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# Performance of a new piezoceramic thick film sensor for measurement and control of cutting forces during milling

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ABSTRACT

Process monitoring and controlling with detailed real-time information such as the cutting force is required for improving the performance of milling processes. This paper presents a novel system for measuring the cutting force in the direct vicinity of the indexable insert. The outlined concept makes use of piezoelectric thick film sensors mounted directly below the insert. The unique design and features of the new sensor enable accurate and continuous force measurements as well as the indication of wear. The results of the experimental investigations are presented and compared to results of a conventional dynamometer.

## 1. Introduction

Milling and turning are still among the most important manufacturing technologies today. Faster development and shorter product lifecycles and the increase in customer-specific solutions pose significant challenges for the production systems of the future [1]. The development of autonomous and unattended systems, which enable optimal processing at any time, is one possibility to meet these demands [2,3]. A key criterion for the development of such process control systems is the appropriate assessment of the process conditions. For this purpose, in-process measurement data is required. Thereby, cutting forces have proven to be very significant parameters [4]. Although current developments in sensor technology provide a wide range of sensors for capturing process data, the implementation of accurate and reliable sensors in real production environments remains a major challenge [5].

Multicomponent dynamometers based on piezoceramic sensors represent the most accurate commercially available solution for measuring cutting forces. However, the use of such dynamometers is restricted regarding size and cost, clamping possibilities and the dynamic influence on the measurement results [6]. Alternative approaches include the evaluation of drive torques, the integration of force sensors into the machine structure or the measurement of spindle displacement using capacitive sensors [7,8]. However, these concepts have the disadvantage of deriving the cutting force over a longer measuring chain instead of acquiring it directly in the cutting zone. As a result, the measurement signal has a lower sensitivity and is subject to more severe falsification.

A significant improvement of the signal quality can be achieved by integrating sensors into the cutting tool. For this purpose, rotary cutting dynamometers can be used, which are mounted between tool and spindle [9].

Conventional 3-component force transducers have been integrated behind the insert to move the measuring point closer to the cutting zone. [10].

The use of commercial sensors, however, results in an unfavorably large packaging space. Piezoceramic materials offer great potential for miniaturization and the integration of sensors and actuators for vibration control, health monitoring, control and measurement of dynamic forces [11]. The stiffness, sensitivity and fatigue behavior of piezoceramic components predestine this technology for use in cutting operations and direct integration into cutting tools.

This paper presents a novel approach to measure the cutting force with piezoceramic layers applied on a carbide sensor plate which is mounted next to the insert. The first prototype of this new measuring system enables high-precision measurement of the cutting force in one direction.

## 2. Design of a new piezoceramic sensor for cutting force measurement

The sensor concept is based on a carbide sensor plate mounted on the milling tool behind the insert (Fig. 1). The use of carbide minimizes the influence of the sensor on the system stiffness. The tangential cutting forces are transmitted from the insert via the sensor plate to the milling tool.

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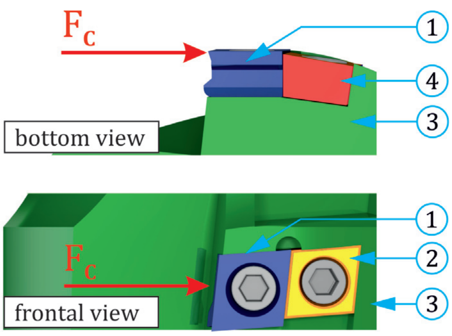

**Fig. 1.** Sensor system. Indexable insert (1), piezoceramic thick film on sensor plate (2), tangential milling tool (3), sensor plate (4).

### 2.1. Layer setup

The sensor plate serves as a substrate for a lead zirconium titanate (PZT $\text{Pb(Zr}_{1-x}\text{Ti}_{x})$) layer. A 4 μm $Al_2O_3$ top layer was applied by Chemical Vapor Deposition (CVD) to prevent the carbide plate from oxidizing during fabrication. Piezoceramic thick-film sensors were screen-printed for high accuracy. After the printing process, the thick-film layers were sintered.

The layer setup comprises a sequence of the bottom gold (Au) electrode, a piezoceramic thick film based on PZT and the top Au electrode. For the PZT thick film, IKTS-PZ5100 paste was used [12]. The Au electrodes and the PZT thick film were successively printed and sintered at 850 °C for 10 min. A polymer passivation layer with a thickness of 19 μm was applied to protect the sensor layer structure from environmental influences such as cooling lubricants and chips. The layer setup is shown in Fig. 2.

Fig. 3 shows the sensor unit after the completion of each layer. The PZT thick film was poled with a 20 kV/cm DC electric field for 2 min at room temperature. A value of $d_{33} = 69$ pC/N was determined for the piezoceramic coefficient. This corresponds approximately to one-third of the average value measured on standard substrate materials such as $Al_2O_3$ or LTCC (low temperature cofired ceramics) [13].

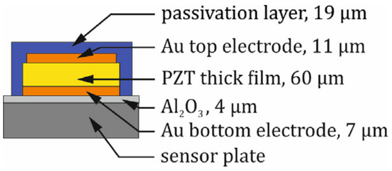

**Fig. 2.** Used layer setup on the sensor plate.

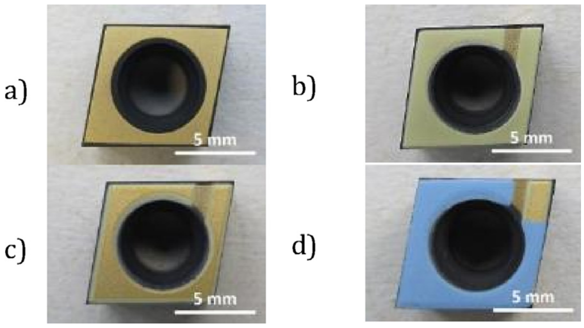

**Fig. 3.** Fabrication steps of the sensor element. (a) Au bottom electrode; (b) PZT thick film; (c) Au top electrode; (d) passivation layer.

### 2.2. Sensor layer position

The PZT layer should be placed on the contact surface between the sensor plate and the milling tool to maximize the sensitivity of the sensor. Here it is necessary that stress of approximately 50 MPa is not exceeded [14]. Otherwise, stress-induced depolarization will occur resulting in the loss of piezoelectric properties.

The maximum cutting forces in all directions were determined using cutting experiments. The results were then used to determine the mechanical stresses on the tool by using FEA simulations. Fig. 4 shows the stress distribution at the contact surface between sensor plate and tool. In the grey areas, which are covering approximately 30% of the surface, the depolarization stress was exceeded; in the red areas no measureable force was applied.

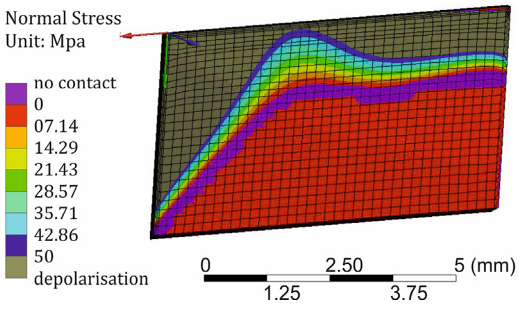

**Fig. 4.** Stress distribution at the contact surface between sensor plate and tool.

Therefore, it is not possible to apply the sensor layer perpendicular to the direction of the force. The parallel surface can be used to avoid depolarization. Since no direct forces are applied to this surface, and the expected deformations of the carbide are very low, depolarization of the PZT layer can be excluded. However, the disadvantage of using the transversal piezo effect is a reduction of sensitivity. The reason for this disadvantage lies in the high stiffness of the carbide sensor plate, which results in low deformations of the PZT layer and consequently in low charge displacement.

## 3. Sensor system

A face milling process was chosen as a reference for the development of the tool-integrated sensor system. This sensor system (SensoTool) consists of the milling tool, the gateway, the antennas as well as the tool-integrated piezoceramic sensor (Fig. 5).

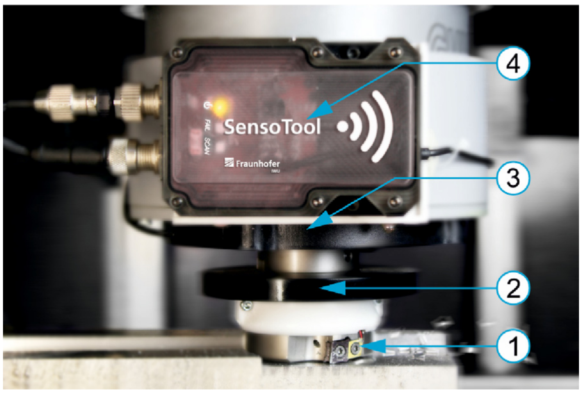

**Fig. 5.** SensoTool in application environment. Milling tool with integrated sensor (1), tool-mounted antenna (2), spindle-mounted antenna (3), gateway (4).

The gateway is the central element of the wireless data and power transmission. Based on RFID technology, it transmits energy from the spindle-mounted antenna to the tool-mounted antenna and serves as a data interface between tool and machine.

The main components of the tool-integrated sensor system comprise the piezoceramic sensor described in Section 2, and the tool integrated electronics. The charge signal generated by the piezoceramic thick film is converted into a charge-proportional voltage by a charge amplifier. The recorded signals are then pre-processed in analog form. Analog pre-processing is necessary because piezoceramic sensors cannot be connected to an analog–digital-converter [15]. The signal is filtered by a second order Bessel filter. The filter frequency results from the bitrate $f_t$ of the radio transmission, which is currently limited to 1.92 kB $s^{-1}$. The resolution $R$ of 12 bit and the overhead $O$ of 4 bit for control data lead to a maximum sampling rate $f_s$ of 960 samples per second. The sampling rate is calculated according to the following formula.

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