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Development of thin-film based sensors for temperature and tool wear monitoring during machining

Entwicklung von Dünnschichtsensoren zur Überwachung von Temperatur und Werkzeugverschleiß während der Zerspanung

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Abstract: The development of thin-film sensors for temperature and wear measurement in machining operations is presented in this work. A functional thin-film system, consisting of an Al_2O_3 insulation layer, a chromium sensor layer structured by photolithography and an Al_2O_3 wear-protection and insulation layer, is deposited by physical vapor deposition (PVD) processes onto the surface of cemented carbide cutting inserts. First specimen of the sensors are successfully fabricated and tested in laboratory experiments as well as in machining operations to demonstrate their functionality. These tool-integrated sensors can be used as an in-process monitoring device to determine the temperatures on the rake face at or close to the tool-chip contact area and to measure the progress of the flank-wear land width. The knowledge of these important process parameters opens up the possibility to develop new in-process control mechanisms in order to modify and improve the surface integrity of manufactured components. Thereby, their performance and lifetime can be enhanced.

Keywords: Thin-film sensor, machining, temperature, tool wear, in-process measurement.

Zusammenfassung: Die Entwicklung von Dünnschichtsensoren zur Temperatur- und Verschleißmessung in der Zerspanung wird in diesem Artikel präsentiert. Ein funktionales Dünnschichtsystem, bestehend aus einer Al_2O_3-Isolationsschicht, einer mittels Photolithographie strukturierten Chrom-Sensorschicht sowie einer Al_2O_3-Verschleiß- und Isolationsschutzschicht, wird per physikalischer Gasphasenabscheidung (engl. physical vapor deposition, PVD) auf der Oberfläche von Hartmetall-Wendeschneidplatten abgeschieden. Erste Proben konnten mit Sensoren gefertigt werden und in Labor- sowie Zerspanversuchen hinsichtlich ihrer Funktionalität getestet werden. Die werkzeugintegrierten Sensoren können zur In-process Messung der Temperaturen auf der Spanfläche im oder in der Nähe des Werkzeug-Span-Kontakts sowie zur Bestimmung der Verschleißmarkenbreite eingesetzt werden. Die Kenntnis dieser wichtigen Prozesskenngrößen bietet die Möglichkeit neuartige In-Process-Regelungsmechanismen zu entwickeln, welche eine gezielte Einstellung der Surface Integrity und damit eine Verbesserung der Leistungsfähigkeit und der Lebensdauer des Bauteils ermöglichen.

Schlagwörter: Dünnschichtsensor, Zerspanung, Temperatur, Werkzeugverschleiß, In-Prozess-Messung.

1 Introduction

The combined effect of severe plastic deformations, high temperature gradients and phase transformations occurring during the cutting process, not only changes the workpiece geometry but also modifies its surface properties. In order to control and enhance the mechanical properties and the surface quality of machined parts, several studies and works were carried out in recent years in the so-called surface integrity field [1]. To model and estimate the changes that the workpiece surface undergoes, it is necessary to obtain reliable information of the process. However, cutting tool temperature and wear measurements during machining still present a challenge to the manufacturing industries. On the one hand, tool-chip interface temperature is not easily measurable, because factors like coolant or the chip itself in the contact area between tool and workpiece, complicate direct measurements [2]. On the other hand, tool wear measurement is affected by the

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same factors, therefore indirect sensing-based tool condition monitoring has drawn the most attention along the last years in turning operations [3].

However, the problem of modeling tool wear influence on tool-chip interface temperature remains unsolved. Tool wear rounds up the cutting edge radius, which translates into an increase in process temperature due to a larger contact surface. In addition, in the case of coated tools, due to abrasive wear and the reduction of coating material, the thermal properties of the cutting tool change, which modifies the heat flux of the process. This results in greater heat transfer to the cutting tool affecting the wear mechanism and the surface integrity of the workpiece [4].

In this research work, tool integrated thin-film sensors for measuring temperature at the tool-chip contact area, crater and flank tool wear are presented. Its working principle, manufacturing and calibration procedures are explained in detail. Performance and reliability studies of prototype temperature, crater and flank wear sensors are presented. Wear sensors were tested in laboratory under controlled conditions. Temperature sensors were tested in real working conditions during dry turning of AISI 4140 quenched and tempered (Q&T) steel.

2 Thin-film sensor systems for monitoring of machining processes

The potential of functional thin-film systems has led to different approaches for temperature and wear measurements on the surface of cutting tools during the last two decades. In order to place thin-film thermocouples on the rake face of cutting inserts close to the cutting edge, two metals or alloys, for instance Ni and NiCr [5, 6] or NiCr and NiSi [7], were structured and embedded in electrical insulation layers or placed on non-conductive inserts. Both conductors overlap each other only in a tiny area, the hot junction, where the temperature is measured. Sugita et al. used micro-grooves on the rake face to form multiple cemented carbide (WC-Co) – chromium (Cr) thermocouples close to the cutting edge. The WC-Co is the cutting tool itself in this case and experiments were conducted with a monomer cast (MC) nylon workpiece [8]. In a similar approach that also used micro-grooves, thermocouples formed by chromel and alumel films were placed between insulating layers of SiN_x for application in machining of titanium alloys [9].

As an alternative, the thermoresistive properties of materials can be used for temperature measurement. Lüthje et al. developed a thin-film system to measure the temperature on the rake face with a conductive layer embedded in two Al_2O_3 insulation layers or placed on an alumina insert. Temperatures of up to 500 °C were measured in turning of aluminum, but wear resistance was not high enough for harder workpieces [10]. Based on these results, thin-film systems with integrated structures for wear detection were developed for measurements on the insert flank face [11]. TiN structures were embedded in two Al_2O_3 insulation layers. The progress of the flank-wear land width led to an increase of the sensor resistance as the conducting path was continuously destroyed. Flank wear sensors on cutting tools were also developed by Schmaljohann et al. [12]. They succeeded to make 30 µm wide chromium structures by photolithography which were placed between two insulation layers of Al_2O_3 or SiO_2. Multiple conducting paths were connected in parallel such that an increase of the total sensor resistance occurred when a path broke. Recently, research on thin-film sensor systems consisting of ferromagnetic coatings based on Fe-Co-Hf-N was done. These can be deposited on cemented carbide inserts in combination with TiAlN and electrical insulation coatings like SiO_2 and are able to monitor the tool wear by the corresponding thermal impact that changes the magnetic properties of the ferromagnetic sensor part [13].

It is worth noting that the workpiece used for testing the presented tool integrated thin-film sensors had a hardness of 36 HRC. This represents a considerable increase of severity of the machining operation in comparing with the thin-film systems state of the art, thanks to advancements in the wear resistance of the applied thin-film systems. Furthermore, sensor designs were improved compared to previous work allowing measurements with higher spatial resolution.

3 Measuring principle

Both the temperature as well as the wear sensors are based on the measurement of resistance changes of metal-based thin-film microstructures that are applied on the surface of the cutting inserts. Their principle is explained in the following.

3.1 Temperature characterization

Metals are positive temperature coefficient (PTC) materials, which means their resistance increases with rising temperature. The temperature dependence of pure metals can be described in a range from ambient temperatures to a few 100 °C by a linear approximation according to Equation (1):

$$\rho(\vartheta) = \rho_{20} \cdot [1 + \alpha_{20} \cdot (\vartheta - \vartheta_{20})], \tag{1}$$

where ρ_{20} corresponds to the specific resistance and α_{20} is the linear temperature coefficient at a reference temperature $\vartheta_{20} = 20\,^{\circ}\mathrm{C}$. By determining this dependence for each sensor beforehand it is possible to calculate the temperature that a sensor structure experiences during the turning process from its resistance. In order to measure the temperature only at the position of interest but not its vicinity, four-wire sensing is used to prevent lead and contact resistances from distorting the measurement. A current, small enough so its Joule heating is negligible, is applied to two leads and the resulting voltage drop via the sensor is tapped over two other leads. The resistance is obtained accordingly by the Ohmic law.

3.2 Wear characterization

Progress of the flank wear land width and crater wear is detected by the arrangement of a series of conducting paths which are worn off at the same time as the insert. The conducting paths are connected in a parallel circuit such that the overall resistance of the circuit is measured over only two contacts. As elaborated in more detail below, the resistance of each conducting path is adjusted in such a way that the change of the overall resistance caused by the interruption of a conducting path is always the same. If the position of the conducting paths is known, the flank wear land width or crater wear can be determined from the overall resistance change.

4 Thin-film sensor production

4.1 Coating materials

Both sensor types are realized with the same thin-film system, which is schematically depicted in Fig. 1. Since electrically conducting cemented carbide tools are used, the sensor layer has to be insulated against it by an insulation layer. Al_2O_3 coating material with a thickness of 3–5 µm is chosen thanks to its dielectric strength combined with excellent mechanical properties and thermal stability that makes it suitable for applications in machining. Concerning to the sensor layer, the requirements are structurability, linear temperature dependence of the resistance and

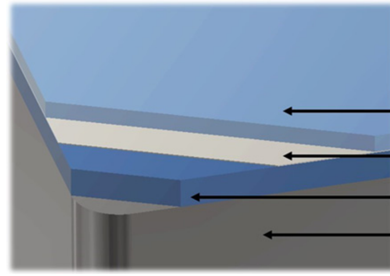


Figure 1: Layer materials of the thin-film systems.

adhesion to the surrounding layers. Chromium has proven to be a suitable sensor material for thin-film temperature sensors in high-load applications like die-cast aluminum or deep drawing processes [14, 15]. It can be structured by photolithography combined with wet-chemical etching or lift-off. In order to insulate the sensor against the workpiece and protect it against wear, another layer has to be deposited onto the sensor layer. Al_2O_3 is chosen due to its aforementioned properties and being a commonly used wear-protection coating for cutting tools. It gives also passivation when using cutting fluids. Its thickness is up to 3 µm. One downside of using Al_2O_3 is its low thermal conductivity which leads to a deviation of the temperature measured by the sensor compared to the actual surface temperature. However, by knowing its thermal properties as well as heat transfer coefficients and thicknesses of the coatings surface temperature can be calculated by a thermodynamic model.

4.2 Temperature sensor design

The design of the sensor structures is done with the aim of a high spatial resolution and careful use of the limited space on the cutting tool. The temperature sensor measures the tool-chip contact temperature, or, if not able to measure it directly due to being placed beyond the contact area, it captures the temperature gradient on the tool surface. Four-wire sensing is used, thus each sensor needs four contact pads for wiring. These have to be placed securely in some distance from the cutting edge and also need a certain space, which is why on one insert two cutting edges are equipped with two temperature sensors each. Fig. 2 shows an overview of the selected design. The white fringe surrounding the conducting paths represents the area which is etched during the photolithographic process. Thereby, the sensors are insulated from their surrounding, but most of the surface remains covered by chromium, which acts as an adhesion layer between the

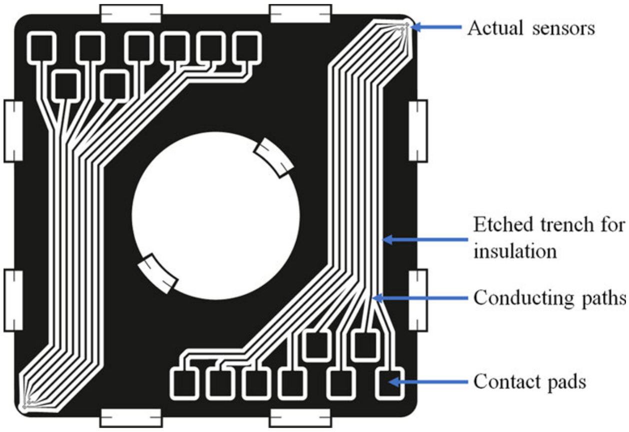
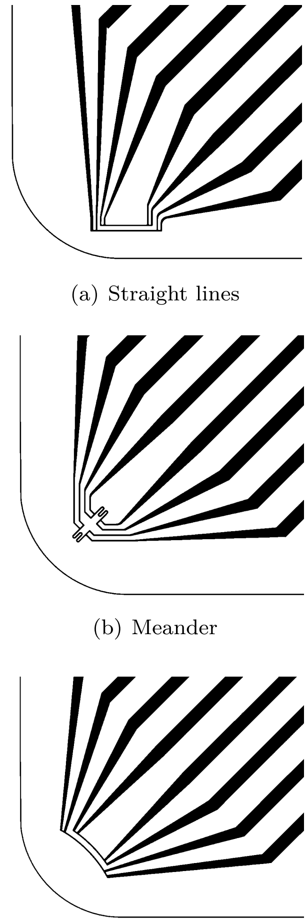


Figure 2: Temperature sensor design.

two Al_2O_3 layers. The sensor design itself is varied in order to test various positions and shapes (see Fig. 3) as well as different line widths. The smaller the sensor structure, the better the spatial resolution. Thus, the goal is to make structures down to 10 µm line width. At the same time, the length of the sensors cannot be infinitely short because a minimum output resistance of 50 Ω is desirable in order to be able to measure resistance changes. The variations range from simple lines shown in Fig. 3(a), measured in a short distance of 30 µm from each other but over a long distance of 250–400 µm, to more confined meander structures as shown in Fig. 3(b), that resemble a more point-like measurement ($80 \times 80\,\mu m^2$) but cannot be placed as close to each other. Also, curved lines shown in Fig. 3(c) are investigated with the aim to capture the isothermal lines.



(a) Straight lines

(b) Meander

(c) Curved lines

Figure 3: Investigated temperature sensor designs.

4.3 Wear sensor design

Wear sensors are developed to measure on the one hand the flank wear and on the other hand the crater wear. For both, the principle is the same as was explained above: resistance changes due to progressing destruction of parallel connected lines (from R_1 to R_n, with n as high as six), as shown in the circuit diagram depicted in Fig. 4. The resistance of each line is chosen by variation of its length and width in a way that results in equidistant resistance changes which allow the direct measurement of the wear. By knowing the resistance interval, it can be concluded from the overall resistance change how far the wear has progressed. The size of added meanders is adjusted to maintain resistance changes in the order of 30 Ω. Fig. 5 shows the wear sensor designs. To detect the flank wear, 20 µm wide conducting paths are aligned along the cutting edge in a distance of 20 µm from each other. This results in a resolution of 40 µm. The meanders for resistance adjustment are placed in a safe distance from the cutting edge. Thereby, the increase of the resistance due to the process temperatures at the cutting edge is minimized. Crater wear is measured with the design in Fig. 5(b). In this case, two sensor structures are aligned orthogonal to each other

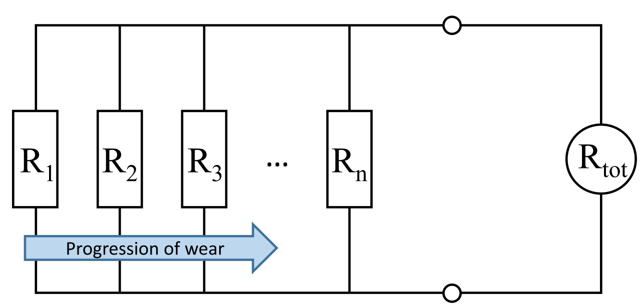
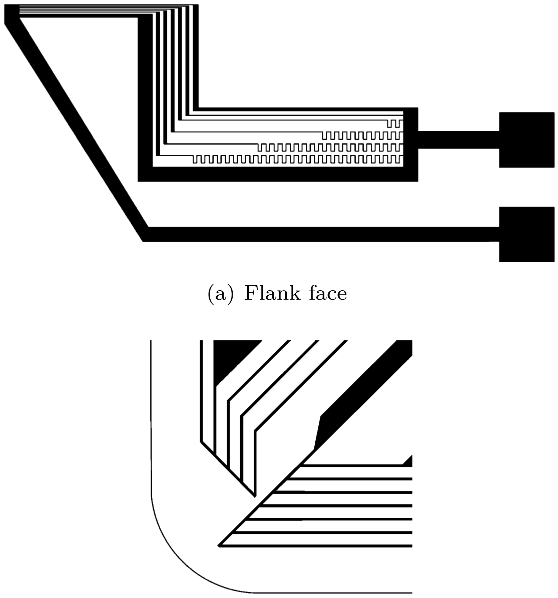


Figure 4: Circuit diagram of wear sensors.



(a) Flank face

(b) Rake face

Figure 5: Wear sensor design for flank and crater wear monitoring.

in order to measure the wear dimension in two directions with a resolution of 140 µm.

4.4 Sensor manufacturing chain

Tool preparation

To improve the quality of the coating process and to reduce the cutting edge radii, rake and flank face of cemented carbide inserts with geometry SNGA 190908 are prepared by plunge-face grinding. A Buehler planar grinder is used in combination with diamond grinding disks. The rotation speed is set to 150 rpm and the grinding single specimen force to 35 N. A Mahr perthometer and a confocal light microscope are used for measuring the prepared cutting edge profiles and the surface roughness respectively. Symmetrically rounded cutting edge radius of $r_\beta = 5\,\mu m$ and surface roughness values of $Rz < 0.1\,\mu m$ were obtained. The tool preparation reduces the risk of shorts due to spikes or pinholes through the insulation layer significantly. Additionally, each insert is cleaned in an ultrasonic bath with a solution of acetone and isopropyl alcohol.

Deposition

The thin-film system is deposited by using physical vapor deposition (PVD). At first, an Al_2O_3 layer is sputtered onto all faces of the inserts. As a result, the surfaces not equipped with a sensor obtain a wear-protection layer as well. A 200 nm thick chromium layer is sputtered homogeneously onto the tool surface and is subsequently structured, which is described in more detail below. The sensors are then protected by the second Al_2O_3 layer, which is deposited with a thickness of 3 µm. Additionally, the contact pads are coated with copper to improve the solderability. For that, the rest of the insert is masked with polyimide tape.

Structuring

An overview of the structuring process is shown in Fig. 6. After applying a photoresist homogeneously onto the chromium layer, a photomask with the desired design is aligned. In areas where the chromium should be removed, the resist is exposed to UV-light. This leads to a change of the chemical structure of the photoresist so that it can be removed with a developer, leaving the sensor structures protected for the following step of wet-chemical etching. After removal of the resist, the sensor structures are obtained. A chromium patterned fused silica photomask is

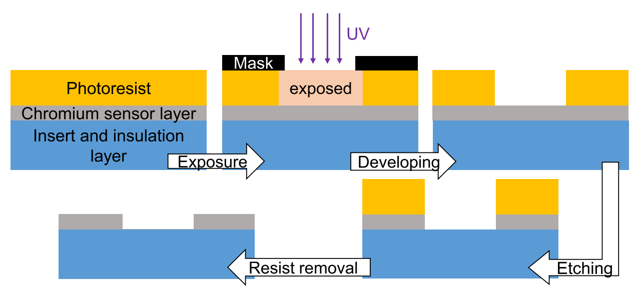
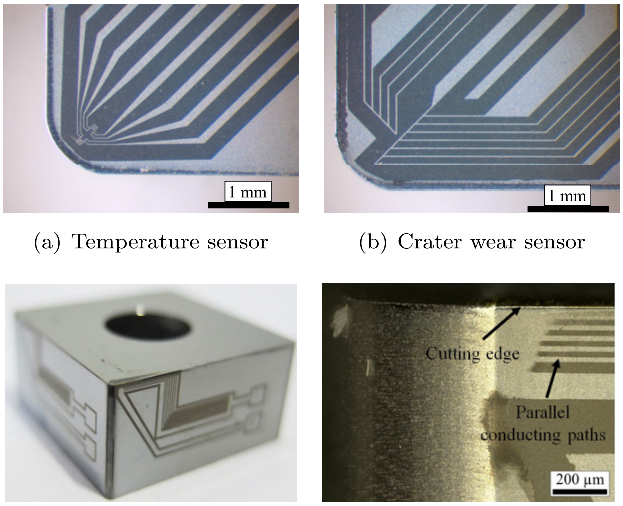


Figure 6: Structuring process diagram.

used for the structuring of the sensors on the planar rake face, allowing to achieve sensors with the best possible resolution. It is also used to fabricate the wear sensors on the planar part of the flank face. In future developments, it is the aim to place the sensors around the edge of the insert, in which case the fused silica mask can no longer be used. Then, a foil mask will be applied which will require larger line widths. Results of the structuring process are shown in Fig. 7. It is possible to place the sensors as close as 200 µm to the cutting edge on the rake face and even closer on the flank face.

Contacting

Shielded cables are soldered to the sensors and subsequently protected against tear-off as well as flying chip during the process by epoxy.



(a) Temperature sensor (b) Crater wear sensor

(c) Flank wear sensor (d) Detail flank wear sensor

Figure 7: Thin-film sensors on cutting tool rake and flank face.

4.5 Sensor calibration

The exact positions and distances of the conducting paths of the wear sensor as well as the positions of the temperature sensors are determined with a microscope. This enables to classify the generated data for further analysis. The thermoresistive characteristic has to be recorded for every temperature sensor in order to determine the output resistance and the exact temperature coefficient which can vary about 10 % between single sensors due to slightly different process conditions. For this purpose, the insert is heated in a furnace up to 170 °C while measuring the resistance of the sensor. A higher characterization temperature is not possible at the moment due to the fusion temperature of the soldered contacts. Alternative contacting techniques will be investigated in future work. The surface temperature is measured with a Pt100 sensor, which is placed on the rake face with heat-conductive paste. An exemplary characteristic is depicted in Fig. 8. Linear extrapolation of the measured curve was performed. A temperature coefficient of $\alpha_{20} = 7.9 \cdot 10^{-4}$ 1/K was obtained, leading to a sensitivity of approximately 0.057 Ω/K.

5 Experimental setup

The performance and durability of the temperature sensors on the insert rake face are evaluated in real working conditions. Dry longitudinal turning tests are conducted on an Index V100 vertical turning machine. As shown in Fig. 9, the experimental setup features a static tool, while

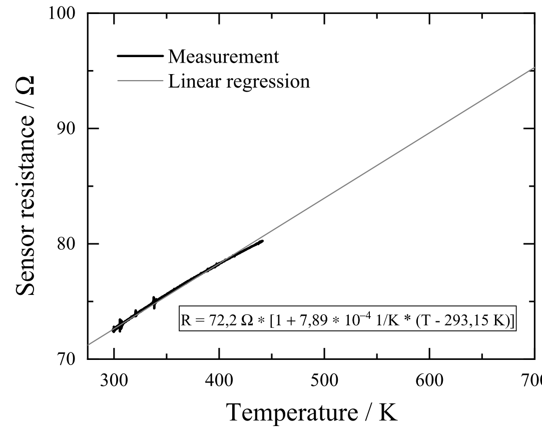


Figure 8: Thermoresistive characteristic curve.

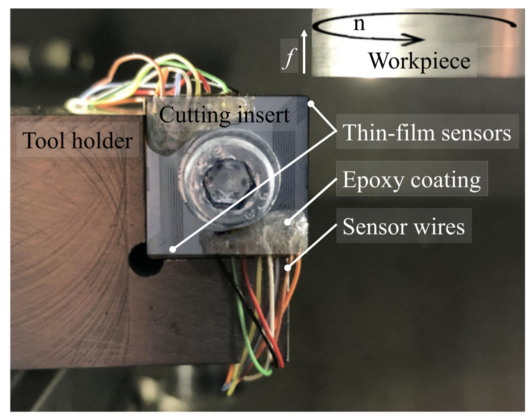


Figure 9: Cutting process setup using in-tool integrated thin-film temperature sensor.

a clamped workpiece rotates and moves downwards. The used workpiece material is AISI 4140 quenched and tempered at 600 °C for 1 hour according to DIN 10083 resulting in a hardness of 36 HRC. The cutting parameters and the insert geometry are specified in Table 1. Here v_c denotes the cutting speed, f the feed rate, a_p the depth of cut, γ the rake angle, α the clearance angle, β the wedge angle, κ_r the principal cutting edge angle, r_ϵ the tool corner radius and r_β the cutting edge radius. The thin-film sensors are wired to the measurement devices which are located outside the turning machine to avoid any damage. A Keithley

Table 1: Cutting conditions.

v_c m/min	a_p mm	f mm/rev	γ deg	α deg	β deg	κ_r deg	r_ϵ mm	r_β µm
100	0.30	0.15	−7	7	90	85	0.8	5

2601 current source is used to apply a constant current of 1 mA to the sensor. The resulting voltage drop across the sensor is recorded with a sampling rate of 100 kHz using a Yokogawa DL750 ScopeCorder. Temperatures are calculated from the measured voltages using the thermoresistive characteristic and additionally filtered with a digital 25 Hz low-pass filter to improve the signal-to-noise ratio, as significant noise is caused by the machine and the process itself.

6 Experimental results and discussion

6.1 Temperature measurements

The temperatures measured during the cutting tests are depicted in Fig. 10, using a thin-film sensor with the design of Fig. 3(a). The temperature rises immediately at the start of the process (0 s), increasing gradually until it drops as soon as the insert is taken out of the cut. The high sampling rate and the small sensor dimensions result in a fast sensor response. It should be noted, that in this experiment the sensor is not lying in the tool-chip contact area, thereby experiencing a significantly lower temperature than this is expected for the tool-chip contact. Further measurements with sensors being much closer to the cutting edge are about to be conducted soon.

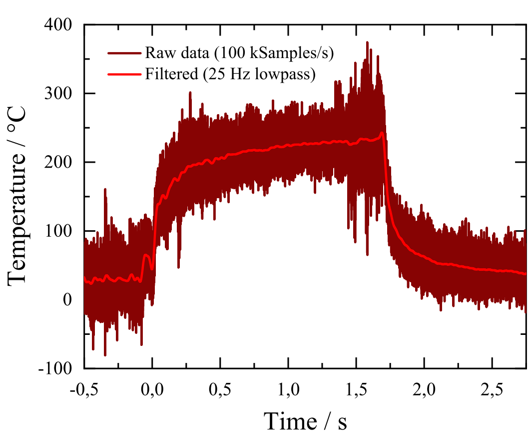


Figure 10: Measured tool-chip interface temperature.

6.2 Wear measurements

The wear sensors are not tested yet in machining operations. In order to validate the measuring principle an experiment is conducted in the laboratory on a prototype sensor by using a scratch tester to simulate the wear. It is used to destroy one conducting path after another while measuring the resistance of the sensor. With each path being interrupted, the resistance rises incrementally (see Fig. 11). Jumps back to the previous value at some points are attributed to momentarily reconnection by the scratch tip, but the overall significance is given nonetheless.

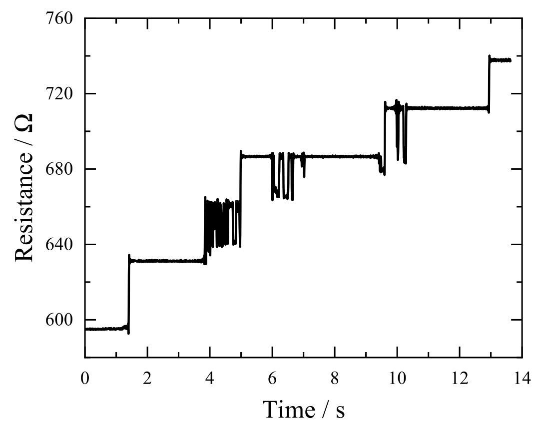


Figure 11: Demonstration of the working principle of wear measurements obtained in a laboratory experiment.

7 Summary and outlook

In this work the development of tool-integrated thin-film sensors was presented with the ability to conduct in-process measurements of rake face temperature as well as crater and flank wear. In first experiments temperature could be measured during dry turning of AISI 4140 Q&T steel, showing the fast response time and high resolution of the thin-film sensor. Future experiments will include the investigation of lifetime, statistical reliability and durability of sensors that are placed in the tool-chip contact area and the evaluation of different design variations. Furthermore, the influence of the thermal properties of the coating materials and the temperature gradient on the surface will be considered by the use of thermodynamic models. The working principle of the wear sensor was demonstrated in this paper and will be tested under real working conditions in the next step. It is the aim not to affect the tool wear behavior with the sensor, as it consists of only a 200 nm thick chromium layer and is placed between conventional tool-coatings.

Eventually, after the implementation of a process model that correlates the process parameters and variables with the resulting surface integrity of the workpiece, the generated data of the thin-film sensors will be used as input for a so-called soft sensor. It will be able to control the process in order to produce reliably and independent of wear a desired surface integrity of the workpiece.

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