measurement times and good operability.
- Analysis of the measurement settings:
  - The resolution and the location of the measurement object have a significant influence on the measurement result.
- Definition of a measurement strategy and transfer to micro milling tools.

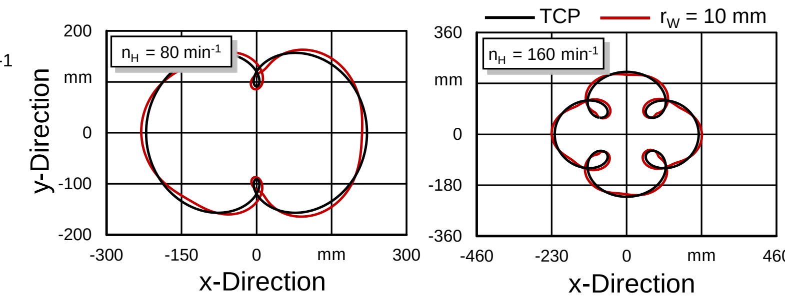
DF 3 Tools
OTEC Präzisionsfinish GmbH, Straubenhardt, Germany
(1) Machine Control, (2) Main Switch, (3) Working Container, (4) Workpiece Holders, (5) Holder of the Workpiece Holders, (6) Rotor, (7) Main Drive, (8) Second Drive

Cutting Edge Preparation





Parameters:
n_R = 40 min^{-1}
DR_R = -1
DR_H = -1



$$v_{res} = \sqrt{v_x^2 + v_y^2}$$

$$v_x = - r_R\,\omega_R \sin(\omega_R t) - r_H(\omega_R + \omega_H)\ \sin(\,t(\omega_R + \omega_H))$$
$$- r_W(\omega_R + \omega_H + \omega_W)\ \sin(\,t(\omega_R + \omega_H + \omega_W))$$

$$v_y = r_R\,\omega_R \cos(\omega_R\,t) + r_H(\omega_R + \omega_H) \cos(\,t(\omega_R + \omega_H))$$
$$+ r_W(\omega_R + \omega_H + \omega_W)\ \cos(\,t(\omega_R + \omega_H + \omega_W))$$

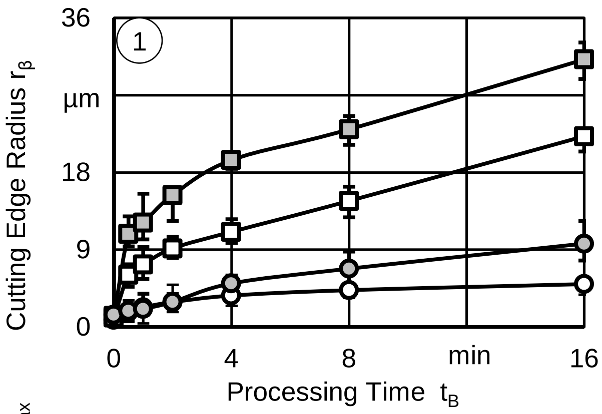
- Immersed tumbling is an appropriate process for the cutting edge preparation.
- The workpieces are fixed on holders and immersed in an abrasive lapping medium.
- The material removal is the result of the relative movement between the workpiece and the abrasive lapping medium.
- The material removal mechanisms are mainly caused by ploughing and furrowing due to impacts and rolling of the abrasive grains on the workpiece surface.

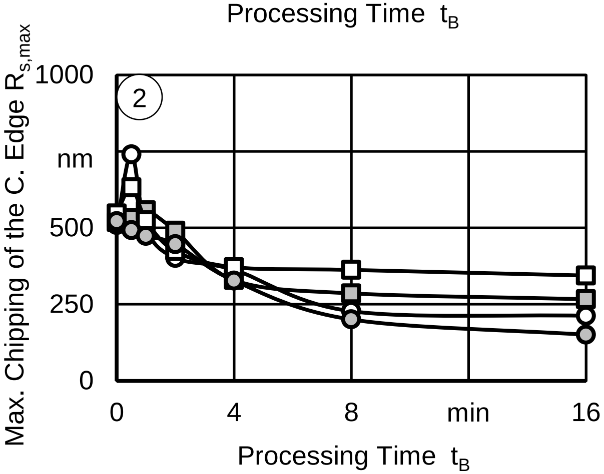
Process:
Immersed
Tumbling

Process Parameters:
n_R = 40 min^{-1}
n_H = 80 min^{-1}
T_E = 100 mm
i_W = 1

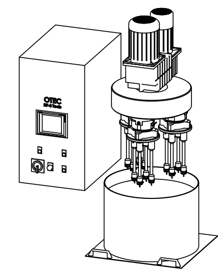
Workpiece:
Two Flute End Mills
Cemented Carbide
No Coating
Diameter D = 1 mm

Lapping Medium:
■ QZ 0.5-0.8
□ HSC 1/300
● H 4/400
○ M 4/400





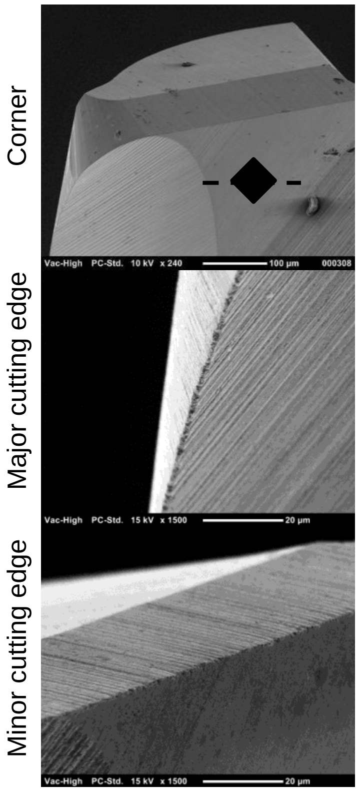
Cutting Edge Preparation

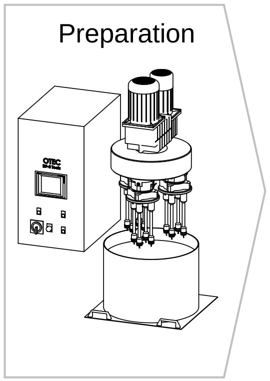


- The highest cutting edge radii r_β could be reached using of the lapping medium QZ 0.5-0.8.
- Very low and smooth radii r_β could be manufactured using the lapping media H 4/400 and M 4/400.
- For example, when using the lapping medium H 4/400 the cutting edge radius r_β is r_β = 5.1 µm after a processing time of t_B = 4 min.
- The investigations showed that the processing time t_B is mainly responsible for the size of the cutting edge radius r_β.
- The choice of the lapping medium determines the chipping of the cutting edge R_s.

Cutting Edge Preparation

Unprepared:
r_β = 2 ± 1.2 µm
$R_{s,max}$ = 0.5 ± 0.1 µm



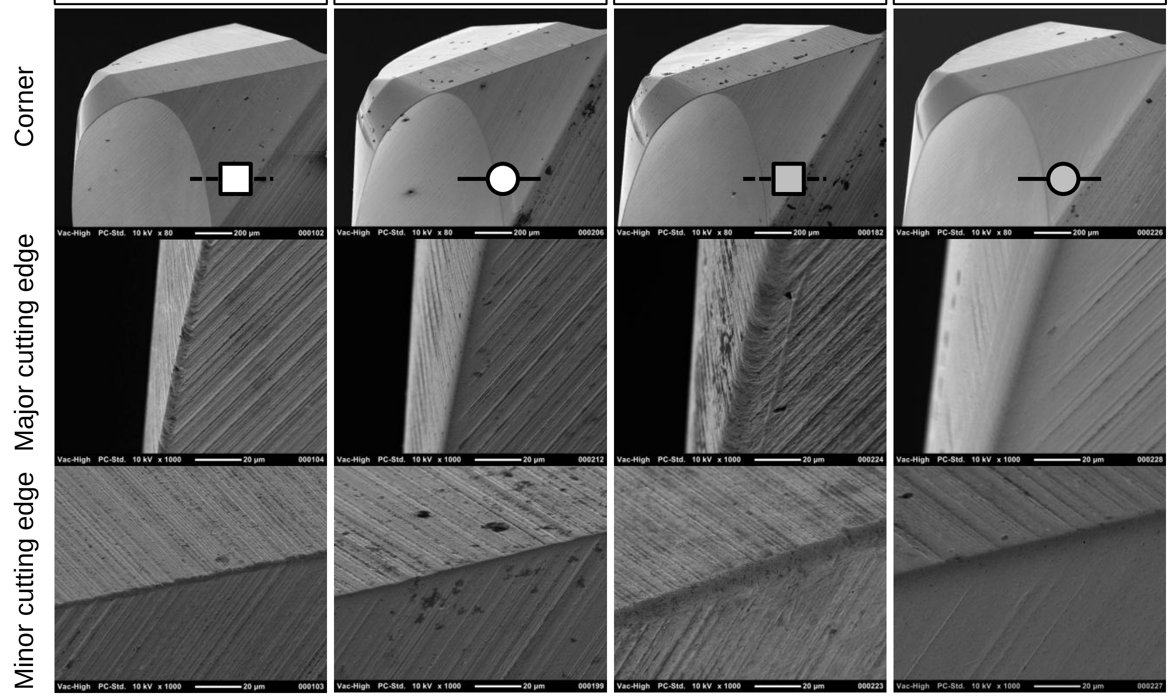


Process:
Immersed Tumbling

Process Parameters:
n_R = 20 min^{-1}
n_H = 40 min^{-1}
i_W = 1

Workpiece:
Two Flute End Mills
Cemented Carbide
No Coating
Diameter D = 1 mm

Processing Time: t_B = 0.5 min T_E = 70 mm, DR = +	**Processing Time:** t_B = 4 min T_E = 70 mm, DR = +	**Processing Time:** t_B = 12 min T_E = 100 mm, DR = -	**Processing Time:** t_B = 18 min T_E = 100 mm, DR = -
Lapping Medium: HSC 1/300	**Lapping Medium:** H4/400	**Lapping Medium:** HSC 1/300	**Lapping Medium:** H4/400
Tool Group 1: r_β = 4 ± 1.2 µm $R_{s,max}$ = 0.4 ± 0.1 µm	**Tool Group 2:** r_β = 4 ± 1.2 µm $R_{s,max}$ = 0.3 ± 0.1 µm	**Tool Group 3:** r_β = 8 ± 1.2 µm $R_{s,max}$ = 0.4 ± 0.1 µm	**Tool Group 4:** r_β = 8 ± 1.2 µm $R_{s,max}$ = 0.3 ± 0.1 µm



Fraunhofer IPK
INSTITUTE PRODUCTION SYSTEMS AND DESIGN TECHNOLOGY

IWF
INSTITUTE FOR MACHINE TOOLS AND FACTORY MANAGEMENT
TECHNISCHE UNIVERSITÄT BERLIN

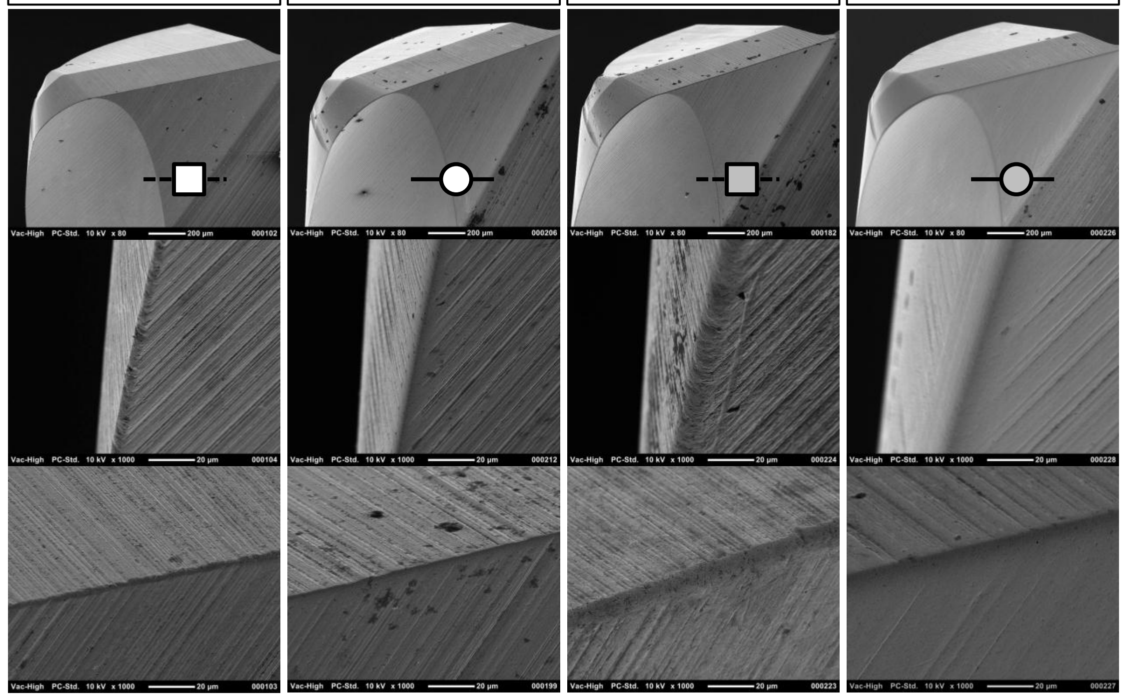
Cutting Edge Preparation

Processing Time: t_B = 0.5 min, T_E = 70 mm, DR = +	Processing Time: t_B = 4 min, T_E = 70 mm, DR = +	Processing Time: t_B = 12 min, T_E = 100 mm, DR = -	Processing Time: t_B = 18 min, T_E = 100 mm, DR = -
Lapping Medium: HSC 1/300	**Lapping Medium:** H4/400	**Lapping Medium:** HSC 1/300	**Lapping Medium:** H4/400
Tool Group 1: r_β = 4 ± 1.2 µm, $R_{s,max}$ = 0.4 ± 0.1 µm	**Tool Group 2:** r_β = 4 ± 1.2 µm, $R_{s,max}$ = 0.3 ± 0.1 µm	**Tool Group 3:** r_β = 8 ± 1.2 µm, $R_{s,max}$ = 0.4 ± 0.1 µm	**Tool Group 4:** r_β = 8 ± 1.2 µm, $R_{s,max}$ = 0.3 ± 0.1 µm

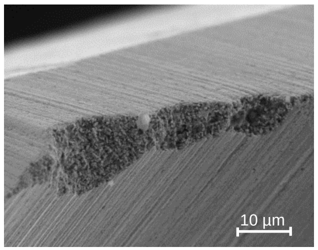
Corner

Major cutting edge

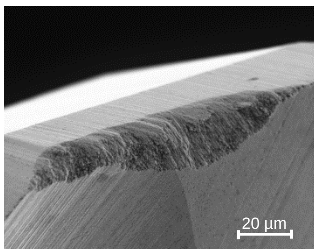
Minor cutting edge



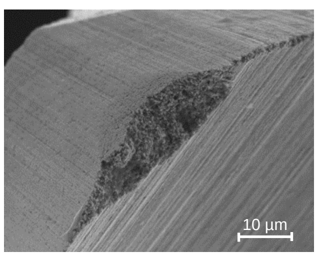
Minor cutting edge

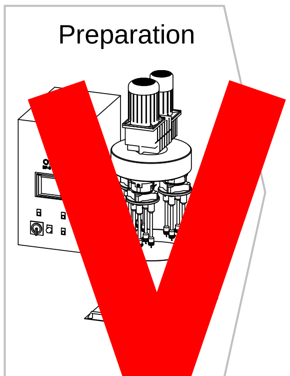


Minor cutting edge



Corner





Process:
Immerse... ing

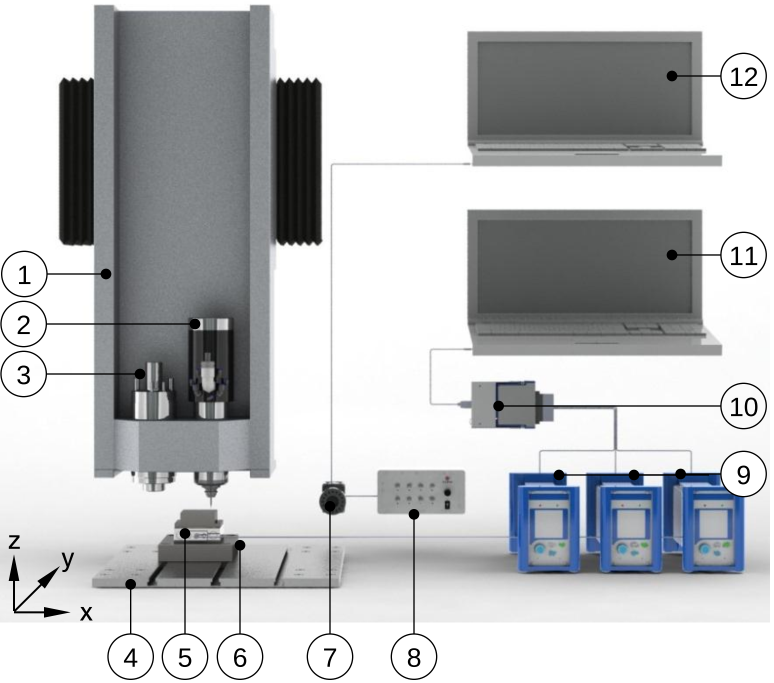
Process Parameters:
n_R = ... min^{-1}
n_H = ... min^{-1}
i_W = ...

Workpiece:
Two Flute End Mills
Cemented Carbide
No Coating
Diameter D = 1 mm

Fraunhofer IPK
INSTITUTE
PRODUCTION SYSTEMS AND
DESIGN TECHNOLOGY

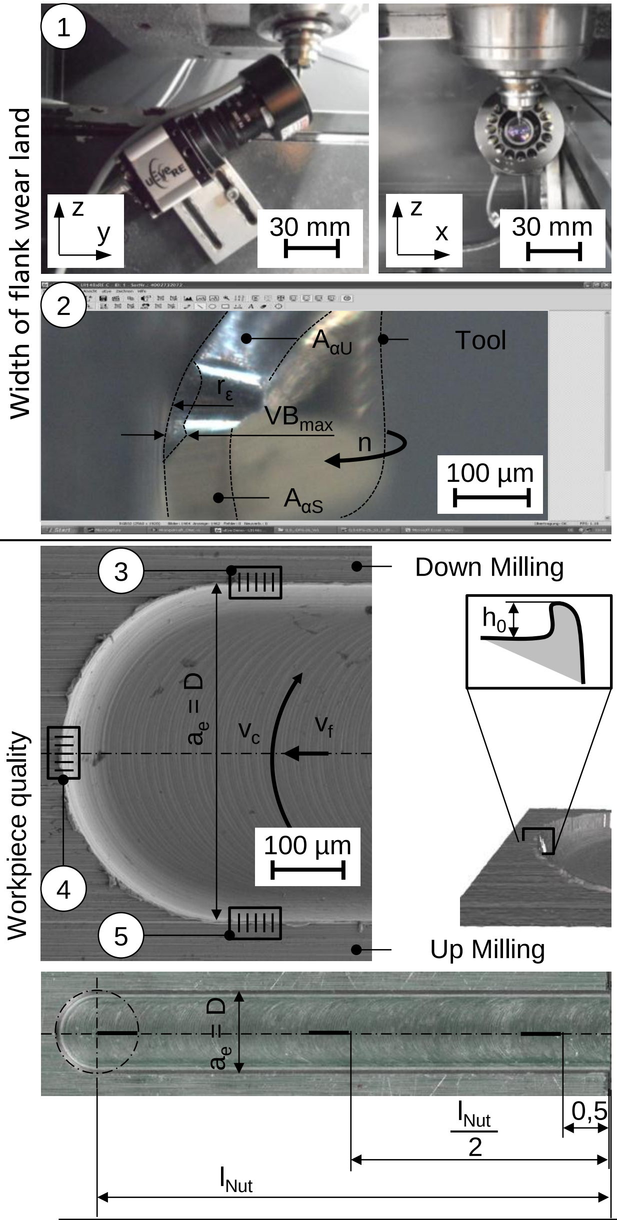
IWF
INSTITUTE FOR MACHINE TOOLS
AND FACTORY MANAGEMENT
TECHNISCHE UNIVERSITÄT BERLIN

Micro Milling with Different Cutting Edge Geometries – Experimental Setup



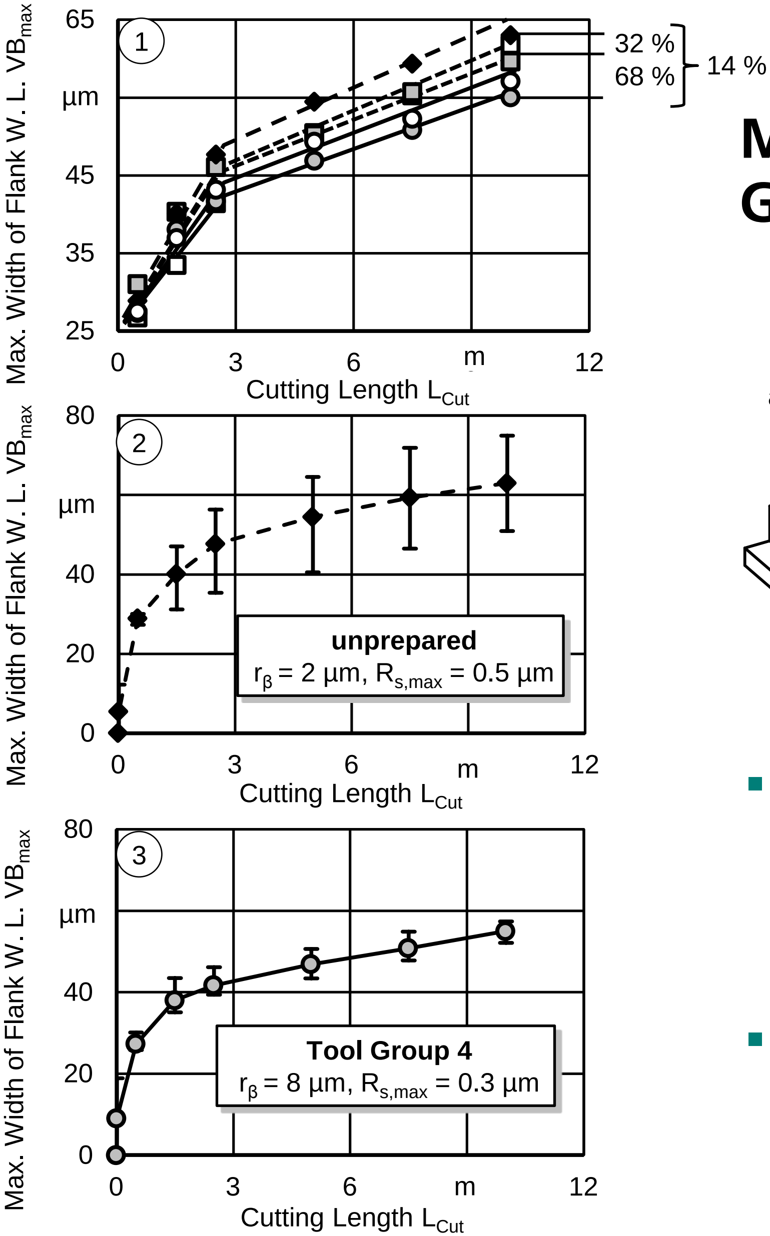
(1) Headstock,
(2) Spindle No. 1,
(3) Spindle No. 2,
(4) Machine Table,
(5) 3-Component Dynamometer,
(6) Interface,
(7) Camera System,
(8) Light Control,
(9) Charge Amplifier,
(10) A/D-Converter,
(11) Force Measurement Computer,
(12) Wear Measurement Computer

- Milling experiments:
  Wissner Gamma 303 High Performance
  - Two spindles: $50000 \leq n \leq 150000$ U min^{-1}; $10000 \leq n \leq 60000$ U min^{-1}
  - Position accuracy: 2 µm / 350 mm
- Camera system for direct detection of tool wear:
  µ-Eye Camera and Pentax lens
  - The system provides the possibility to capture the cutting edge and to measure the width of flank wear land VB without unclamping the tools
- Piezoelectric dynamometer for the indirect tool condition assessment:
  Kistler MiniDyn Type 9256C2
  - High dynamic force measurement (100 kHz) $-250\text{ N} \leq F \leq 250\text{ N}$

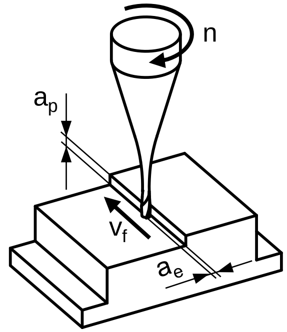


Micro Milling with Different Cutting Edge Geometries – Evaluation of the Experiments

- Maximum width of flank wear land VB_{max}
  - Detection of the flank wear land at fixed intervals in the machine by the integrated camera system
  - Detecting of the flank wear land at the end of the experiments with an optical measuring device from Alicona
  - Measuring the width of flank wear land VB using an image processing program
- Workpiece quality: Burr height and surface roughness
  - Optical measurement of the burr height h_0 at three measuring positions by Alicona InfiniteFocus
    - 3 measurement positions with 5 profiles each
  - Tactile roughness measurement by Hommel Nanoscan 855
    - 3 measuring positions with 3 repetitions



Micro Milling with Different Cutting Edge Geometries – Wear



Process:
Micro Milling

Process Parameters:

n = 31800 min^{-1}
v_c = 100 m min^{-1}
f_z = 15 µm
a_p = 100 µm
a_e = 100 µm

Tools:
Two Flute End Mills
Cemented Carbide
No Coating
Diameter D = 1 mm

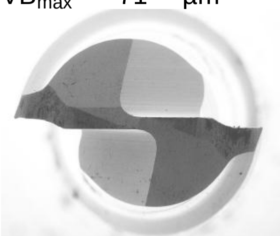
Workpiece Material:
M261, BÖHLER
HV 10 = 267 kN mm^{-2}

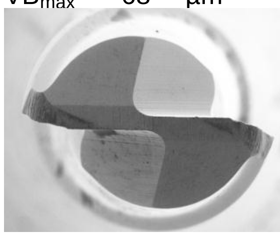
unp. r_β = 2 µm, $R_{s,max}$ = 0.5 µm
T. 1 r_β = 4 µm, $R_{s,max}$ = 0.4 µm
T. 2 r_β = 4 µm, $R_{s,max}$ = 0.3 µm
T. 3 r_β = 8 µm, $R_{s,max}$ = 0.4 µm
T. 4 r_β = 8 µm, $R_{s,max}$ = 0.3 µm

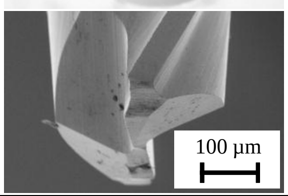
- Overall the end mills of the group T. 4 showed the lowest maximum width of flank wear land VB_{max}.
  - Reduction of wear by 14 % (max. 30,5 %)
  - Decrease of the tool wear variance up to 92 %
- The results show that the chipping of the cutting edge R_s has a greater influence in comparison to the size of the cutting edge radius r_β.

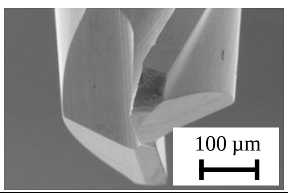
Micro Milling with Different Cutting Edge Geometries – Wear

unprepared	Tools 2
Cutting Edge:	**Cutting Edge:**
$r_?$ = 2 µm	$r_?$ = 4 µm
$R_{s,max}$ = 0.5 µm	$R_{s,max}$ = 0.3 µm
Process Parameters:	**Process Parameters:**
f_z = 5.9 µm	f_z = 5.9 µm
v_c = 40 m min^{-1}	v_c = 40 m min^{-1}
Width of Flank Wear:	**Width of Flank Wear:**
VB_{max} = 71 µm	VB_{max} = 68 µm





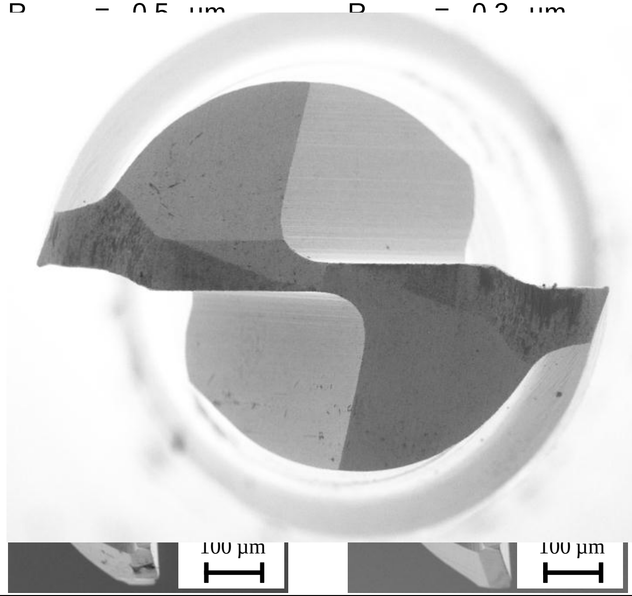




- In addition to the wear land on the flank of the tools, also apparent crater wear can be observed at the cutting edges of the unprepared end mills.
- Crater wear deteriorates the stability of the cutting edge and can cause sudden chipping or breakage of the cutting edges.
- The end mills which were machined by immersed tumbling showed no crater wear after the same cutting length L_{Cut}.

Micro Milling with Different Cutting Edge Geometries – Wear

unprepared	Tools 2
Cutting Edge:	**Cutting Edge:**
r? = 2 µm	r? = 4 µm



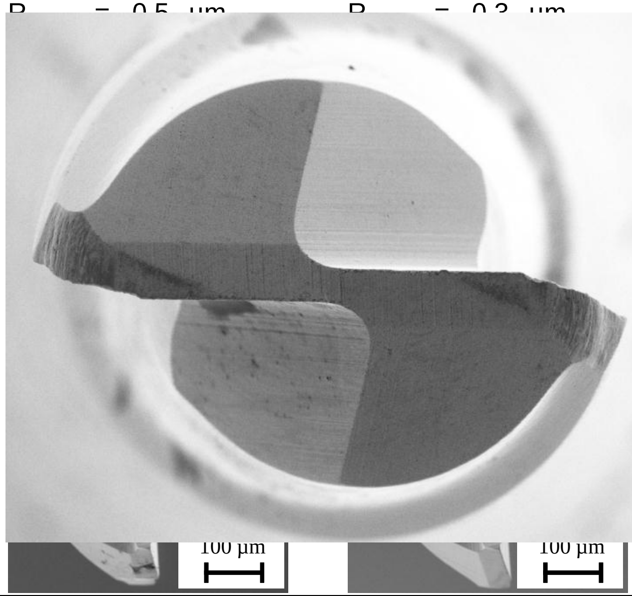
- In addition to the wear land on the flank of the tools, also apparent crater wear can be observed at the cutting edges of the unprepared end mills.
- Crater wear deteriorates the stability of the cutting edge and can cause sudden chipping or breakage of the cutting edges.
- The end mills which were machined by immersed tumbling showed no crater wear after the same cutting length L_{Cut}.

Fraunhofer
IPK
INSTITUTE
PRODUCTION SYSTEMS AND
DESIGN TECHNOLOGY

INSTITUTE FOR MACHINE TOOLS
AND FACTORY MANAGEMENT
TECHNISCHE UNIVERSITÄT BERLIN

Micro Milling with Different Cutting Edge Geometries – Wear

unprepared	Tools 2
Cutting Edge:	**Cutting Edge:**
$r_?$ = 2 µm	$r_?$ = 4 µm



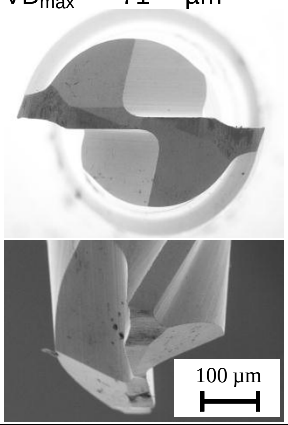
- In addition to the wear land on the flank of the tools, also apparent crater wear can be observed at the cutting edges of the unprepared end mills.
- Crater wear deteriorates the stability of the cutting edge and can cause sudden chipping or breakage of the cutting edges.
- The end mills which were machined by immersed tumbling showed no crater wear after the same cutting length L_{Cut}.

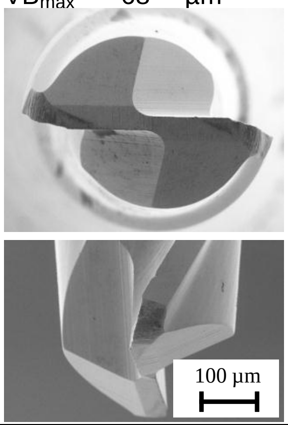
Fraunhofer IPK
INSTITUTE PRODUCTION SYSTEMS AND DESIGN TECHNOLOGY

IWF
INSTITUTE FOR MACHINE TOOLS AND FACTORY MANAGEMENT
TECHNISCHE UNIVERSITÄT BERLIN

Micro Milling with Different Cutting Edge Geometries – Wear

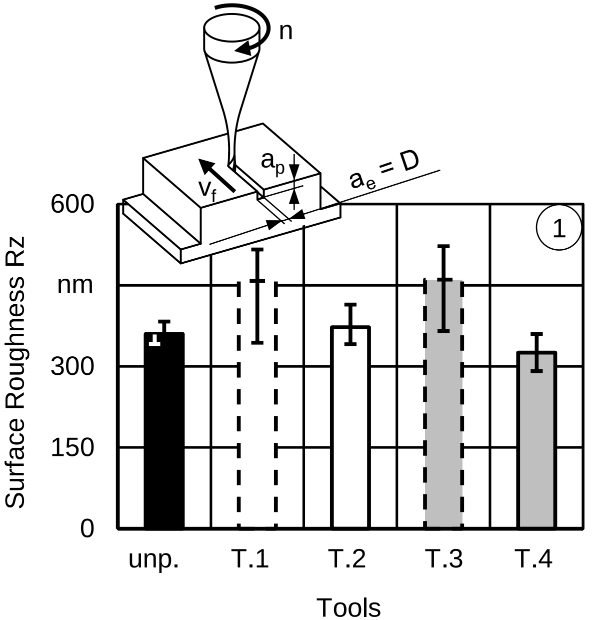
unprepared	Tools 2
Cutting Edge:	**Cutting Edge:**
$r_{?}$ = 2 µm	$r_{?}$ = 4 µm
$R_{s,max}$ = 0.5 µm	$R_{s,max}$ = 0.3 µm
Process Parameters:	**Process Parameters:**
f_z = 5.9 µm	f_z = 5.9 µm
v_c = 40 m min^{-1}	v_c = 40 m min^{-1}
Width of Flank Wear:	**Width of Flank Wear:**
VB_{max} = 71 µm	VB_{max} = 68 µm

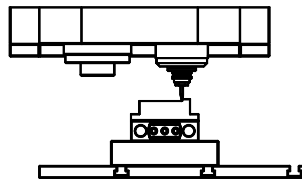




- In addition to the wear land on the flank of the tools, also apparent crater wear can be observed at the cutting edges of the unprepared end mills.
- Crater wear deteriorates the stability of the cutting edge and can cause sudden chipping or breakage of the cutting edges.
- The end mills which were machined by immersed tumbling showed no crater wear after the same cutting length L_{Cut}.

Micro Milling with Different Cutting Edge Geometries – Surface Roughness





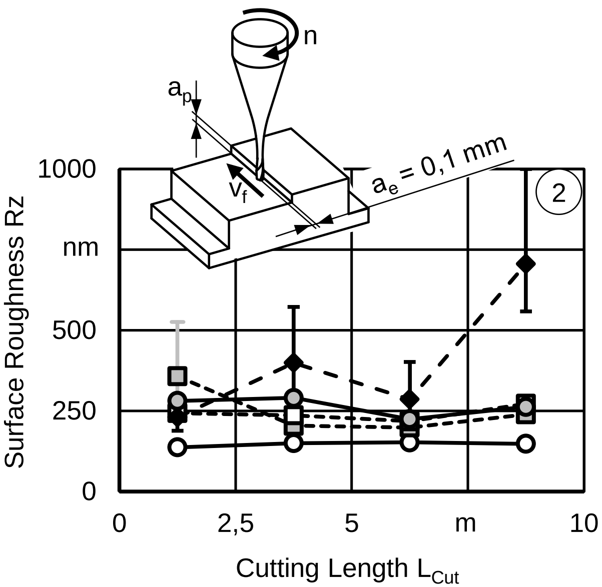
Process:
Micro Milling

Process Parameters:
n = 31800 min^{-1}
v_c = 100 m min^{-1}
f_z = 15 µm
a_p = 100 µm

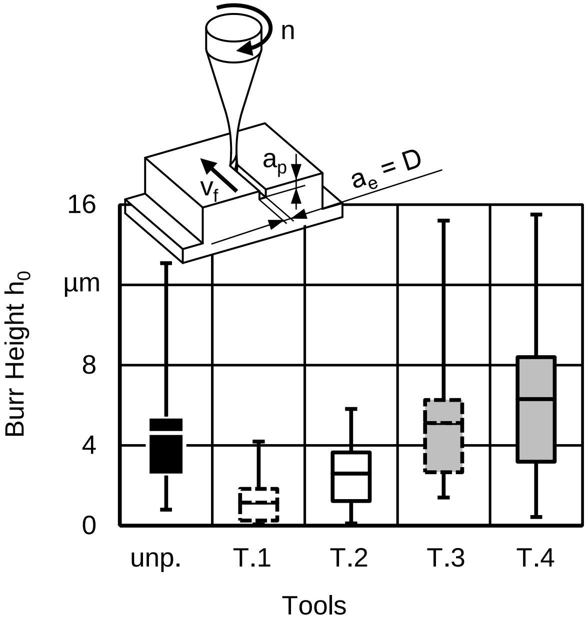
Tools:
Two Flute End Mills
Cemented Carbide
No Coating
Diameter D = 1 mm

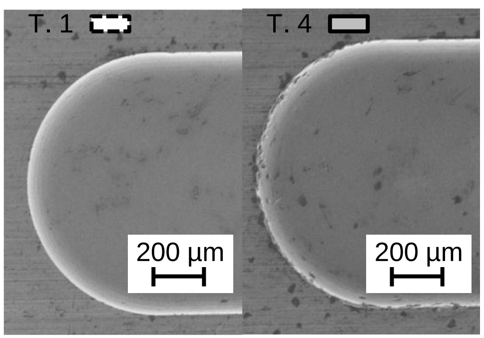
Workpiece Material:
M261, BÖHLER
HV 10 = 267 kN mm^{-2}

			1.	2.
unp.	r_β = 2 µm,	$R_{s,max}$ = 0,5 µm		
T. 1	r_β = 4 µm,	$R_{s,max}$ = 0,4 µm		
T. 2	r_β = 4 µm,	$R_{s,max}$ = 0,3 µm		
T. 3	r_β = 8 µm,	$R_{s,max}$ = 0,4 µm		
T. 4	r_β = 8 µm,	$R_{s,max}$ = 0,3 µm		

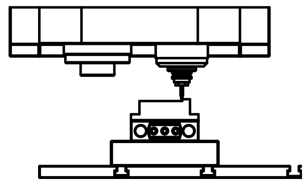


- The increase of the cutting edge radius r_β does not results in an increase of the surface roughness Rz when "smooth" cutting edges are used.
- Consistent results are achieved with prepared tools through a cutting length of L_{Cut} = 10 m.
  - Tool group 2 showed the lowest surface roughness Rz.





Micro Milling with Different Cutting Edge Geometries – Burr Height



Process:
Micro Milling

Process Parameters:

n	=	31800 min^{-1}
v_c	=	100 m min^{-1}
f_z	=	15 µm
a_p	=	100 µm

Tools:
Two Flute End Mills
Cemented Carbide
No Coating
Diameter D = 1 mm

Workpiece Material:
M261, BÖHLER
HV 10 = 267 kN mm^{-2}

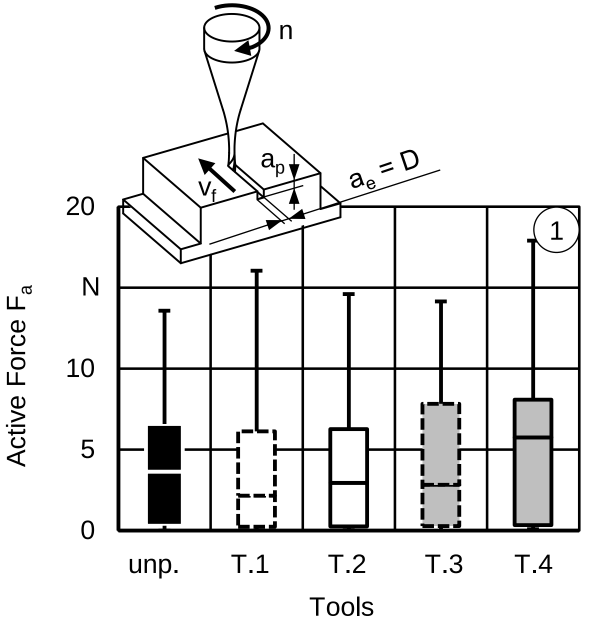
1.

unp.	r_β = 2 µm,	$R_{s,max}$ = 0,5 µm	
T. 1	r_β = 4 µm,	$R_{s,max}$ = 0,4 µm	
T. 2	r_β = 4 µm,	$R_{s,max}$ = 0,3 µm	
T. 3	r_β = 8 µm,	$R_{s,max}$ = 0,4 µm	
T. 4	r_β = 8 µm,	$R_{s,max}$ = 0,3 µm	

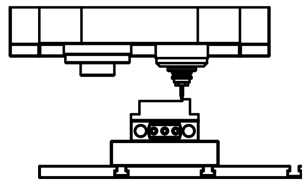
- A reduction of the chipping of the cutting edge R_s has caused an increase of the burr height h_0 of 30% in the experiments.
- When using the prepared tools an increase of the cutting edge radius r_β has led to a significant increase of the burr height h_0.

Fraunhofer
IPK
INSTITUTE
PRODUCTION SYSTEMS AND
DESIGN TECHNOLOGY

INSTITUTE FOR MACHINE TOOLS
AND FACTORY MANAGEMENT
TECHNISCHE UNIVERSITÄT BERLIN



Micro Milling with Different Cutting Edge Geometries – Active Force



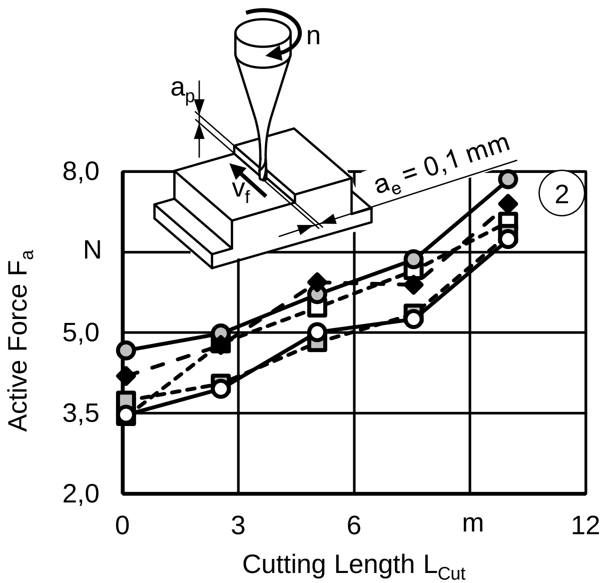
Process:
Micro Milling

Process Parameters:
n = 31800 min^{-1}
v_c = 100 m min^{-1}
f_z = 15 µm
a_p = 100 µm

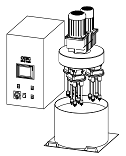
Tools:
Two Flute End Mills
Cemented Carbide
No Coating
Diameter D = 1 mm

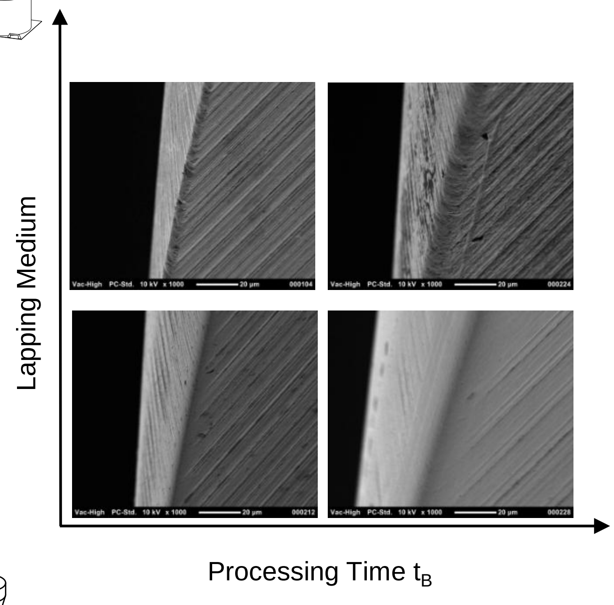
Workpiece Material:
M261, BÖHLER
HV 10 = 267 kN mm^{-2}

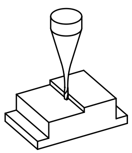
			1.	2.
unp.	r_β = 2 µm,	$R_{s,max}$ = 0,5 µm		
T. 1	r_β = 4 µm,	$R_{s,max}$ = 0,4 µm		
T. 2	r_β = 4 µm,	$R_{s,max}$ = 0,3 µm		
T. 3	r_β = 8 µm,	$R_{s,max}$ = 0,4 µm		
T. 4	r_β = 8 µm,	$R_{s,max}$ = 0,3 µm		

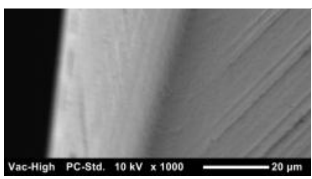


- Higher edge radii r_β lead to higher active forces F_a.
  - Increased resistance to penetration of the cutting edge into the workpiece material.
- Rougher cutting edges result in lower active forces F_a.
  - Reduced surface contact and friction force portions.
- No significantly increased tool strain by a cutting edge preparation.

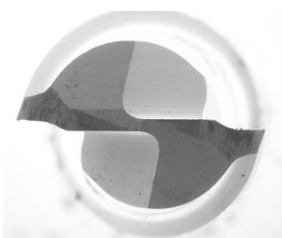


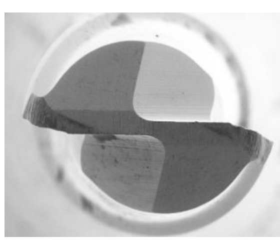






Tool Group 4:
r_β = 8 ± 1,2 µm
$R_{s,max}$ = 0,3 ± 0,1 µm





Conclusion

- Immersed tumbling:
  - The processing time t_B is mainly responsible for the size of the cutting edge radius r_β and the lapping medium defines the chipping of the edge R_s.
  - Cutting edge radii in the range of 4.0 µm ≤ r_β ≤ 31.2 µm with a maximum chipping of the cutting edge in the range of 0.3 µm ≤ $R_{s,max}$ ≤ 0.4 µm were manufactured.
- Milling experiments:
  - End mills with a cutting edge radius of r_β = 8 µm and a maximum chipping of the cutting edge $R_{S,max}$ = 0.3 µm showed overall the lowest maximum width of flank wear land VB_{max}.
  - In comparison to unprepared end mills the maximum width of flank wear land VB_{max} could be reduced by 14 % and the variance of the results could be reduced up to 92 %.
  - The tools which were prepared by immersed tumbling showed no tendency for crater wear.

Thank you for your attention

- Contact
  - Dr.-Ing. Armin Loewenstein
  - Department Micro Production Engineering
  - Fraunhofer Institute Production Systems and Design Technology IPK
    Pascalstrasse 8-9
    10587 Berlin
  - Tel.: +49 (0)30 / 3 90 06 410
  - E-Mail: armin.loewenstein@ipk.fraunhofer.de
  - Internet: www.ipk.fraunhofer.de