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# Sensory workpieces for process monitoring – an approach

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**Abstract**

Several research projects deal with the development of sensory machine components for process monitoring. Especially those components, which are closely located to the process, show acceptable sensitivities to process loads and are therefore convenient for sensor integration. Considering that workpieces represent the focus of each manufacturing process and the origin of acting force and heat fluxes, they offer a „higher quality“ information source for mechanical and especially thermal process loads. The development of sensory workpieces allows novel process monitoring strategies. It leads, however, to totally different challenges concerning sensor placement, energy and data transmission. So far sensory workpieces have been subject to little research.
This paper focuses on the vision and the actual developments of sensory workpieces for milling operations. First, the technical challenges are identified and concepts to meet the function requirements are introduced. Then, a simulation-based approach for the placement of strain sensors in workpieces to detect the mechanical load while machining is discussed in details. Finally, the design of signal devices and the data communication by a sensor network for process monitoring tasks are presented.



*Keywords:* Workpiece distortion, sensor integration, process monitoring, machine tools

## 1. Introduction

In process monitoring tasks, information about mechanical and thermal loads on workpieces while machining is generally required. Such information allows the early detection of process failures and quality degrading effects such as chattering, tool deflection and workpiece distortion.

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In several research, force signals or correlating signals are widely used to describe the state of the process [1, 2]. With respect to process monitoring in milling, such signals can be generated, on the one side, from the machine control using current signals of spindles [3, 4, 5, 6] or feed drives [4, 6, 7]. On the other side, they can be provided by external sensors, which are integrated into machine components within the force flux in order to achieve acceptable sensitivities to load and higher signal qualities. For instance, different sensors are incorporated into machine components like tool holders [8, 9], spindle units [10, 11, 12], clamping systems [12, 13, 14, 15, 16, 17] and axis slides [18, 19].

In contrast to process forces, the thermal load on workpieces is more difficult to be monitored in real-time by sensory machine components. That is generally because of the very low sensitivity of the components to thermal process changes. To achieve better sensitivities, temperature sensors have to be integrated very close to the workpiece. Tools are therefore very suitable. Although, several research show promising approaches for sensor integration in tools for turning operation [20, 21, 22], the application into rotating tools for milling processes is still more difficult and challenging.

Considering that workpieces represent the focus of each manufacturing process and the origin of acting force and heats, they may offer a „higher quality“ information source for mechanical and especially thermal process loads. So far, little work have been devoted to sensor integration into workpieces. Sensors are used temporarily in workpieces only for process developments and experimental investigations [23, 24, 25]. The development of sensory workpieces allows novel process monitoring strategies. It leads, however, to totally different challenges concerning sensor integration, energy supply and data transmission.

The subproject N1 of the CRC 653 pursues the vision of “feeling” workpieces by enabling their sensing and communication capabilities [26]. Such workpieces detect intrinsically loads during machining and communicate detected failures to machine control.

## 2. Technical challenges and requirements

The most important challenge by the development of sensory workpieces is to find optimal positions in the workpieces, where sensors can be integrated. These positions should provide sufficient sensitivities in order to detect correctly the mechanical or thermal loads. Generally, two factors may influence such sensor positions. On the one hand, the sensor positions depend on the changing of the workpiece geometry during processing. In milling, while the structure differs slightly from the initial geometry between process steps by semi-finished parts like forging or casting parts, it is dramatically changing in case of solid blocks. On the other hand, considering that each process step requires often different clamping configurations in the machine tool, the process steps have also influence on the sensor positions. Changes in workpiece structure and clamping situation mean generally changes in workpiece stiffness and thermal boundary conditions, and are therefore the reason for variable sensitivities.

Furthermore, the cost-effectiveness, the practicability and the robustness of the sensing system represent challenging aspects to be taken in account by designing sensory workpieces. With regard to cost-effectiveness, the sensor integration in workpieces should demonstrate a functional benefit for process monitoring and optimization. Here, few sensors as possible should still allow the accurate detection of the caused forces and thermal loads. Concerning the practicability, especially the power supply of the signal devices and the data communication should be developed in such a way, that they do not prevent the make-ready or the cutting within the machine tool. Considering that sensors and signal devices are exposed to several external influences during cutting like coolants, metal chips and electromagnetic disturbances, finally the sensing system requires a robust protecting design.

## 3. Concept for sensory workpieces

The sensing system for workpieces can be made from a single sensor or a network of sensors in combination with miniature electronic devices that allow the signal processing and the communication with an industrial PC. The sensors and the electronic devices can be integrated permanently and fully embedded in the workpiece or temporarily mounted to it. For this research purpose, a low-cost concept is created (Fig. 1). Thereby, strain gauges for mechanical and thermal load detection are used.

In a suitable position on the workpiece, a strain gauge and a socket are applied and linked together. An aluminum lid with integrated electronic device can be plugged into the socket and allows hereby the temporarily connection with tension relief between strain gage and the device. In addition, the lid allows the sealing and the protection of the whole sensor system against humidity, chips and electromagnetic disturbances while cutting. The power supply is realized by rechargeable batteries, which can keep the device under voltage during processing. The data communication is build wireless by integrated transmission chip on the device side and a receiver on the industrial PC side.

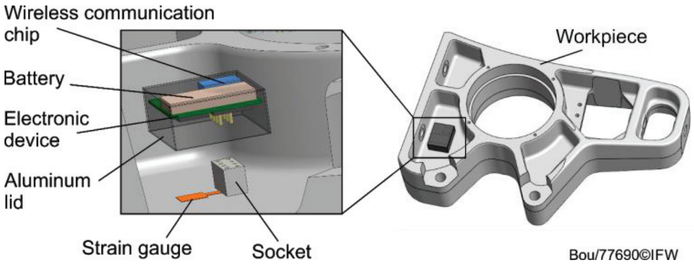


Fig. 1: Concept for sensor integration in casting workpiece.

## 4. Sensor placement for force detection

The integration of strain gauges in mechanical structures represents generally a promising and a cost-effective way to measure occurring forces. In order to estimate the occurring strain and to determine optimal sensor positions in workpieces, static structural finite element analyses on ANSYS® Workbench™ are conducted. First tests with the developed simulation-based approach are performed using an easy understandable example of an aluminum workpiece with L-shape. The workpiece is assumed to be clamped on selected clamping surfaces on one side, and to be milled on the machining surface on the other side. Some of the remaining free surfaces, where sensors can be safely integrated, are selected as sensing surfaces for sensor application (Fig. 2).

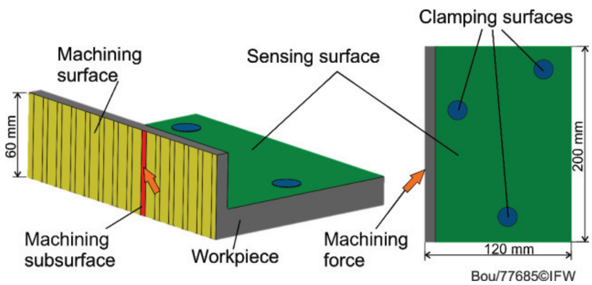


Fig. 2: Setup for simulation.

After meshing the workpiece, the clamping surfaces are modeled as fixed supports by fixing correspondent mesh nodes. During simulation, the forces and the correspondent point of load are shifted equidistantly along a predefined path in the machining surface. In each simulation step, the sequential selection of a subsurface from the machining surface, the application of forces with predefined direction in that subsurface and finally the export of the strain values of the sensing surfaces after computing are performed automatically by an APDL (Ansys Parametric Design Language) script. The APDL shows big benefits for case studies especially by simulation of various workpieces with more complex shapes, many machining surfaces and by modelling various load and engagement conditions.

The optimal positions and even the load sensitivity of the sensors depends generally on the resulting force flux, which is mainly affected by the point of load of the applied forces and the clamping situation of the structure. The movement of the point of load by the clamped workpiece along the tool path during processing causes a variation on the force flux and therefore a variation in the strain state. This is depicted exemplarily in (Fig. 3). The fact of changing force flux in workpiece structures has to be considered by designing the sensor system.

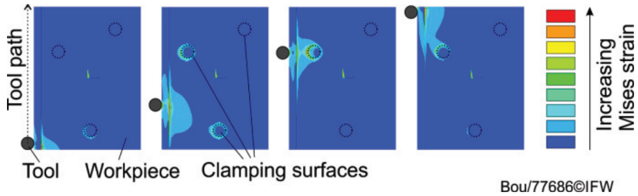


Fig. 3: Simulated strain state in workpiece by a moving tool.

Based on the exported strain values of the sensing surfaces, each mesh node of these surfaces are statistically evaluated by building the mean value and the deviation of its strain for the simulated load steps (Fig. ). The strain mean value provides information about the sensitivity to load of the mesh node, however, its deviation is a measure of the sensitivity variation on that node while the tool is moving along its path. Accumulations of adjoining mesh nodes showing similar sensitivity behavior represent optimal positions for sensor integration. It is distinguished between two kinds of sensor positions (Fig. 5): the first kind comprises path-dependent positions. Such positions show high mean values of strain and strain deviations. In these positions, strain sensors would generate intense signals showing strong deviation along the tool path. In this case a sensor calibration with respect to tool movement is indispensable for accurate measuring of the process forces by the investigated workpiece. The second kind of positions represent path-independent sensor positions. They show generally lower mean values and lower deviations of strain in comparison to path-dependent position. However, in such positions, sensor signals with sufficient amplitudes but nearly independent of the actual tool position would be provided.

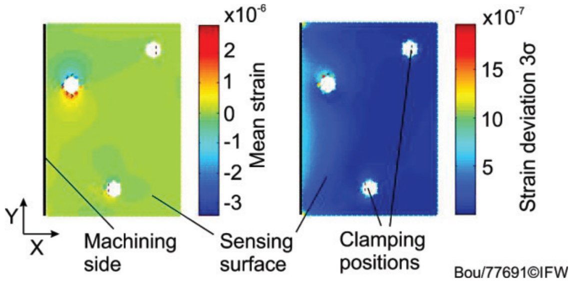


Fig. 4: Statistical evaluation of the resulted strain in Y direction for an applied force of 100 N.

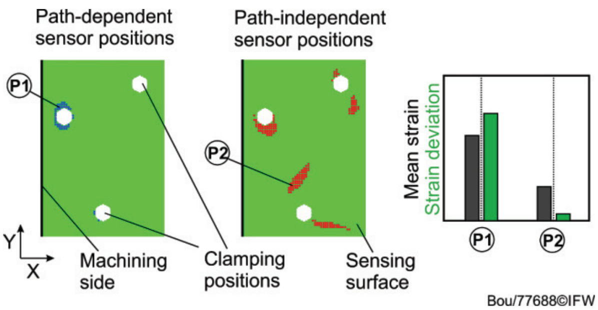


Fig. 5: Identified sensor positions from the resulting strain in Y direction.

Because the force flux is generally concentrated near to machining surface and around the clamping positions, the sensor positions appear mostly near to that clamping positions and machining surface or in-between. First simulations of the workpiece show that the identified sensor positions depend on the direction of the applied force (Fig. 6), the considered direction of resulted strain (Fig. 7) and the clamping situation of the workpiece (Fig. 8). The size of identified sensor position depends on the applied restriction by node filtering like the minimum of required strain and the maximal permissible strain deviation. Positions on the outer side of the workpiece represent noisy nodes and cannot be used as sensor positions.

This approach is also transferable to workpieces with more complex shapes and many processing steps. Here, the statistical evaluation of the strain should be considered for all tool positions over all processing steps. It is expected, that the number of path-dependent sensor positions (high strain, high deviation) increases with the number of the considered processing steps, however the number of path-independent sensor positions (low strain, low deviation) decreases.

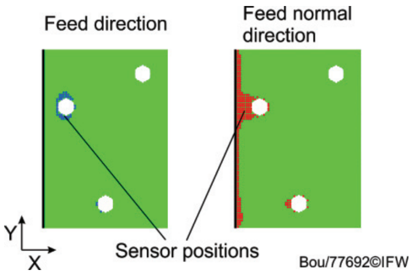


Fig. 6: Identified sensor positions (path-dependent) for different force directions.

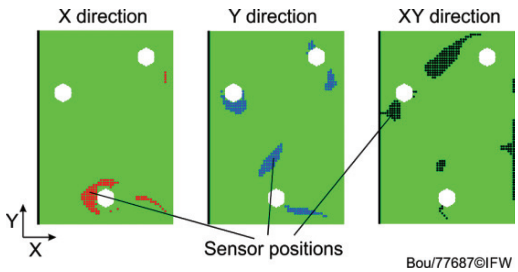


Fig. 7: Identified sensor positions (path-independent) for different strain directions.

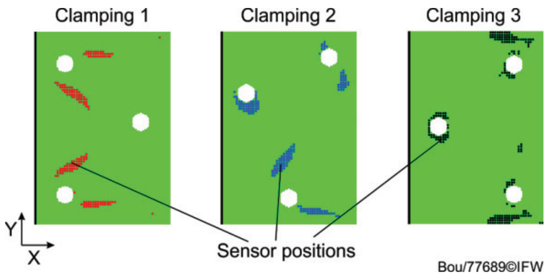


Fig. 8: Identified sensor positions (path-independent) for different clamping situations.

## 5. Electronic signal device and data communication

The used strain gages are connected up as a Wheatstone bridge to an electronic device for signal processing. Within the electronic device, strain signal is filtered, amplified, sampled and finally communicated via CAN-BUS to an industrial PC. In addition, the signal device is able to balance automatically the Wheatstone bridge before beginning with the signal sampling. The integrated balancing unit is required for active compensation of big signal offsets, which result especially after clamping the workpiece because of its caused distortion, and could not be reset by the software. In the framework of this work, a first version of miniature low-cost electronic devices is developed allowing amplification factors up to 13000 sampling rates up to 2000 Hz (Fig. 9). For first test, the power supply and the bus connection are temporarily solved by electrical wires. In further device generations, rechargeable batteries and wireless communication chips will be integrated into the device to achieve more flexibility by using sensory workpieces within machine tools.

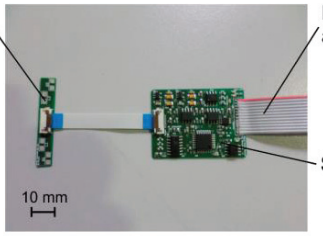


Fig. 9: First version of signal device for strain gauges.

## 6. Conclusion and outlook

Workpieces represent the source of mechanical and thermal loads and are therefore suitable for sensor integration for process and quality monitoring tasks. The presented paper shows latest results from the development of sensory workpieces for milling operations. The main function of sensory workpieces is to detect the acting forces and the resulting temperatures during milling. The challenges are, on the one side, the finding of suitable and sensitive sensor positions for load detection on the workpiece, and on the other side, the cost-effectiveness, the practicability and the robustness of the sensor integration. Therefore, a concept for sensor integration based on strain gauges is introduced. Furthermore, a simulation-based approach for sensor placement to detect moving milling forces is presented and simulations on a first workpiece are discussed. They show that sensor position depends generally on the considered directions of applied force, resulted strain and on the clamping situation of the workpiece. For strain measuring a first version of signal device is developed and presented.

Future works will focus on the experimental verification of the presented approach on workpieces with L-shape and under the same clamping and boundary conditions as in the conducted finite element analyses. Furthermore, the investigated approach will be extended for workpieces with more complex shape (circle shape, multi-walled parts, etc…) in combination with several operation steps. The approach will be also extended for temperature measuring using strain gages or Pt100 sensors.

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## References


[1] Teti R, Jemielniak K, O'Donnell G, Dornfeld D. Advanced monitoring of machining operations. CIRP Annals Manufacturing Technology. Volume 59 (2); 2010. p. 717-739.
[2] Lauro C H, Brandão L C, Baldo D, Reis R A, Davim J P. Monitoring and processing signal applied in machining processes – A review. Measurement. Volume 58; 2014. p. 73-86.
[3] Aggarwal S, Nešic´ N, Xirouchakis P. Cutting torque and tangential cutting force coefficient identification from spindle motor current. Int. J. Adv. Manuf. Technol. Volume 65 (1–4); 2012. p. 81-95.
[4] Denkena B, Dahlmann D, Damm J. Self-tuning of Teachless Process Monitoring Systems with Multi-criteria Monitoring Strategy in Series Production. Procedia Technology. Volume 15; 2014. p. 613-620.
[5] Kim G D, Know W T, Chu C N. Indirect cutting force measurement and cutting force regulation using spindle motor current. Int. J. manuf. Sci. technol. 1; 1999.
[6] Yohannes B. Industrielle Prozessüberwachung für die Kleinserienfertigung. Dr.-Ing, Diss. Leibniz Universität Hannover; 2013.
[7] Li X, Ouyang G, Liang Z. Complexity measure of motor current signals for tool flute breakage detection in end milling. Int. J. of Machine Tools and Manufacture. Volume 48 (3-4); 2008. p. 371-379.
[8] Denkena B, Brinkhaus J W, Lange D. Possibilities of sensor transponders in machine tools. 10th international scientific conference on production engineering, computer integrated manufacturing and high speed machining; 2005.
[9] Smith D A, Smith S, Tlusty J. High Performance Milling Torque Sensor. Journal of Manufacturing Science and Engineering. Volume 120; 1998. p. 504-514.
[10] O'Donnell G, Kelly K, Byrne G. Use of a Sensor Integrated Motor Spindle for Monitoring of a Flexible Machining Centre. 2nd CIRP Int. Sem. on ICME, Capri, Italy; 2000. p. 383-388.
[11] Jun M, Ozdoganlar B, DeVor R, Kapoor S, Kirchheim K, Schaffner G. Evaluation of a Spindle-based Force Sensor for Monitoring and Fault Diagnosis of Machining Operations. International Journal of Machine Tools and Manufacture. Volume 42; 2002. p. 741-751.
[12] Möhring H C, Litwinski K M, Gümmer O. Process monitoring with sensory machine tool components. The Int. Acad. Prod. Eng. Anna–Manuf. Technol. Volume 59; 2010. p. 383-386.
[13] Litwinski K M. Sensorisches Spannsystem zur Überwachung von Zerspanprozessen in der Einzelteilfertigung. Dr.-Ing Diss. Leibniz Universität Hannover; 2011.
[14] Denkena B, Kiesner J. Strain gauge based sensing hydraulic fixtures. Mechatronics, DOI: 10.1016/j.mechatronics.2015.05.008; 2015.
[15] Hesselbach J, Hoffmeister H, Schuller B, Loeis K. Development of an active clamping system for noise and vibration reduction. The Int. Acad. for Prod. Eng. Anna. Volume 59; 2010. p. 395-398.
[16] Leopold J, Clauß D, Klärner M, Poppitz A, Baldoli M, Merlo A, Gimenez M, Larranaga J. Investigations to new fixturing principles for aerospace structures. In: APT 07, international conference on applied production technology; 2007. p. 173-189.
[17] Rashid A, Nicolescu C M. Active vibration control in palletized workholding system for milling. Int. J. Mach. Tools. Manuf. Volume 46 (12/13); 2006. p. 1626-1636.
[18] Denkena B, Litwinski K M, Brouwer D, Boujnah H. Design and analysis of a prototypical sensory Z-slide for machine tools. Production Engineering Research and Development (WGP). Volume 7 (1); 2013. p. 9-14.
[19] Denkena B, Litwinski K M, Boujnah H. Detection of tool deflection in milling by a sensory axis slide for machine tools. Mechatronics DOI: 10.1016/j.mechatronics.2015.09.008; 2015.
[20] Stoney R, Donohoe B, Geraghty D, O'Donnell G E. The development of surface acoustic wave sensors (SAWs) for process monitoring. 5th CIRP Conference on High Performance Cutting; 2012.
[21] Aneiro F M, Coelho R T, Brandão L C. Turning hardened steel using coated carbide at high cutting speeds. J. Brazilian Soc. Mech. Sci. Eng.; 2008. p. 104-109.
[22] O'Sullivan D, Cotterell M. Temperature measurement in single point turning. J. Mater. Process. Technol. Volume 118 (1-3); 2001. p. 301-308.
[23] Davoodi B, Hosseinzadeh H. A new method for heat measurement during high speed machining. Measurement. Volume 45 (8); 2012. p. 2135-2140.
[24] Sivasakthivel P S, Sudhakaran R. Optimization of machining parameters on temperature rise in end milling of Al 6063 using response surface methodology and genetic algorithm. Int. J. Adv. Manuf. Technol.. Volume 67 (9-12); 2012. p. 2313-2323.
[25] Lauro C H, Brandão L C, Ribeiro Filho S L M. Monitoring the temperature of the milling process using infrared camera. Sci. Res. Essays. Volume 8 (23), 2013. p. 1112-1120.
[26] Denkena B, Mörke T, Krüger M, Schmidt J, Boujnah H, Meyer J, Gottwald P, Spitschan B, Winkens M. Development and first applications of gentelligent components over their lifecycle. CIRP Journal of Manufacturing Science and Technology. Volume 7 (2); 2014. p. 139-150.