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# MICRO-MILLING PROCESS FOR MANUFACTURING OF MICROFLUIDIC MOULDS

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***Abstract.*** *Modern technological devices demand high precision components and due to increasing miniaturization of these components, the industries are faced to new challenges in the manufacturing processes. Micro-machining has several advantages among these new manufacturing processes, due to its capability of producing complex, high-precision geometries with micro-features in a wide range of materials. However, it has different phenomena compared to conventional machining. In order to increase their application in industries, micro-machining processes must fit in productivity and quality standards, thus needing further research to comply with these requirements. In this context, the project Micro-Milling Process Optimization (Micro-O) has been initiated in the scope of BRAGECRIM (Brazilian-German Collaborative Research Initiative on Manufacturing Technology), which is a Brazilian-German research platform for exchanging and developing know-how among partners, supporting research institutes and industries in both countries in achieving higher competitiveness levels on micro machining technologies. Micro-O's main goals are to improve micro-production chain, developing knowledge regarding machining process and the setup procedure as well as part control and process simulation. In this paper, initial results based on experiments conducted on a micro-machining center are presented, allowing analysis of data leading to optimized process values. A part geometry based on fundamental micro-features commonly used on molds for microfluidic devices was developed using CAD/CAM software. Finally, the procedures "design", "tool path generation", "process setup", "machining" and "part inspection" have been documented and analyzed with regard to their time consumption.*

***Keywords:*** *Micro-milling, CAD/CAM processing, Quality inspection, Microfluidic device, Micro-manufacturing*

## 1 INTRODUCTION

Manufacturing technologies and machine tools for micro-machining have achieved a high proficiency level in industry and research. The increasing demand for micro-structured parts and products with optical functional surfaces requires enhancing productivity, to develop new as well as to improve existing manufacturing technologies and thus, to enable for a faster and more reliable micro-production (Bliedtner and Gräfe, 2010).

This work aims at improving the micro-production chain to generate knowledge about related process stages, including potential improvements of productivity and quality. First, the process planning will be focused on the analysis of significant impact factors in micro-machining and on the reduction of processing times. Secondly, the process setup and the machining itself will be investigated focusing on its improvement by using enhanced monitoring and simulation techniques. Finally, the part control will be improved regarding measurement methodologies to effectively and accurately provide part information. In order to consider all these different aspects and their impact on the micro-milling chain, the partners will join their forces and bring their specific knowledge and experience from different disciplines for jointly contributing to the improvement of micro-milling processes based on their particular expertise.

## 2 LITERATURE REVIEW

Micro-machining enables the production of miniaturized parts as well as high precision machining of functional surfaces. Micro-milling is different from macro-cutting process. Chip thickness and grain sizes of different materials are in the range of cutting edge radius (Bliedtner and Gräfe, 2010). Moreover, the commonly used spindle speed is very high (Byrne, *et al.*, 2003; Uhlmann, *et al.,* 2009). According to DIN 8580 (DIN 8580, 2003) micro-machining, and hence micro-milling, is part of micro-manufacturing with geometrically determined cutting edge. In this project, micro-machining will be understood in terms of micro-milling process. The main advantages are higher material removal rate and better dimensional accuracy. However, industrial application of micro-milling is still dependent of more knowledge and understanding of issues involved in this process, such as tool wear and resulting surface quality (Schauer and Uhlmann, 2006; Uhlmann, *et al*., 2011). During machining of materials that are difficult to cut, unpredictable tool life and premature failure may become a major issue since it raises manufacturing costs and lower-quality (Cristofaro, *et al*., 2012; Rodrigues, *et al*., 2012). Micro-milling process manufacturing is developed in micro-milling process planning, monitoring systems for micro machines and quality inspection of micro-structured parts.

***Micro-milling process planning***. Micro-milling as a comparably young production method suffers drawbacks of relatively high cost and low productivity. Increasing productivity and at the same time maintaining the high level of precision, means to apply technologies such as high-speed and high-precision micro-milling. It also means to develop new and innovative processes, specific technologies and methods which face challenges of the micro-scale machining processes affecting especially process planning, cutting conditions and part control (Sodemann and Mayor, 2011; Aurich, *et al*., 2012). Machining of parts with micro features requires representation through a CAD geometric model. However, these models must hold the requirements concerning accuracy demands of micro-structured products. It needs to be assured, that CAD/CAM systems provide functions and capabilities adequate for micro-milling process and include specific modules required for this process chain (Biermann, *et al*., 2012).

***Monitoring systems for micro machines.*** Micro-milling process requires monitoring systems to increase the productivity and quality. Monitoring methods already used on macro scale manufacturing are no more suitable for micro-milling. Therefore, development of new monitoring methods and tools are on demand (Gandarias, *et al*., 2008). The machine set up is challenging because part alignment and fixture, tool length, diameter and run-out need to be determined very precisely. Contact and non-contact sensors are used to measure these variables. The touch probe is mainly used for part referencing (Popov, *et al*., 2009) presented a reliable method for setting up the work coordinate system for micro-milling operations. Tool length is affected by spindle thermal growth, so the length measurement should consider the machine heat up with the work spindle rotation. Measurement of tool diameter and run out are affected also by tool wear and dirt. Nowadays, laser systems are used to perform those measurements (Popov, *et al*., 2009).

***Quality inspection of micro-structured parts***. Micro-devices can be defined as having at least two critical dimensions in sub-millimeter range (Tosello, *et al*., 2009) or a component whose feature has at least one critical dimension significantly smaller than 0.1 mm, typically with tolerance ranges of a few micrometers, while the whole device may have larger dimensions. This typical miniaturized component creates a multi-fold measurement problem (Petz, *et al*., 2012). Inspection of parts with micro-features and critical dimensions requires new procedures to guaranty a complete quality validation. The microstructures have to be measured with more than one single instrument to cover the whole range, creating the need of associating measurement results and uncertainties from different data sources. Nowadays, multi-sensor technology is available and offers a combination of measurements from contact and non-contact sensors. Measurement complexity increases due to the critical dimensions and sensors employed resulting in the necessity of using data fusion techniques (Weckenmann, *et al.,* 2009). Validation of measurement procedures to ensure confidence on results becomes more essential due to the complexity associated to measurement uncertainties (Fleischer, *et al*., 2008).

## 3 IMPROVEMENT IN MANUFACTURING PARTS WITH MICROFEATURES

This work focuses on the development of knowledge and solutions for innovating critical aspects of micro-milling processes, concentrating on parts production with micro-structures, targeting the improvement of productivity, efficiency and on the advancement of strategies for optimizing costs and quality. The research project faces some important challenges described in the scope and framework of BRAGECRIM (Brazilian-German Collaborative Research Initiative on Manufacturing Technology). In this paper, preliminary results concerning the design and tool path generation in CAD/CAM system, process set up, machining and quality inspection are presented. Micro-injection moulds are defined in such a way that they fulfil one or more of the following specifications: 1. weight is less than 1 mg; 2. micro-structures with dimensions smaller than 100 µm; tolerances less than 5 µm (Attia, *et al.,* 2009).

A part was defined in the scope of the research work presented here, on the basis on common features necessary for microfluidics applications such as linear microchannel with single inlet-outlet, micro-mixer with serpentine geometry and micro-diffusor with vortex geometry. The part design is shown in Fig. 1a. Its surface is square with an edge length of 15 mm and it contains walls with a width of 100 µm and 300 µm. The wall height is 1 mm. Dimensional tolerances are less than 5 µm. Features such as a draft angle of 3 ° in the walls are considered to ensure that the microfluidic device can be demolded. For wall sides and all floors a center line average roughness of Ra < 0.5 µm is to be achieved.

### 3.1 CAD/CAM processing of parts with micro-features

The parts with micro-structures were developed in the CAD-CAM program NX9, Siemens, München, Germany. The processing was conducted on the Workstation Z600 2x Xeon QC5620 2.4GHz, 12 Gb RAM, HD SAS 300 Gb, with the graphic card nVidia Quadro FX 1800. A kinematic model of the five-axis ultra-precision machining center KERN Evo has been implemented in NX9 as depicted in Fig. 1. In this study, software capabilities were analyzed regarding design of microstructures, generation of tool paths for micro-machining and resulting machining times.

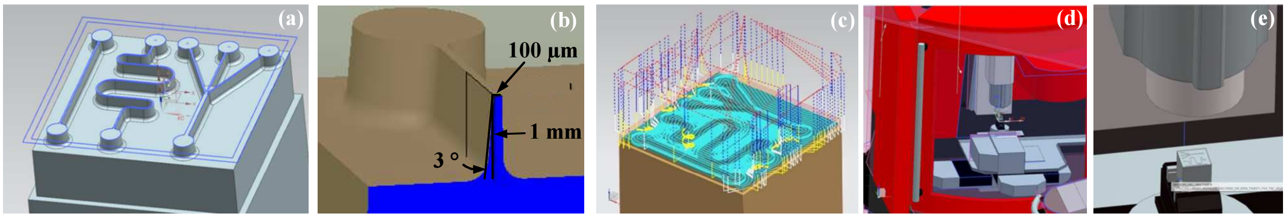


Figure 1. CAD/CAM processing: (a) CAD part with micro features; (b) Microchannel transversal section; (c) CAM tool path generation; (d) kinematic model of KERN Evo; (e) Virtual machine simulation

The micro-milling tool path generation was subdivided into five cutting operations: Roughing, referencing, semi-finishing 1, semi-finishing 2 and finishing. Cutting parameters and operation strategies have been chosen as shown in Tab. 1. A tolerance of 0.001 mm was set for all operations. Roughing implies shape contouring by removing material in planar cut levels normal to a fixed tool axis. Referencing operation was added for the purpose of part referencing in measurement. In semi-finishing 1, a flat mill tool with diameter of 2 mm was used. After semi-finishing 2, few material was left in form of the part stock of 0.01 mm. Finishing was set with radius mill tool with diameter of 0.5 mm.

Table 1. Parameters and machining strategy for tool path generation

| Cutting operation | Operation strategy | Tool | Tool diameter [mm] | Feed rate [mm/min] | Spindle speed [rpm] | Cutting depth $a_p$[mm] | Cutting width $a_e$ [mm] | Part stock [mm] | Cut strategy | Machin-ing time [min] |
|---|---|---|---|---|---|---|---|---|---|---|
| Roughing | Floors and Walls | Flat Mill | 8 | 3200 | 8000 | 0.7826 | 0.7826 | 0.1 | Zig-Zag | 00.15 |
| Referencing | Cavity Mill | Flat Mill | 8 | 3200 | 8000 | 1 | 0.5 | 0 | Follow Part | 00.02 |
| Semi-Finishing 1 | Cavity Mill | Flat Mill | 2 | 3200 | 32000 | 0.1 | 0.2 | 0.05 | Follow Part | 00.44 |
| Semi-Finishing 2 | Cavity Mill | Flat Mill | 1 | 1300 | 30000 | 0.1 | 0.1 | 0.01 | Follow Part | 03.18 |
| Finishing | Cavity Mill | Ball Mill | 0.5 | 1200 | 40000 | 0.05 | 0.05 | 0 | Follow Part | 07.54 |

The kinematic model of KERN Evo is applied with the purpose of verifying collisions between tool and machine or part. Furthermore, compile cycles e.g. for tool change and specific machine parameter have been implemented. According to the simulation an overall machining time of 12.43 min is expected. In difference to the machining process described in section 3.2, a second semi-finishing was introduced here, resulting in a significant decrease of machining times. Finally, the post-processed cutter location data resulting in NC-code are evaluated regarding their size. The amount of data with high precision is challenging to be processed in the CNC of the machine tool, which also has to fulfill various other tasks during a PLC cycle. Table 2 lists the time needed to calculate the tool path, NC file size and number of lines to be processed by CNC for each cutting operation.

Table 2. NC program size and number of lines

| Method | Time to calculate tool path | NC file size | Number of lines in NC program |
|---|---|---|---|
| Rouging | 3 s | 12 KB | 522 |
| Semi-Finishing 1 | 13 s | 354 KB | 13223 |
| Semi-Finishing 2 | 13 s | 361 KB | 14538 |
| Finishing | 19 s | 517 KB | 21175 |

The amount of data is already comparably high for the simple micro-structured part with low complexity. With increase of complexity and tolerance lower than 0.001 mm, the time for calculations and amount of data further increases.

### 3.2 Process set up and machining

Micro-structured part has been machined on two different micro-milling centers, the five-axis micro-milling center Primacon PFM 4024-5D (Primacon) located at the IWF in Berlin, Germany and the five-axis ultra-precision machining center KERN Evo (KERN Evo) located at the IPT in Sao Paulo, Brazil. Technical data of both machines can be found in Tab. 3. As can be seen, both machine tools are capable of high-precision milling and are comparable in their specifications. The main stages in machine tool set-up can be subdivided into: 1) Clamping of tool and determination of its length and diameter, 2) Clamping of work piece as well as identification of its reference and 3) CNC set-up which includes CAM post-processing, setting point of origin and, when indicated, predefinition of monitoring devices.

Table 3. Technical data of 5-axis micro-milling centers KERN Evo and Primacon PFM 4024-5D

| Specification | KERN Evo | Primacon |
|---|---|---|
| Longitudinal axis X | 300 mm | 400 mm |
| Lateral Axis Y | 280 mm | 240 mm |
| Vertical Axis Z | 250 mm | 436 mm |
| Linear axes | 16 m/min | 40 m/min |
| Positioning accuracy | P = 0.005 mm | P = 0.005 mm |
| Positioning instability | PS = 0.001 mm | PS = 0.001 mm |
| Acceleration | 8 m/s² | 10 m/s² |
| Work piece clamping system | GIN-VS30 | MZU 170-60 |
| Tool clamping and chuck | HSK25 with ESX 16 | HSK25 with PG 15 |

For machining with the Primacon, the tool was clamped with a PG 15 powRgrip collet chuck, REGO-FIX AG, Tenniken, Switzerland, which has a radial run-out of less than 0.003 mm. In case of the KERN Evo, the tool was clamped using a HSK 25 tool holder with ESX 16 high precision collet chuck to ensure high vibration damping as well as a sufficient clamping force. In both cases, the diameter and tool length was measured using the laser system Nano-NT, Blum-Novotest GmbH, Grünkraut-Gullen, Germany, which allows for measurement of tools with a diameter bigger than 15 µm and has repeatability better than 0.1 µm. Both systems can be driven automatically and routines are given in CNC control. The work piece fixture is an important impact factor in micro-machining processes. The machine tool set-up for both milling centers can be seen in Fig. 2.


Figure 2. Set-up of micro-milling centers: (a) Primacon PFM 4024-5D and (b) KERN Evo

In case of Primacon, the cubical work piece with edge length of approximately 16 mm was fixed in the mechanical centric clamping system MZU 170-60, Spreitzer GmbH & Co. KG, Gosheim, Germany. The clamping force amounts to 15 kN. On the KERN Evo the clamping system was installed over the machine table in the top of base surface and the material block is fixed in the middle of the clamping chuck using a clamping force of 4.3 kN. In both cases the work piece material is Aluminium. Both machines are equipped with an infrared touch probe for referencing of the work piece. Machining operations have been structured into Roughing, Referencing, Semi-finishing and Finishing. The Roughing consisted of face-milling using an end-mill with a diameter of d = 8 mm in order to get well defined blank dimensions. With the aid of the same tool the reference edges were milled afterwards. For Semi-finishing the tool was changed to an end-mill with a diameter of d = 2 mm. Finally, the microstructures were finished with the help of a third end-mill with a diameter of d = 0.5 mm in case of Primacon and d = 0.8 mm in Kern Evo. The cutting parameter and tolerances for both Finishing operations can be obtained in Tab. 4. The tool radius measured was feed back into the

CAM system. Due to the low cutting depth and feed rate per tooth the CAM processing was repeated for the finishing with measured radius to regard for real radius. Radius compensation in the control is possible as well, but cutting conditions are undetermined in this case. A tool radius or length uncertainty of only 5 µm changes the cutting conditions by 10 % in case of Primacon and 20 % in case of KERN Evo. Thus, in the experiments, the machining was found to be more stable, when the actual tool radius had been set in the CAM tool path generation already.

Table 4. Finishing process and CAM settings implemented for micro-milling centers KERN Evo and Primacon

| Parameters | Finishing KERN Evo | Finishing Primacon | Parameters | Finishing KERN Evo | Finishing Primacon |
|---|---|---|---|---|---|
| Work piece material | Aluminium | Aluminium | Cutting width $a_e$ [mm] | 0.025 | 0.05 |
| Tool | End Mill | End mill | Wall stock [mm] | 0 | 0.05 |
| Tool diameter d [mm] | 0.8 | 0.5 | Floor stock [mm] | 0 | 0.05 |
| Number of teeth z | 2 | 2 | Cutting speed $v_c$ [m/min] | 100.5 | 94 |
| Cut pattern | Offset | Follow Part | Feed per tooth $f_z$ [mm] | 0.006 | 0.01 |
| CAM tolerance [mm] | 0.005 | 0.001 | Spindle speed n [rpm] | 40000 | 60000 |
| Depth of cut $a_p$ [mm] | 0.025 | 0.05 | Feed rate $v_f$ [mm/min] | 500 | 1200 |

Regarding the machine tool set-up, the main effort had to be put into setting the work piece blank and the CNC accordingly, both processes which can be improved significantly. Clamping-, referencing- as well as machining-times are compared for experiments on Primacon and KERN Evo in Tab. 5. The values for duration of clamping, measurement and referencing have been determined by procedures repeated by an experienced machine tool operator.

Table 5. Processing times for tool and work piece set-up as well as machining

| Set-up operation | Processing time KERN Evo | Processing time Primacon |
|---|---|---|
| Tool clamping and measurement | 54 s | 3 min 15 s |
| Work piece clamping and referencing | 12 min 23 s | 4 min 50 s |
| Machining | 1 h 10 min 14 s | 44 min 19 s |

The set-up of micro-milling processes has been analyzed regarding the time an operator needs to clamp tool and part as well as to determine tool length and radius and work piece reference. Setting up the KERN Evo took 13 min 17 s (16 % of the overall machine time). In case of Primacon, the set-up took 8 min 5 s (15 % of total process time).

### 3.3 Quality inspection

Quality inspection of parts with micro-features focuses on the selection of measurement strategies and systems in order to ensure adequate accuracy and reasonable measurement effort in contrast to the amount of information necessary to fully characterize the part quality. Regarding the requirements for the micro-injection mold with tolerances less than 5 µm and Ra < 0.5 µm, preliminaries tests, reported here, were carried out with different measurement systems. The systems are compared to each other with regard to their accuracy and applicability to determine characteristics of micro-features as well as the overall time necessary to conduct measurements on each device.

***Inspection with confocal laser scanning microscope:*** Confocal laser scanning microscope MicroProf MPR100, FRT GmbH is a measurement system which allows surface topography measurement in form of a 3D Map with height of points in a parametrized mesh. Its axis have accuracy < 1 µm. The vertical axis includes a sensor head with a resolution < 50 nm which is moved towards the surface to be measured. Results are showed in Fig. 3.

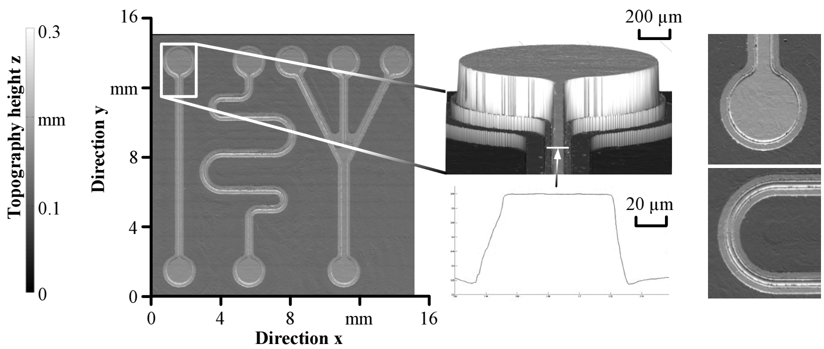


Figure 3. Topography and details of machined part using confocal laser scanning microscope

Two measurements have been conducted. Resolution for the first measurement was 10 µm, which resulted in a mesh of 1500x1500 points. The overall measurement time was 1.56 h. A second measurement with resolution of 1 µm in x-direction was conducted to gather more precise results regarding form accuracy of the micro-walls, which have a target width at the surface top of 63 µm. The overall time for this measurement was 13.23 h, resulting in approximately 0.84 h/$10^6$ points.

***Inspection with CMM Machine:*** Multisensor CMM (Coordinate Measurement Machine) Werth Video Check IP, allows dimensional and geometric measurement with a scale resolution of 0.1 µm. The measurement was conducted with optical sensor, with 10 times amplification, using lens with focal distance of 37 mm. The microchannel height is defined as the distance between the lowest plane and the plane on top of the channel. To calculate the lowest plane, points were collected using auto focus strategy and bright field illumination, with distance between points of 2.1 mm. To calculate the planes on top of each channel, points were collected using the auto focus strategy along the top plane, with a distance of approximately 0.35 mm between them on the circles and 1.4 mm on the other parts of the geometry. Microchannel width is defined as the distance between lines determined at each side of the straight segment, on the top plane of the geometry. To identify these lines, the plane on top of the geometry determined to calculate the height was set as XY plane for the coordinate system and used to perform a contour scan of the geometry edges. From this scan, two lines were calculated using gauss strategy. The curves were defined as the diameter calculated at the curved segment on top plane of the geometry. To calculate this diameter, the plane on top of the geometry determined to calculate the height was set as XY plane for the coordinate system and used to perform a contour scan of the edges of the geometry. From this scan, the respective area was selected and the diameter was calculated using gauss strategy. The inspection of the micro-features with optical sensor is shown in Fig. 4a. It represents the points collected in the measurement while Fig. 4b and 4c display a segment of a linear and a curved microchannel.

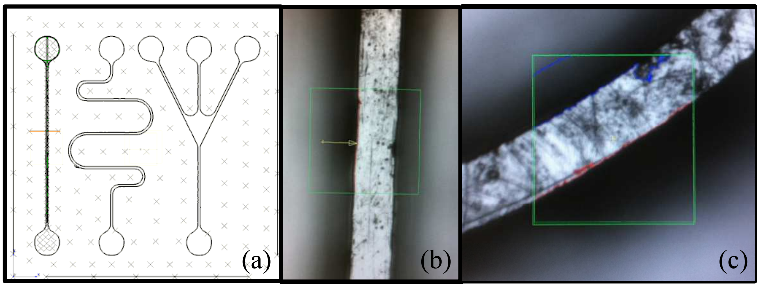


Figure 4. Inspection of dimensional quality using the CMM video check IP machine with optical sensor: (a) Points collected of the geometry, (b) linear microchannel, (c) curved microchannel

***Inspection with stylus profiler***. Stylus profiler DektakX applies measurement technique stylus profilometry using contact and 2D/3D surface profile measurements. It has sensors of stylus low inertia with force from 10 mN to 150 mN. The stylus radius can be varied from 50 nm to 25 µm. The step height repeatability is less than 5 Å on a vertical range of 1 mm, and minimum vertical resolution of 1 Å. It is capable for measuring step heights less than 10 nm. Fig. 5a presents the stylus point in a microchannel of geometry 3. Figure 5b and 5c show 3D profile of curved microchannel. Figure 5d represents the profile slice. The measurement for aluminum part was configured with a height range of 524 µm, radius style probe of 12.5 µm, stylus force of 100 mN and resolution of 0.1 µm/pt. The profiles were calculated with 4501 points and speed of 30 µm/s. The linear microchannel height measurement time was of 200 s. The 3D profile measurement was configured with 10 µm/trace and 930 traces. The average measurement time in 3D profile was 20 h for the complete part.

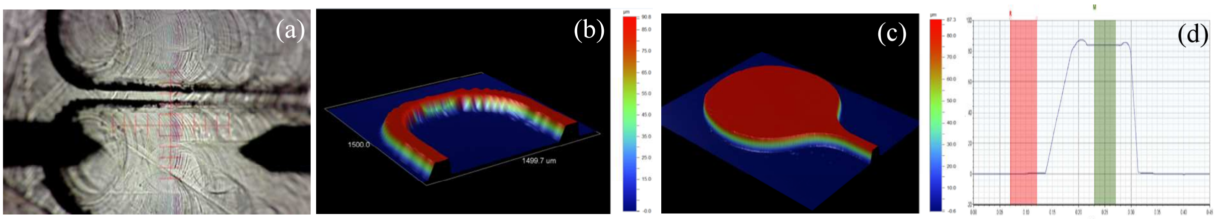


Figure 5. Profiler system: (a) Stylus point in microchannel, (b) - (c) 3D profile and (d) Profile Analyse Measurement

***Inspection with digital microscopy.*** The digital microscope Keyence VHX-600E allows application of automatic edge detection functions, 3D profile, volume, plane distance and angle measurements. The system has optical lenses VH-Z50L with zoom factor of 50 - 500 with 85 mm of observation distance and VH-Z100R with zoom factor of 100 - 1000 and 25 mm observation distance. Its profile measurement unit VHX-S15CE has motor stages resolution of

0.05 µm/pulse, positioning accuracy of 6 µm, and repeatability of ± 0.5 µm. It is constituted by a camera that works at frame rate of 15 - 28 frames/sec and resolution of 54 million pixels and 16 bit resolution. Figure 6a shows a microchannel profile obtained using 3D depth composition trough images with a pitch variation of lens in z-axis. The microchannel was measured using lens zoom factor 500, while z-axis recorded intervals of 4.33 µm. Figure 6b shows an inlet with lens zoom factor 500 and interval of 9.84 µm. The time for height measurements using zoom factor 100, taking 50 images and applying autofocus is approximately 22 min.

***Inspection with optical microscopy.*** Optical microscope AxioScope A1 is a system useful for quality control, material analysis and inspection of parts with microstructures. Functions can be applied for surface examination such as material characteristics, edges, walls, channels, chip formation and structure characterization. Figure 6c and 6d show measured sections of part with micro-features using optical microscope. The micro-channel shown in Fig. 6c is measured using zoom factor 20, 16 bit grey levels, X-Y scale factor of 0.67 µm and exposure time of 46.1 ms. The curved channel shown in Fig. 6d has been measured with zoom factor 5, 8 bit grey levels, X-Y scale factor of 2.713 µm and exposure time of 32 ms. The time to conduct the measurement was approximately 1 h 7 min.

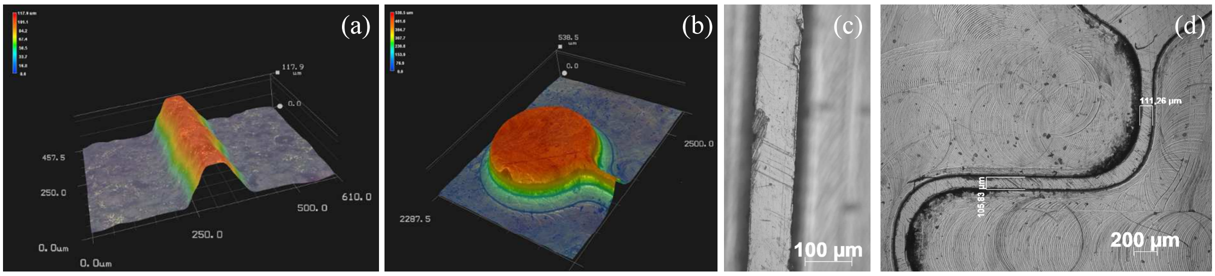


Figure 6. Measurement of micro-features with digital and optical microscopes: (a) - (b) 3D profile with digital microscope of linear microchannel and inlet, (c) - (d) microchannels with optical microscope

The assessment values assigned for performance comparison of measurement systems are characteristics of measurement system such as resolution scale and accuracy, measurement capability regarding micro-structures and time to conduct the measurement. Table 6 includes the comparison and specifications of the measurement systems.

Table 6. Comparison of measurement systems to determine the quality of parts with micro features (on example of part with microfluidic features and surface size 15 mm x 15 mm)

| **Measurement system** | **Measurement Accuracy** | **Effort - approximated measurement time** | **Roughness Ra** | **Dimensional 2D x-y plane** | **Dimensional 3D** | |
|---|---|---|---|---|---|---|
| | | | | | **Height** | **Inclination of channel** |
| Confocal laser scanning microscope | < 1 µm | 13 h | + | + | + | +/- |
| Optical microscope | 2.5 µm | 1 h | - | + | - | - |
| Digital microscope | 3 µm | 0.4 h | - | +/- | + | +/- |
| Stylus Profiler (contact sensor) | 0.2 µm | 20 h | + | +/- | + | +/- |
| CMM VideoCheck IP (optical sensor) | 4 µm | 8 h | +/- | + | + | + |

With confocal laser microscope system it is possible to measure micro-features in 2D and 3D, but data amount and measurement time can become an issue as they increase with resolution. The inclination angle and side-wall roughness are more difficult to inspect with precision. The CMM VideoCheck IP with optical sensor is able to measure micro-features with high resolution in 2D and 3D. However, it is not possible to conduct roughness measurement and to measure inclination angles with precision. The digital microscope with profiler unit is capable to measure 3D profiles of different microstructures with time reduced but with lower resolution than the CMM VideoCheck IP system. The measurement in 2D has systematic errors due to the uncertainty of the measurement nodes in each feature. This system is not able to ensure roughness measurement with precision. With optical microscope it is possible visualize the surface of final part such as edges and material in the finishing process. It is possible to check 2D dimensional part, but each measurement consumes time. This system is not able to measure dimensional 3D. The stylus profiler system is able to measure micro-features in 3D and surface roughness according to the requirements Ra < 0.5 µm and tolerances < 5 µm. However, common geometries in 2D and 3D require more measurement time and the accuracy is related with the appropriate measurement tools and functions in post-processing. With increasing the resolution and points in the measurement, not only the amount of data increases, but also the measurement time.

## 4 CONCLUSIONS

Micro-milling still reveals a significant optimization potential regarding the productivity. While research on micro-milling usually addresses machining process, the work presented in this paper focusses on productivity increase of micro-milling implying the whole manufacturing chain. This concerns the CAM-system, process set-up, machining and quality control. Therefore, basic geometries oriented at application of microfluidic devices have been defined and a part with micro-structures has been derived in CAD program accordingly.

The tool path generation with tolerance of 1 µm consumes calculation time which depends on the complexity of the micro-structures. As shown, tool path generation for finish cutting operations for a comparably simple structure implemented on a regular desktop computer takes about 10 s. This calculation time will increase significantly, considering tolerances down to 0.1 µm or miniature details in large size parts. Thus, either the calculation time has to be reduced or modules should be integrated into the commonly used CAD-CAM system to satisfy micro-milling demands. While the machining time can be significantly reduced by introducing a second semi-finishing, methods and procedures have to be defined to reduce set-up times while maintaining the accuracy needed.

Five different measurement systems have been presented and assessed regarding their applicability and capability to determine the quality and measurement time of micro-structured parts. While scanning systems allow for a high information density, the measurement time is very high. To obtain a complete evaluation of the critical dimensions such as inclination angles and the width of the segments in different heights, as well as roughness, it is necessary to integrate strategies. Measurements systems with contact and non-contact sensors and data-fusion analyses are required, with the purpose of increasing accuracy, reducing measurement times and obtaining complete quality inspection of the part with micro-features.

Further investigations will focus the extension of CAM systems to support the user regarding the choice of cutting strategy and machining parameters, in order to reduce the number of calculations necessary to derive satisfying tool paths. Another approach followed within this research project is to simulate the machining process holistically. The improvement of process setup will focus on strategies to reduce the setup time by additional monitoring systems such as vibration, forces, temperature, humidity sensors, cameras and others. The measurement process will be improved by balancing effort and benefit of design of experiments.

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## 6 REFERENCES

Attia, U. M.; Marsona, S.; Alcockb, J. R. Micro-Injection Moulding of Polymer Microfluidic Devices. Microfluidics and Nanofluidics, Vol 7/1, pp. 1-28, 2009.

Aurich, J. C.; Reichenbach, I. G.; Schüler, G.M.: Manufacture and application of ultra-small micro end mills. Annals of the CIRP - Manufacturing Technology, Vol. 61/1, pp. 83 - 86, 2012.

Biermann, D.; Krebs, E.; Sacharow, A.; Kersting, P.: Using NC-path Deformation for Compensating Tool Deflections in Micromilling of Hardened Steel. 5th CIRP Conference on High Performance Cutting. Procedia CIRP 1, pp. 132 - 137, 2012.

Biermann, D.; Steiner, M.; Krebs, E.: Investigation of Different Hard Coatings for Micromilling of Austenitic Stainless Steel. 46th CIRP Conference on Manufacturing Systems. Procedia CIRP 7, pp. 246 - 251, 2013.

Bliedtner, J.; Gräfe, G.: Optiktechnologie – Grundlagen, Verfahren, Anwendungen, Beispiel. Leipzig: Carl Hanser Verlag, 2010.

Byrne, G.; Dornfeld, D.; Denkena, B.: Advancing Cutting Technology. Annals of the CIRP - Manufacturing Technology, Vol. 52/2, pp. 483 - 507, 2003.

Câmara, M. A.; Rubio, J. C. C.; Abrão, A. M.; Davim, J. P.: State of the Art on Micromilling of Materials, a Review. Journal of Materials Science and Technology, Vol. 28/8, pp. 673 - 685, 2012.

Cristofaro, S. de; Funaro, N.; Feriti, G. C.; Rostagno, M.; Comoglio, M.; Merlo, A.; Stefanini, C.; Dario, P.: High-speed micro-milling: Novel coatings for tool wear reduction. International Journal of Machine Tools and Manufacture, Vol. 63, pp. 16 - 20, 2012.

DIN 8580: Fertigungsverfahren – Begriffe, Einteilung. Beuth Verlag, Berlin, 2003.

Fleischer, J.; Lanza, G.; Schlipf, M.: Statistical quality control in micro-manufacturing through multivariate µ-EWMA chart. Annals of the CIRP - Manufacturing Technology, Vol 57/1, pp. 521 - 524, 2008.

Gandarias, E.; Ivanov, A.; Gallego, I.; Popov, K.; Aristimuño, P.; Aperribay, J.: An innovative tool-monitoring system (MICROM ) to detect drastic tool failures in micro-milling. Proceedings of the EUSPEN International Conference, 2008.

Petz, M.; Tutsch, R.; Christoph, R.; Andraes, M.; Hopp, B.: Tactile–optical probes for three-dimensional microparts. Measurement 45, pp 2288 - 2298, 2012.

Popov, K.; Dimov, S.; Ivanov, A.; Pham, D. T.; Gandarias, E.: New tool-workpiece setting up technology for micro-milling. The International Journal of Advanced Manufacturing Technology, Vol. 47/1 - 4, pp. 21 - 27, 2009.

Rodrigues, A. R.; Balancin, O.; Gallego, J.; de Assis, C. L. F.; Matsumoto, H.; de Oliveira, F. B.; Moreira, S. R.; Silva, N.; da Otavio, V.: Surface integrity analysis when milling ultrafine-grained steels. Materials Research, Vol. 15, pp. 125 - 130, 2012.

Schauer, K.: Entwicklung von Hartmetallwerkzeugen für die Mikrozerspanung mit definierter Schneide. Berichte aus dem Produktionstechnischen Zentrum Berlin. Hrsg.: Uhlmann, E., Fraunhofer-Verlag: Stuttgart, 2006.

Sodemann, A.; Mayor, J. R.: Experimental evaluation of the variable-feedrate intelligent segmentation method for high-speed, high-precision micromilling. Journal of Manufacturing Science and Engineering, Vol. 133/2, 2011.

Tosello, G.; Hansen, N.H.; Gasparin, S.: Applications of dimensional micro metrology to the product and process quality control in manufacturing of precision polymer micro components. Annals of the CIRP - Manufacturing Technology 58, pp. 467 - 472, 2009.

Uhlmann, E.; Wagner, U. v.; Mahr, F.; Shi, Y.: Micro Milling – Investigations on Process Structure Interactions. Proceedings of the 9th EUSPEN Conference. San Sebastian, 2009.

Uhlmann, E.; Roeder, M.; Richarz, S.: Cutting of titanium matrix composite using statistical design of experiments. CIRP General Assembly, Session STC C, Budapest, Hungary, August 21-27, 2011.

Weckenmann, A.; Jiang, X.; Sommer, K.-D.; Neuschaefer-Rube, U.; Seewig, J.; Shaw, L.; Estler, T.: Multisensor data fusion in dimensional metrology. Annals the CIRP – Manufacturing Technology, Vol 58, pp. 701 - 721, 2009.

## 7 Responsibility notice

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