5D Precision Process Monitoring

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Abstract

Process monitoring, well established for standard machine tools, currently becomes more important for ultra-precision processes as the demands for process reliability, production continuity and quality management rise steadily. In this context, state-of-the-art process monitoring methods have to be carefully adapted to the high requirements of ultra-precision components and the according manufacturing processes. Acoustic emission sensors have proven a reliable, easy to integrate and very sensitive technology to detect effects of tool wear, machining dynamics or material inhomogeneity. Nevertheless, the acquired data has to be intensively processed to allow for a suitable evaluation. State-of-the-art method use data filtering, Fourier transform or image processing algorithms to generate evaluation criteria for the determined processes, trying to allow for automated process estimation. In contrast to these time or spectrum plots, the Fraunhofer IPT approach adds the position information captured by the linear scales of the machine tool to the evaluation algorithms. In this manner, the sensor data can be visualized not only time-based but locally associated to the tool path of the manufactured workpiece. Hence, an online evaluation by the machine operator can be performed intuitively while the precision part is being machined. The paper presents the process monitoring approach, the hardware and software concepts and first experimental results.

1 Introduction

In a global information society the demands for highly advanced components with very precise contour accuracy and surface quality are rapidly increasing. Applications in the fields of photonics and optics, automotive, medical and biotechnology, consumer electronics and renewable energy require more and more advanced and miniaturized components. To meet these demands, production machines and processes have to be improved with respect to not only the high aims for precision, but also issues of standardization, automation and quality management. In this context, process monitoring becomes a key

technology to achieve a better understanding of ultra-precision machining and the possibilities to optimize production processes and process parameters as well as to enable process continuity, quality management and documentation.
In the manufacturing of precision components many influences affect the quality of the workpiece contour and surface. Tool wear or micro damages to the diamond tool, the cutting parameters, the dynamic machine behavior, material variations as well as environmental influences can lead to lower quality of the machined workpiece or even to rejected parts. Process monitoring, being well established in standard machine tools, is an effective method to detect, analyze and overcome malfunctions resulting from the aforementioned influences. To transfer the possibilities of process monitoring to ultra-precision processes, the choice and integration of sensor probes, the evaluation and visualization of metrology data and the communication with the machine control have to be adapted with respect to the required accuracy and dynamics.

At Fraunhofer IPT a precision process monitoring system has been developed combining data acquisition, analysis, storage and visualization into one integrated system. Hardware and software of the system have been developed using industrial standard components to enable the flexible adaption to different sensors, machine controls and processes.

This paper presents all aspects necessary for a flexible and fully integrated precision process monitoring system for ultra-precision diamond machining processes. Beginning with the choice of a suitable sensor probe and the in-process integration of metrology, over strategies for data acquisition, filtering and analysis, to the visualization of process data ranging from 2D to 5D plots, all topics will be addresses both from hardware and software point of view. The demonstrated system provides the machine operator with online and in-situ process information allowing for process optimization, quality management and the definition and monitoring of evaluation criteria for the workpiece quality. To achieve this, the in-process sensor data is mapped onto a virtual tool path generated using the linear scale positions of the machine tool within the process monitoring system. With this method the machine operator gets the opportunity of visually inspecting the workpiece quality online while the part is being machined. Monitoring the sensor data with regard to time and location of its acquisition enables variable evaluation possibilities far beyond the standard time plot or spectrum analysis methods. The developed system is flexibly adaptable to various processes such as turning, fast tool turning, milling or fly cutting and it allows for the use of multiple sensors such as acoustic emission, acceleration or force.

2 Process Monitoring using Acoustic Emission Sensors

To detect process effects such as tool wear in an ultra-precision diamond machining process, which is characterized by low process forces and high demands for surface quality, very sensitive sensor probes have to be used. Force or acceleration sensors, generally ideally suited for detecting chattering or vibrations, are not sensitive enough to allow for a detailed analysis of precision machining processes. Acoustic emission (AE) sensor probes, integrated for instance into the tool holder, are very sensitive and provide high resolution and high frequency metrology data [1]. Figure 1 shows a process monitoring example of a cylindrical work piece and the according sensor plot captured by an acoustic emission sensor.

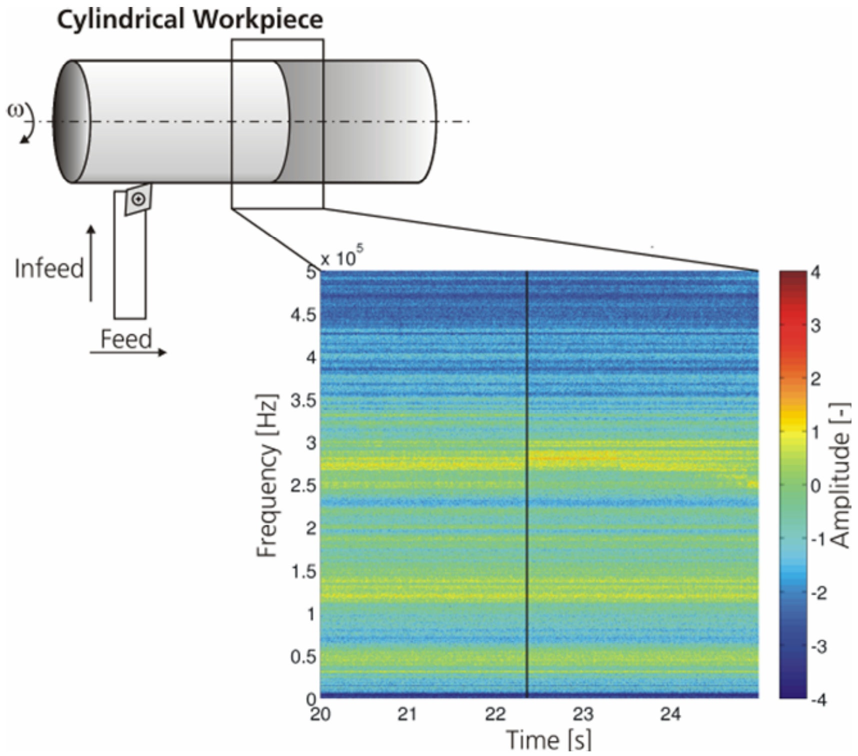

Figure 1: Process monitoring of a cylindrical workpiece using acoustic emission

Plotting the frequency and amplitude of the AE sensor signal versus the manufacturing time, periodic patterns can be visualized, which change with the process influences. Tool wear, initiating a signal modification due to vibrations, can be detected by inspecting the plots and evaluating a threshold for the signal amplitude. Figure 2 shows acoustic emission plots of 100 finishing cuts with one diamond tool machining a precision bearing roll. Effects of tool wear can easily be detected by analyzing the changing sensor signal amplitude. During the first

30 runs the amplitude of the signal is very low; between runs 30 and 90 the amplitude steadily increases; after run 91 the tool is worn out and a strong change in the acoustic emission signal can be seen.

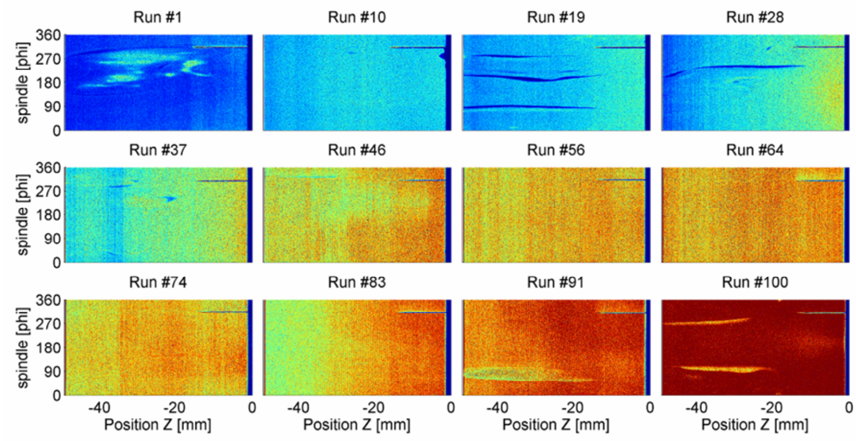

Figure 2: Effects of tool wear detected by acoustic emission sensor

3 State-of-the-art Precision Process Monitoring

Manually the aforementioned effects can be detected and analyzed. Developing an automated algorithm that evaluates the AE signal data against a pre-defined threshold and enables a detection of tool wear in-situ, two major problems arise. First, a pattern recognition algorithm has to be parameterized and configured for each process, for each part and for each tool. Second, as the acoustic emission sensor is very sensitive, small process adaptions affecting the signal analysis have to be recognized and extracted from the evaluation algorithms. For instance, the position of a nozzles for cooling lubricant, process parameters such as feedrate and infeed or vibrations of the tool holder have an impact on the AE sensor signal. Thus, to enable automated data analysis all of these effects have to be taken into consideration and have to be eliminated for the actual evaluation algorithms.

Multiple data processing strategies have been analyzed by Fraunhofer IPT as well as other research institutes during the last years including spectral analysis, image processing strategies and statistical evaluations. Figure 3 and Figure 4 show three plots of an AE signal and the processed data (for run 2 and run 68 of the aforementioned bearing roll finishing cut experiment). The upper plots display the sensor signal of the acoustic emission probe. The amplitude is plotted versus time logarithmically and the color code shows the signal amplitude. The middle plots show the signal after analysis with Law’s texture energy measures [2] and the lower plots show the signal after analysis with Law’s algorithm using thresholds.

For data processing the sensor signal is first being transformed into a matrix description e.g. by short-time Fourier transform (STFT). Afterwards the matrix can be treated as an image containing discrete data information and can be analyzed using image processing strategies such as Law's analysis or Haralik's textural image classification [3]. In a final step statistical analysis can be performed to find characteristic patterns for the individual process.

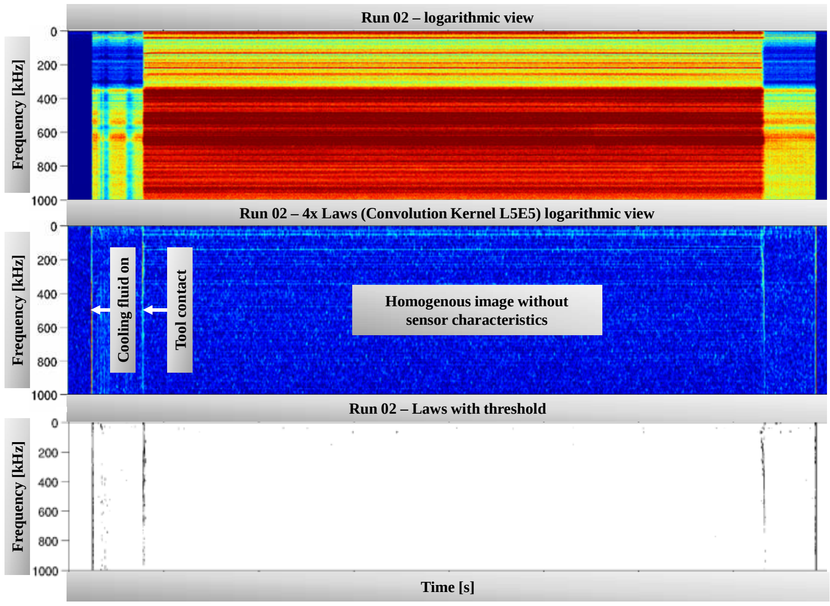

Figure 3: Sensor plot Run 2 – original and processed data

In Figure 3 two effects become visible. First, process impacts such as starting the cooling liquid flow or the first tool contact with the work piece are clearly visible both in the sensor data plot and in the processed data plots. Designing an automated evaluation algorithm, these effects have to be eliminated as only impacts resulting from tool wear should be taken into consideration. Second, the processed data plot after Law's analysis (without and with threshold) show a homogeneous pattern without any sensor characteristics. Hence, no characteristic feature for automated analysis can be defined for run 2.

The plots for run 68 (Figure 4) show ripples at certain frequencies as well as peaks at certain points in time. These effects of the slightly worn out diamond tool are visible in the logarithmical sensor signal plot as well as in the processed data plot. Using Law's algorithm with threshold, characteristic peaks at certain points of time can be generated, which can e.g. be counted over a defined period of time and can be used as a criterion for automated evaluation. Nevertheless, other process effects such as the first tool contact entering the work piece generate peaks as well, so that a clear separation of impacts resulting from tool wear or from other process effects is not possible.

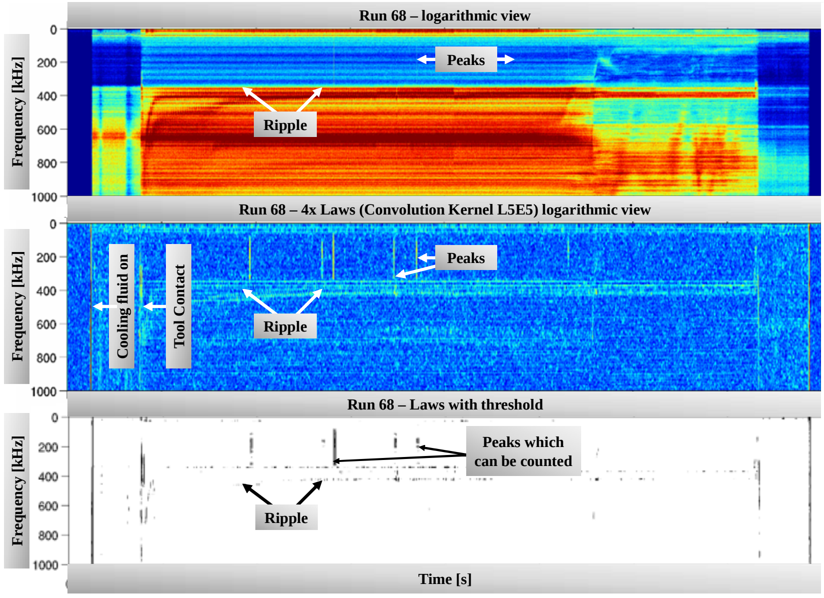

Figure 4: Sensor plot Run 68 – original and processed data

4 5D Precision Process Monitoring Approach

To enhance the evaluation opportunities of process monitoring data in ultra-precision processes, further information – the tool path, measured with the linear scales of the machine tool axes – can be added to the process monitoring system. With this approach a sensor signal analysis not only time-based, but locally referred to the geometry of the work piece is possible. Using the 3D tool path, measured during machining, and superposing the AE sensor signal color-coded, which means plotting the sensor along a virtual tool path on the work piece, a 4D metrology plot results. Performing the data acquisition, data processing and data visualization in real-time while the part is being machined, a 5D process monitoring tool has been developed at Fraunhofer IPT.

Figure 5 shows the integration of the IPT 5D process monitoring system into an ultra-precision lathe. An AE sensor probe is molded into the tool holder to detect acoustic emission of the process close to the diamond tool. The feedback signals of the machine axes as well as of the spindle are captured directly from the encoders. For this purpose galvanically isolated signal splitters for 1 Vpp sin/cos encoders have been developed to access the original feedback signal without affecting it by the splitting process. The process monitoring hardware acquires the position signals and the sensor signals synchronously. In addition to AE sensors, other sensor probes such as force, acceleration or vibration can be attached to the system and can be evaluated synchronously to the other data as well. As the splitter boxes capture the original feedback data and as various sensor probes can be applied, the process monitoring system is independent of the machine tool, of the CNC control and of the processes to be analyzed. It can be easily adapted to all ultra-precision processes and can be integrated into any control system.

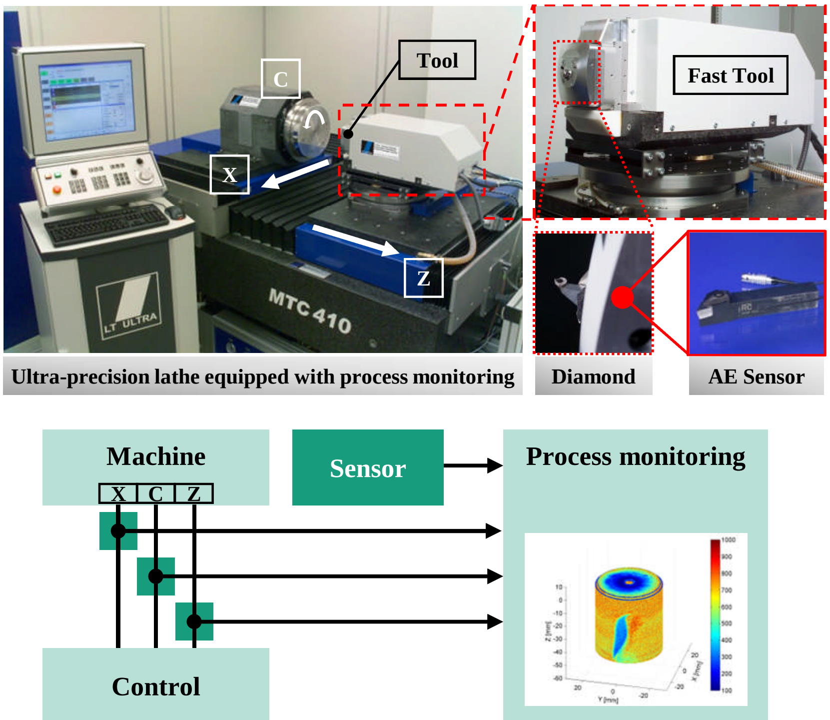

Figure 5: 5D process monitoring approach – block diagram set-up

The system has been designed as a black box consisting of industrial standard components (IPC, metrology boards, connectors) and acquires all data signal synchronously at high sampling rates. After the acquisition various pre-processing features are implemented. The individual signals can be filtered using common digital filters. They further can be scaled and converted so that the electrical signals match the mechanical and physical conditions. Before the original analysis and visualization routines are applied, the initial sensor data can be saved into a HDF5 container file including metadata to describe the process monitoring environment [4].

Within the software layer of the process monitoring system three processing steps are implemented. First, the acquired and pre-processed data can be further analyzed. Common methods such as the aforementioned Fourier transform, filtering, image processing, pattern recognition or statistical evaluation can be used to analyze the sensor data in detail. After the signal analysis a kinematics transformation is applied to generate a virtual tool path according to the position signals. Finally, the sensor signal is color-coded and mapped onto the virtual tool path for visualization. Figure 6 summarizes the hardware and software features and the process monitoring process chain.

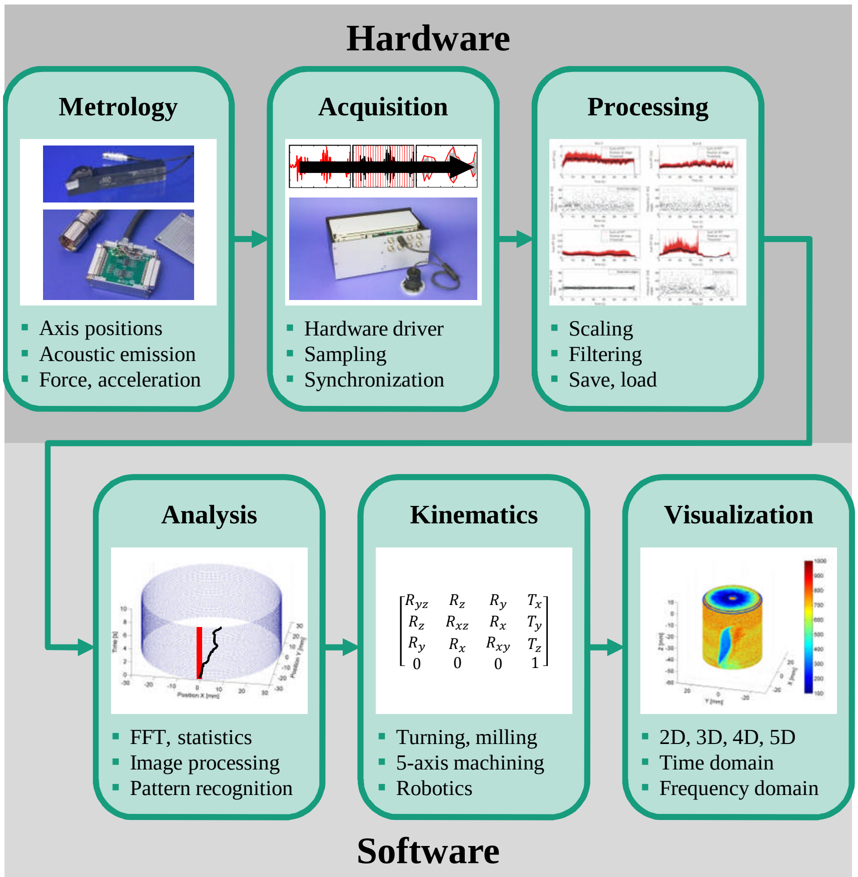

Figure 6: 5D process monitoring approach – hardware and software algorithms

5 Experimental Results

The novel 5D precision process monitoring system has been set-up and initial operation and optimizations have been executed. To validate the system various experimental tests have been performed. The above shown bearing roll has been provided with a reference groove to analyze the sensitivity and capability of local assignment of the system. Figure 7 shows a picture and a 4D plot of the bearing roll after the finishing cut. The impact at the edges (reference groove and tool entering and exiting the work piece) can be clearly seen. Figure 8 displays the according 2D and 3D color-coded plots.

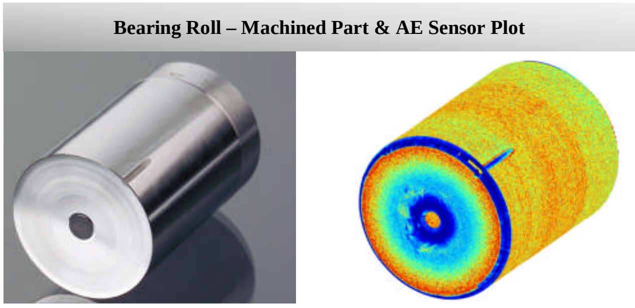

Figure 7: Experimental results of a bearing roll process analysis

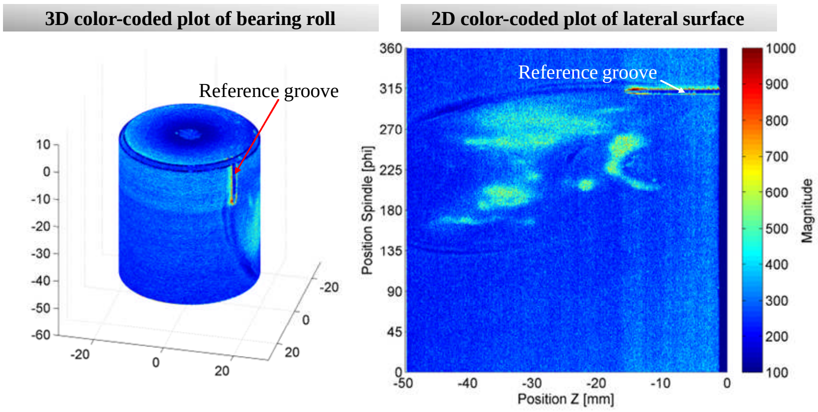

Figure 8: 2D and 3D color-coded plot of a bearing roll

Figure 9 shows a comparison between a rough machining step and the finishing cut of the bearing roll. The sensor signals differ in amplitude, but the reference groove as well as a spot with material inhomogeneity can be detected in both plots so that an evaluation by the operator is possible in both process steps.

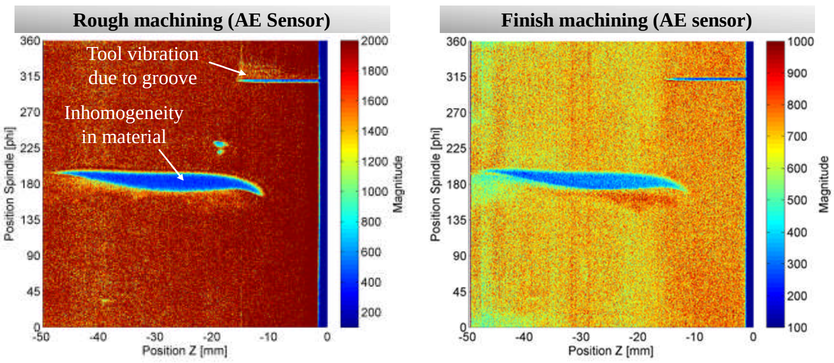

Figure 9: 2D process analysis of a roll bearing – rough vs. finish cut

To determine the sensitivity and accuracy of the system two scientific demonstrators have been machined and monitored. Figure 10 shows an optical mold insert consisting of various freeform surface geometries (top) and a microstructured facet mirror (bottom). In both plots tool impact effects at the edges can be visualized and the accuracy of the system shows very good results.

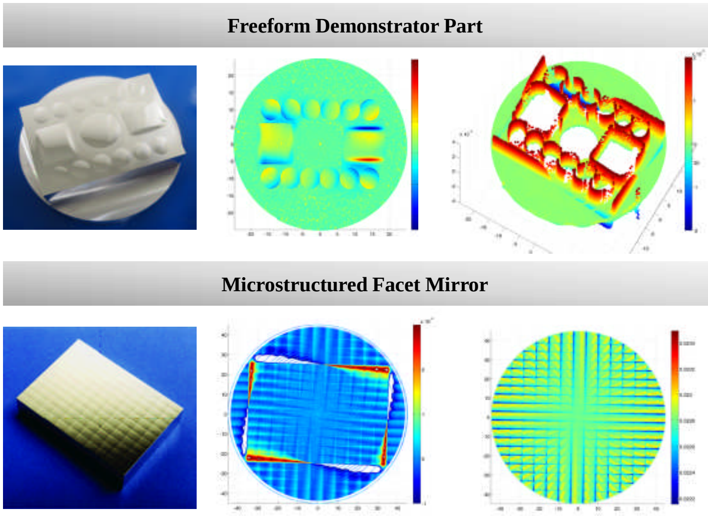

Figure 10: Experimental results of demonstrator parts

6 Summary and Outlook

At Fraunhofer IPT a 5D precision process monitoring system has been developed and tested that maps sensor data onto the tool path while a work piece is machined. With this method a local reference between part geometry and AE sensor signal is possible enabling evaluation strategies beyond state-of-the-art monitoring methods. Further research work will focus on porting and integrating the system to various machines and processes to prove its comparability.

References

[1] Köhler, J.O.A.; Schäfer, C.; et al.: Ein körperschallbasiertes Überwachungssystem für die Ultrapräzisionsfertigung. 34th annual conference for acustics, Dresden, 2008, pp. 823-824 (German)

[2] Laws, K.: Textured Image Segmentation. Ph.D. Dissertation, University of Southern California, January 1980

[3] Haralik, R.M.; Kelly, G.L.: Pattern Recognition with Measurement Space and Spatial Clustering for Multiple Images. Proceedings of the IEEE, Vol. 57, No. 4, April, 1969, pp. 654-665

[4] The HDF Group: http://www.hdfgroup.org/HDF5/doc/