Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 101 (2021) 85–88

www.elsevier.com/locate/procedia

9th CIRP Conference on High Performance Cutting (HPC 2020)

Wear-resistive thin-film sensors on cutting tools for in-process temperature measurement

Marcel Plogmeyer[a,]*, Germán González[b], Saskia Biehl[c], Volker Schulze[b], Günter Bräuer[a,c]

[a]TU Braunschweig, Institute for Surface Technology (IOT), Bienroder Weg 54E, 38108 Braunschweig, Germany
[b]wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany
[c]Fraunhofer Institute for Surface Engineering and Thin Films (IST), Bienroder Weg 54E, 38108 Braunschweig, Germany

* Corresponding author. Tel.: +49-531-2155-661; fax: +49-531-2155-900. *E-mail address:* m.plogmeyer@tu-braunschweig.de

Abstract

In-process control of machining operations allows to develop strategies to modify and improve the surface integrity of manufactured components and thereby enhancing their performance and lifetime. These control strategies require reliable real-time data like cutting forces, process temperatures and tool wear. In this work, a wear-resistive thin-film sensor is developed to measure temperature of the cutting tool surface during machining. A multi-layer sensor system is applied on the tool surface by physical vapor deposition (PVD). The tool-sensors are subsequently tested for their functionality and durability in turning operations of AISI 4140q&t steel.

Keywords: thin-film sensor; temperature; in-process measurement; physical vapor deposition (PVD)

1. Introduction

The recent efforts of the industrial and manufacturer companies for a better understanding and control of their processes and products have drastically transformed most of the technological paradigms, giving rise to the era of the digitalization. Machining processes are also undergoing continuous development, pursuing the optimal product manufacturing chain and production quality performance. In order to control and enhance the mechanical properties and the surface quality of machined end-components, several studies and works were carried out in recent years in the so-called surface integrity field [1].

It is well known that the impact of the thermal and mechanical load during machining processes can change the surface layer states which influences the mechanical properties. Temperature measurement presents a challenge though, because in the tool-chip contact area, where the highest temperature gradients are located, other factors like coolant or the chip itself complicate the sensors labor. This, for example, makes the usage of infrared cameras in this area difficult, even beside problems with emissivity.

In a scientific environment, pyrometers or embedded thermocouples are often implemented into cutting inserts with great effort [2], but can be limited by slow thermal conduction while weakening the tool structure.

In order to measure directly in the desired spot, the use of thin-film sensors placed directly on the tools was studied over the years as a new approach. For instance, thin-film thermocouples made of Ni, NiCr or chromel-alumel-junctions were embedded in an electrical insulating layer on the rake face of cutting tools [3] or build in micro-grooves [4, 5]. Alternatively, multilayer thin-film systems were applied directly on cutting tools to measure temperatures and wear on the rake face [6] and later also on the flank face [7]. The thin-film systems were based on aluminum oxide (Al_2O_3)

10.1016/j.procir.2021.02.011

encapsulating a sensor layer of TiN or CrN. Many of those sensors failed due to electrical shorts and they could only be tested in aluminum turning processes because the wear-resistance was not given for steel processes. Over the years, the sensor thin-film system was improved and adopted for many other applications, like sensor modules for strip drawing processes [8] or mold cores for die-cast aluminum with temperatures of more than 500 °C [9].

In this study, the development of new wear-resistant temperature thin-film sensors is presented. The sensors were experimentally tested during turning of AISI 4140q&t.

2. Thin-film sensor

2.1. Description and sensor design

Thin-film sensor systems can be applied directly to the surface of tools or components without the need to make major modifications on existing structures. It is the aim to develop integrated temperature sensors with high sensitivity that at the same time have a high spatial resolution to allow their data to be used efficiently.

The different layers that build the sensor system are deposited directly on the rake face of uncoated cutting tool inserts as shown in Figure 1.

- For proper sensor operation, thermally stable and defect free insulation layers are necessary. For this labor, based on previous work [9], Al_2O_3 coating material was deposited underneath the sensor layer in a thickness of 5 µm.
- 200 nm thick chromium (Cr) was chosen as sensor material because of its positive temperature coefficient of resistance.
- Above the sensor layer a second 3 µm thick Al_2O_3 layer was deposited to provide tool-wear protection as well as insulation against the workpiece.

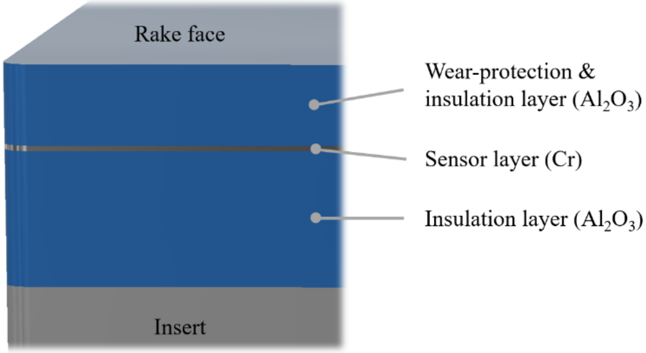

Fig. 1. Thin-film sensor system representation for integrated sensors on the rake face of cutting tools.

The optimal sensor layout presents a design with structures as small and condensed as possible to realize a high spatial resolution. This stands in contrast to the feasibility of the structuring process and the measurability of the sensor signal. In Figure 2 (a) an overview of the complete sensor design is depicted. The sensors are located close to the cutting edges and their contact pads are placed in a safe distance. Figure 2 (b) and (c) show magnifications of exemplary sensors. In both cases, two sensors are placed next to each other in order to measure the temperature gradient. Four-terminal sensing is used to avoid lead and contact resistances distorting the measurements. The sensor structures (highlighted in orange) shown in Figure 2 (b) are made of two 20 µm wide lines placed in a 30 µm distance from each other. They measure the integral temperature over their full length, thus showing good vertical but less horizontal resolution. Figure 2 (c) presents an alternative, more point-like sensor design with 10 µm meander structures which measure the temperature over an 80 x 80 µm² area.

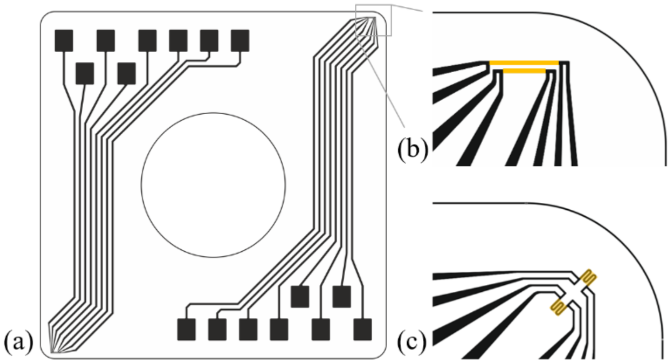

Fig. 2. (a) Overview of the sensor design including contact pads.
(b) & (c) Magnifications of two possible sensor structures. The sensing area is highlighted in orange.

Each sensor must be calibrated individually obtaining its thermoresistive characteristic. It is later used to calculate the process temperatures from the measured resistances. The design shown in Figure 2 (b) was selected to carry out the experiments, as it was the smallest feasible structure at the time of the experiments, while the more advanced design of Figure 2 (c) was realized after optimization of the structuring process.

2.2. Cutting tool preparation

Surface roughness has a strong influence on the effective electrical isolation of thin films as breakthroughs caused by local spikes result in electrical short circuits. Since a defect free insulation layer is needed for the proper sensor operation, the tool rake faces were ground and polished. Both the roughness and the cutting edge rounding were analyzed tactilely with a perthometer by Mahr obtaining surface roughness values of less than Rz = 0.1 µm and cutting edge radius of r_β = 5 µm.

2.3. Sensor manufacturing process

Cemented carbide tools were coated using sputtering processes, which are a physical vapor deposition (PVD) technique. After the first Al_2O_3 coating was applied, the sensor layer was deposited next and was structured in a photolithographic process. A photoresist was applied and subsequently exposed with UV light through a chromium patterned fused silica photomask. After development of the resist, wet-chemical etching of the Cr and removal of the resist, the sensor structures were encapsulated with a second Al_2O_3 layer. Figure 3 shows exemplary the structuring results. In first attempts, undercutting occurred when structuring small conducting paths of 20 µm or less (a). Due to the proximity to the sharp cutting edge, the structuring process is hampered, leading to longer development and etching times and thereby weakening the resist. This challenge could be overcome by improved process strategies leading to successfully structured 10 µm meander structures as close as 200 µm to the cutting edge. As these advancements were achieved only recently, the temperature data presented below was generated with the highlighted, partly etched away sensor structure in (a).

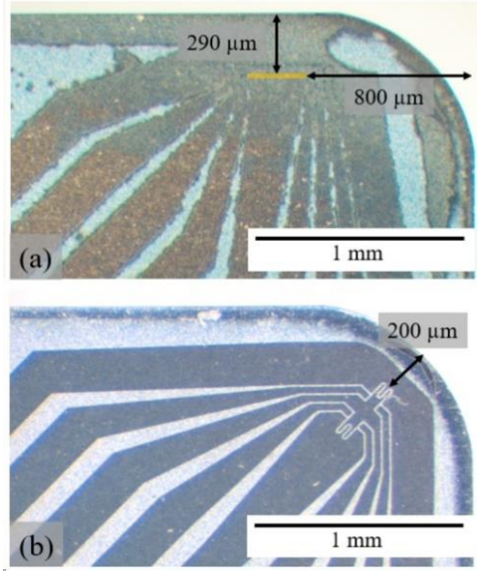

Fig. 3. Structuring results of (a) 20 µm sensor structures partly etched away and (b) 10 µm meander structures.

2.4. Thermoresistive characterization

Shielded cables were soldered to the sensors paths and were subsequently encapsulated with an epoxy coating for protection. To expand the range of the calibration curve, linear extrapolation was used as shown in Figure 4.

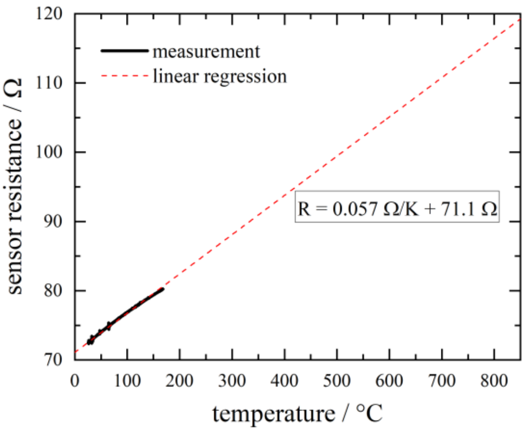

Fig. 4. Thermoresistive characteristic.

To obtain the thermoresistive characteristic, the inserts were heated in a furnace to approximately 170 °C and cooled down. The sensors are designed to measure a specific range of temperatures. In this work, the upper end of the target range was set according to the expected tool-chip interface temperature, this means temperatures up to 700 °C for the selected process parameters. The soldered contacts are safely placed far away from the highest temperatures during cutting, but their fusion temperature limits the range of the calibration. The sensor resistances were measured by four-terminal sensing and the surface temperature was recorded by using a commercial Pt100 sensor which was placed on the rake face of the tool. A resolution of 0.057 Ω/K was obtained.

3. Cutting tests

Longitudinal turning tests were carried out without coolant on an Index V100 vertical turning center. As shown in Figure 5, the experimental setup featured a static tool, while a clamped workpiece rotates and moves downwards. The cutting material was made of AISI 4140 in a state quenched and tempered at 600 °C with a hardness 330 HB. Cemented carbide inserts with geometry SNGA 190908 coated with the thin-film sensor system were used as tool and as temperature sensor in the experiments. The rake, wedge and clearance angles were set to $\gamma = -7°$, $\beta = 90°$ and $\alpha = 7°$. The process parameters are listed in Table 1.

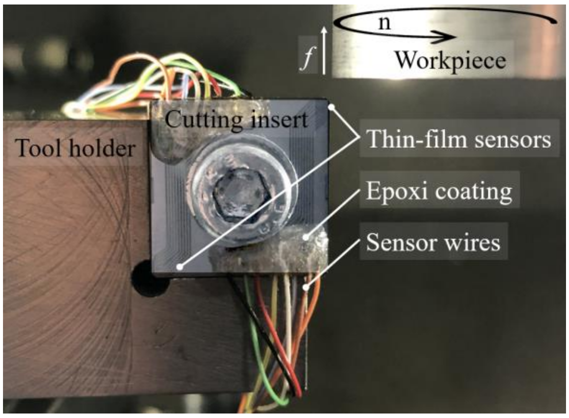

Fig. 5. Set-up of the turning experiments.

Table 1. Process parameters of the cutting tests.

Test	v_c [m/min]	a_p [mm]	f [mm/rev]
1	100	0.05	0.15
2	100	0.10	0.15
3-5	100	0.30	0.15

The thin-film sensors were wired to the measurement devices which were located outside the turning machine to avoid any damage. A Keithley 2601 was used as current source applying a constant current of 1 mA to the sensor. The resulting voltage drop across the sensor was recorded using a Yokogawa DL750 ScopeCorder with a sampling rate of 100 kS/s.

4. Results and discussion

4.1. Temperature measurements

Temperatures were estimated from the measured voltages using the thermoresistive characteristic, assuming for simplicity that the effect of the temperature gradient on the resistance in the tool cancels out at both ends of the sensor. Additionally, data was filtered with a digital 25 Hz lowpass-filter to improve the signal-to-noise ratio. Figure 6 shows the resulting temperature profiles measured in the cutting experiments. It should be noted that these do not yet represent the actual temperature at the tool-chip contact as the sensor is located 800 µm from the cutting edge and protected by a low thermal conductivity coating. At t = 0 s, the tool comes into contact with the workpiece, leading to a fast temperature rise. Between t = 1.5-2 s, depending on the cutting length, the temperature decreases significantly when the inserts were taken out of the cut. The sensors show a fast response to the changes, demonstrating their high sensitivity. In tests 3-5, the same process parameters were used to investigate the reproducibility of the sensor signals. Only slight variations can be seen in the temperature profiles with a repeatability of about ± 5 %.

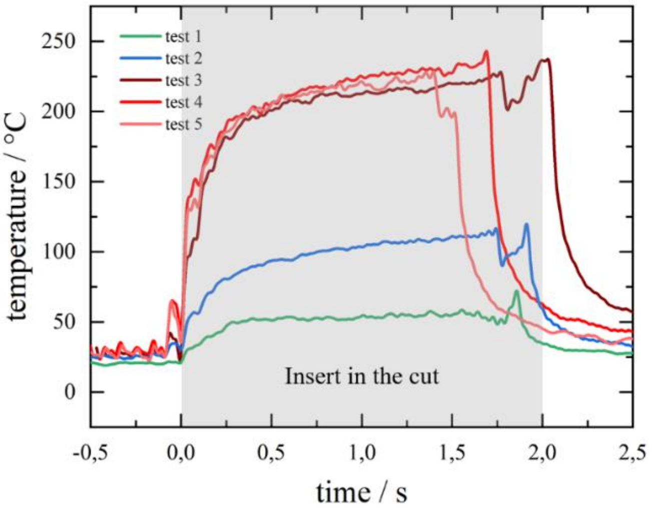

Fig. 6. Temperature profiles of the cutting experiments.

4.2. Wear analysis

The wear of the coated inserts was detected in two different ways. Since the sensors were located close to the cutting edge, crater wear led to interruptions of the conducting paths of the sensors, which then could be recognized in the electrical signal. Each insert was also analyzed before and after the cutting tests with an optical microscope. Figure 7 shows the wear resulting from the experiments of Table 1. While the sensor is still functional, the delamination of the thin-film system already starts at the cutting edge.

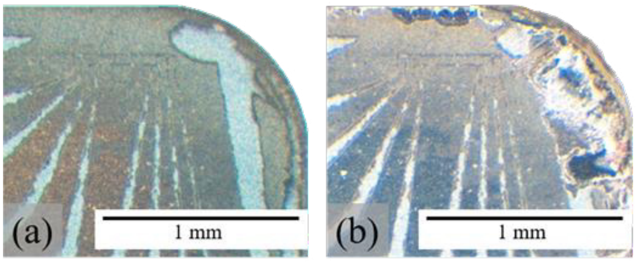

Fig. 7. Comparison of the cutting edge with thin-film sensor (a) before and (b) after the experiments.

5. Outlook and future directions

Important developmental steps towards integrated thin-film temperature sensors on cutting tools for turning operations were presented. Despite lingering questions concerning the durability of the thin-film system, the potential of this technology was demonstrated, showing a fast response and good reproducibility in first cutting tests. In the ongoing development, improved adhesion of the layers as well as the deposition of an additional wear-protection layer will be addressed to prolong the sensors lifetime and to measure temperatures closer to the tool-chip contact. The already improved structuring process will enable the latter one and increase the spatial resolution of the sensors by smaller confined structures. Usage of an alternative bonding technique, like micro welding, will increase the range of temperatures for the sensor characterization significantly. To account for the temperature gradient in the tool, position of the sensor and the heat barrier presented by the wear-protection layer, thermodynamic models will be developed. It is further the aim to integrate wear- and force-sensing structures into the thin-film system, so that all required process variables can be detected by one multi-functional thin-film system.

Acknowledgements

The scientific work has been supported by the DFG within the research priority program SPP 2086. The authors thank the DFG (BR 2178/47-1) and (SCHU 1010/63-1) for this funding and intensive technical support.

References

[1] Jawahir IS, Brinksmeier E, M'Saoubi R, Aspinwall D, Outeiro J, Meyer D, Umbrello D, Jayal AD. Surface integrity in material removal processes: recent advances. CIRP Annals, 2011, 60:603-626.
[2] Davies MA, Ueda T, M'saoubi R, Mullany B., Cooke A L. On the Measurement of Temperature in Material Removal Processes. CIRP Annals, 2007, 2(56):581–604.
[3] Basti A, Obikawa T, Shinozuka J. Tools with built-in thin film thermocouple sensors for monitoring cutting temperature. International Journal of Machine Tools and Manufacture, 2007, 47(5):793-798.
[4] Sugita N, Ishii K, Furusho T, Harada K, Mitsuishi M. Cutting temperature measurement by a micro-sensor array integrated on the rake face of a cutting tool. CIRP Annals, 2015, 64(1):77-80.
[5] Li J, Tao B, Huang S, Yin Z. Built-in thin film thermocouples in surface textures of cemented carbide tools for cutting temperature measurement. Sensors and Actuators A: Physical, 2018, 279:663-670.
[6] Lüthje H, Löhken T, Böttcher R. Direct Control of Cutting Tools by Novel Microtechniques. VDE World Microtech.Congress, 2000, 489.
[7] Lüthje H, Bandorf R, Biehl S, Stint B. Thin film sensor for wear detection of cutting tools. Sensors and Actuators A: Physical, 2004, 116(1):133-136.
[8] Biehl S, Rumposch C, Paetsch N, Bräuer G, Weise D, Scholz P, Landgrebe D. Multifunctional thin film sensor system as monitoring system in production. Microsystem Technologies, 2016, 22(7):1757-1765.
[9] Biehl S, Meyer-Kornblum E, Bräuer G, Gebauer-Teichmann A, Adam M, Klenke T, Röders G. Entwicklung von thermoresistiven Dünnschichtsystemen auf Formkernen zur lokalen Temperaturmessung beim Aluminium-Druckgießen. Gießerei, Vol.103, 2016, 12:50-53.