Wear resistant thin film sensor systems for industrial applications

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Abstract: After the age of low cost mass-production the industry has in these days to tackle the task of a flexible and customer-oriented production. Therefor the need of sensor systems for the measurement of temperature and load, the two most important categories in production, is rising. For getting the real specification during the production process the integration of sensor elements in high load regions of machinery is very important. Thus wear resistant thin film sensor systems directly applied onto the surface of plant components are in development. These multilayer systems combine excellent wear resistance with sensory behavior. The sensor data will lead to a deeper process understanding, to optimization of simulation tools, to reduction of rejects and to an improvement of flexibility in production.

Key-Words: thin film sensor system, piezoresistive, thermoresistive, wear resistant, sensory washer, sensory tool

1 Introduction

The development of thin film sensor systems for the measurement of temperature und load in different applications is a big theme all over the world. For temperature sensors carbon nanotubes as new sensing material is an area under investigation [1]. Temperature sensors based on a multi-walled carbon nanotube/styrene-b-(ethylene-co-butylene)-b-styrene (MWCNT/SEBS) nanocomposite are fabricated on polyimide films. This material has a negative temperature coefficient. They show an electrical resistance decrease with increasing temperature. On the other hand there are many scientists who are working on the development of metal based temperature sensors. Thermal sensors built up out of Pt/Cr and Pt/Cr_2O_3 thin film layers on SiO_x/Si substrates show thermal stability and a positive temperature coefficient [2]. Also metallic thin film sensor systems are developed for local temperature measurements for the characterization of grinding process. Therefor steel wafer with polished surface were coated with the photoresist SU8 and temperature thin film structures out of a Cr/Au two-layer system were fabricated on top of this insulating layer. Sensor inlays were cut out of the wafer and integrated in the workpiece [3].

All these examples of thin film sensor developments show amazing results but they cannot be directly integrated under load because they are not wear resistant.

Piezoresistive thin film load sensors can be fabricated as strain gauge. There are different materials under investigation. Carbon based resistive strain gauge sensor systems fabricated on Ti using micro-dispensing direct write technology [4] as well as strain sensitive Pt-SiO_2 nano cermet thin films for high temperature pressure and force sensors [5].

The integration of thin film temperature sensor structures in combination with piezoresistive load sensors in one wear resistant layer system is the next level of development.

2 Problem Formulation

The deposition of wear resistant layer systems directly onto tool surfaces is an established theme, e.g. TiN on the surface of drills or diamond like carbon (DLC) layer in different modifications are well known tribological layer systems [6, 7, 8, 9, 10]. These developments were done for a rising lifetime of tools due to the fact that production can get more cost-effective. In these days the wish of industry is rising for getting sensor systems directly integrated in machinery as near as possible to the workpiece. So it is obvious to combine tribological and sensory layers in one multifunctional thin film system.

3 Problem Solution

Embedding temperature sensor meander structures out of Cr between two insulating Si and O modified carbon layers is the idea for the fabrication of wear resistant temperature sensors. Under this layer system a piezoresistive hydrogenated carbon coating is placed. In the areas, where the load has to be measured, local electrode structures also out of Cr are fabricated. The carbon based piezoresistive coating is called DiaForce® due to the fact that this layer combines force measurement with high hardness and wear resistance. This layer is deposited in a plasma enhanced chemical vapor deposition (PECVD) process. It has a hardness of 24 GPa and a coefficient of friction against steel of 0.17. It is an amorphous hydrogenated layer with about 20 at% hydrogen and about 80 at% carbon. The Si and O modified insulating carbon coating is also fabricated in a PECVD process.

The structuring of the Cr layer, deposited in a physical vapor deposition (PVD) process, is done by photolithography and chemical wet etching in combination. Schematically the multifunctional layer system is shown in Fig.1.

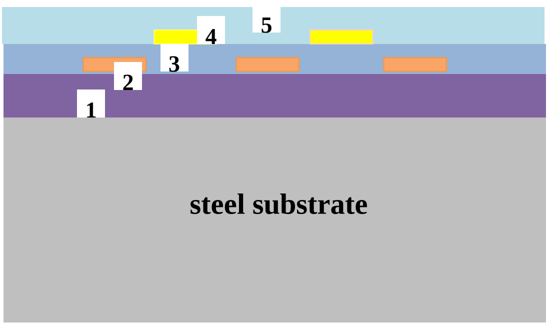


Figure 1: Schematic of the multifunctional thin film system.

At first the piezoresistive DiaForce® layer (1) is deposited in a thickness of 6 µm. After that the electrode structures out of Cr (2) are fabricated in a lift off process. Therefore the surface is coated with a photoresist and structured under UV light. After the development process just the electrode areas are unprotected and get coated with Cr in a PVD process in a thickness of 200 nm. Just small transition areas of the electrodes get masked by photoresist in the same way as before. These small fields will later be the contact area of the circuit paths. The first insulating layer (3) deposition in a thickness of 1 µm is followed by the removement of the photoresist. The second Cr layer (4) is deposited in a thickness of 200 nm. This film is structured with meander designs by a combined process of photolithography and chemical wet etching. Finally, the insulating top coating (5) in a thickness of 3 µm is deposited.

2.1 Applications

There is a big variety of applications for the multifunctional thin film sensor system. The integration of this layer system in the track of bearings [11] or as monitoring system directly applied in the contact zone between spindle shaft and tool holder for the measurement of the clamping force of the tool holder, the imbalance of the used tool and the process forces during machining in high speed cutting systems [12]. In these applications the DiaForce® coating is integrated as piezoresistive sensor film in different layer systems. The explained system is integrated directly on top of the tools for deep drawing and for building up sensory washer systems.

2.1.1 Sensory tool

The application of the thin film system, shown in Fig. 1, directly on the surface of the blank holder tool is a challenge for the structure technology regarding to the complex geometry shown in Fig. 2.

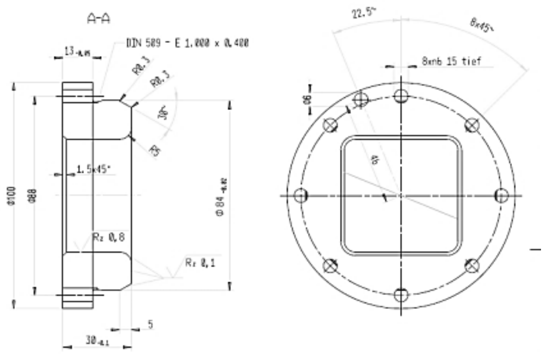
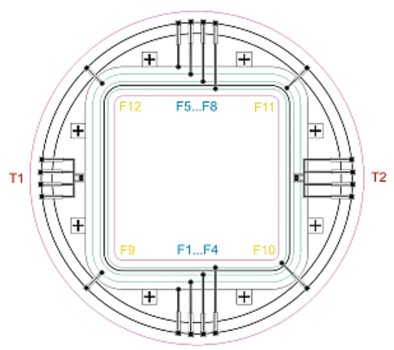


Figure 2: Mechanical drawing of the blank holder tool.

The arrangement of the sensor structures is shown in Fig. 3.

Figure 3: Arrangement of the load sensor structures



(F) and the temperature sensor structures (T).

Fig.4 shows the tool after the last wet etching process. All the sensor structures are fabricated now without the top coating.

Figure 4: Structured Cr layer on top without the insulating and wear resistant coating.

In Fig. 5 the tool with the complete sensory coating is shown.

Figure 5: Blank holder tool with the multifunctional thin film system.

The load sensor structures are placed in the curved corners and the lateral surface. Also two temperature sensors are structured on the curved lateral face. The following light microscopy pictures in Fig. 6 and 7 show in detail the challenge of structuring the load sensor structures.

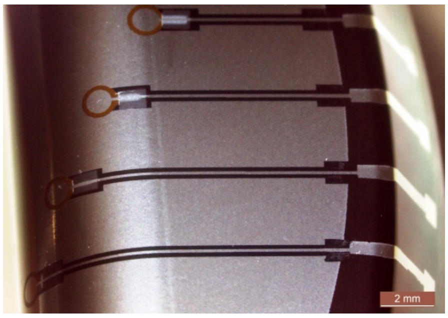


Figure 6: load sensor structures arranged on the lateral surface of the tool.

On the right site the contact areas are placed and on different areas of the curved region the load measuring circular fields are structured connected by electrical circuit paths.

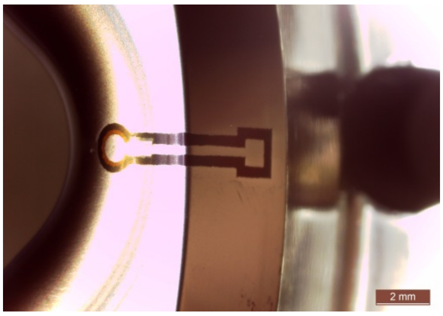


Figure 7: Load sensor structure placed in the corner.

For the load sensor structures arranged in the corners of the tool the structuring of the conductive circuit path was realized in a lift off process. Before the metallization a laser cut polyimid foil was applied onto the surface.

Before the deep drawing tests the characterization of the thermoresistive and piezoresistive behavior of the sensor structures were done. Therefor the sensor structures were heated in a furnace and the temperature depending resistance changes were measured. The results are shown in Fig. 8 and 9.

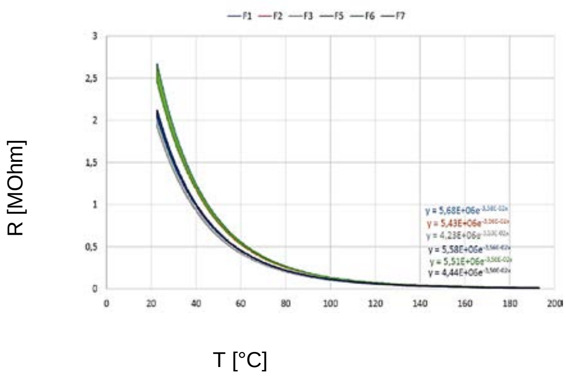


Figure 8: Exponential resistance dependency on the temperature of the load sensor structures.

For these measurements series connections with a constant resistor of 2 MOhm were used and a voltage of 5 V was applied.

For the characterization of the temperature meander structures a constant current of 2 mA was applied through the outer contacts and through the inner contacts the voltage was measured.

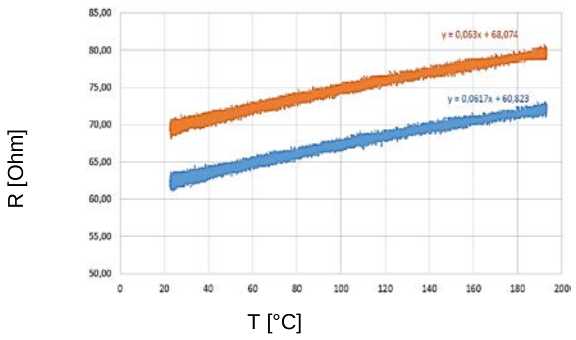


Figure 9: Linear resistance dependency on the temperature of the Cr meander structures.

Just the load sensor structures F1 and F5 were pre-characterized under normal load due to the fact that they are placed in the plane area of the tool. The test setup is shown in Fig. 10.

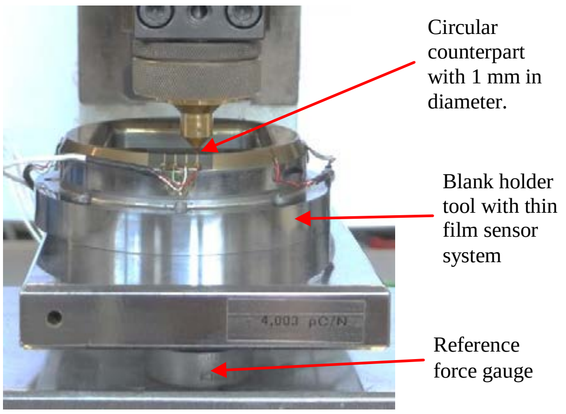


Figure 10: Test arrangement for the characterization of the piezoresistive behavior of the thin film sensor structures.

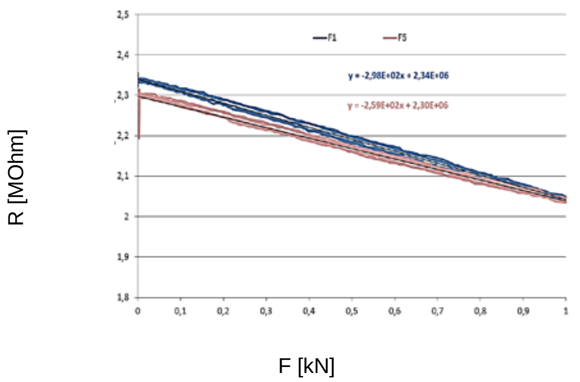


Figure 11: Linear resistance dependency of the load sensor structure on the load.

In Fig. 11 the results of the load dependent resistance changes are shown. The three load-unload cycles of each sensor structure show the same linear dependency on the load.

After the pre-characterization the sensory tool was integrated in the deep drawing machine (Fig. 12).

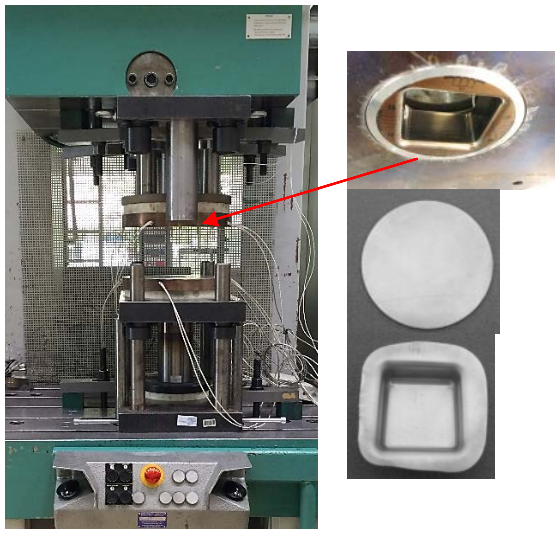


Figure 12: Deep drawing machine with integrated sensory tool for the forming of Al sheet (right site).

On measurement result of such a deep drawing process is shown in Fig. 13.

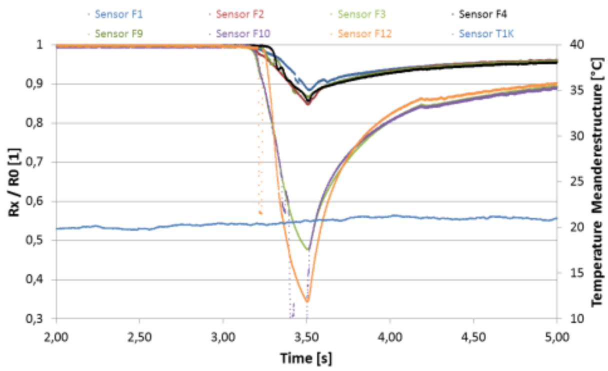


Figure 13: Result of the resistance changes during on deep drawing process.

The resistance change of e. g. load sensor structure F1 is 12%, caused by heating of the surface and the applied load. The Cr meander structures show a temperature change of just 1 K. That means the resistance change caused by temperature is 3% and 8% by applied load. By taking the pre-characterization results as a basis that means that the pressure at load sensor structure F1 is in the range of 433 MPa.

2.1.2 Sensory washer

As a universal measurement system washer based sensors can be applied retroactively in a multitude of standard screwed joints to determine long time stable static preload forces or dynamic load changes. In mobile or rotating machinery wired measurement units can be an obstacle. For this purpose, an active smart sensor system with wireless data transmission based on Bluetooth Low Energy was developed. A steel substrate with washer geometry is used for the piezoresistive thin film system with a balcony-like bulge added. The thin film system is shown in Fig.1. With an angle of 120° three load sensitive areas (F1, F2, F3) were applied to determine preload forces as well as uneven loads in the screwed joint. For temperature compensation another two sensor areas (T1, T2) are placed in the unloaded region of the DiaForce® thin film. Also a meander structure as temperature sensor is integrated in the thin film sensor system, as shown in Fig. 14.

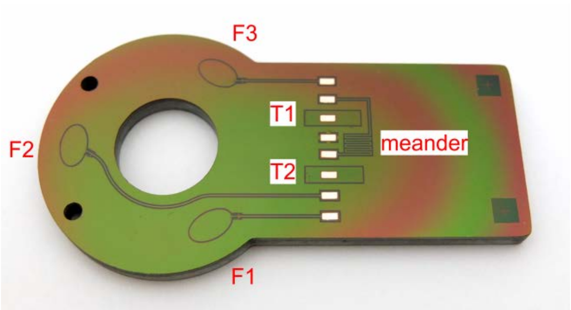


Figure 14: Sensory washer with three load sensor structure, two structures for temperature compensation and one meander structure for temperature measurement.

A loaded (F) and an unloaded (T) sensor are connected in series to construct a voltage divider as a branch of a Wheatstone half-bridge. The single load sensors are driven sequentially by a multiplexer to be measured by only one acquisition unit. The measurement and data transmission circuit is reduced to a size of a 4 cm² both sided board which includes the processing of the analog signal, the digitalization with a 16-bit ADC and the data handling in an internal ATMEL ATmega328P microcontroller. The data transmission is provided by a Bluetooth Low Energy module on the backside of the circuit board. This board is shown in Fig. 15.
On the bulge of the base body the measurement unit is stacked with a 240 mAh accumulator which is needed to provide the transmission energy under a capsular housing, shown in figure 16.

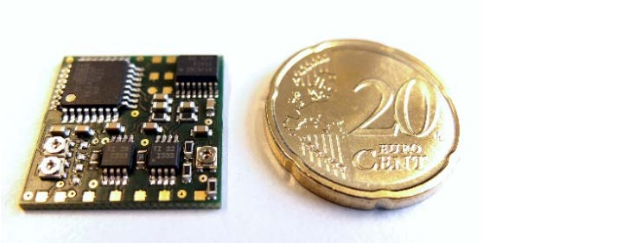


Figure 15: The just 4 cm² circuit board of the sensory washer.

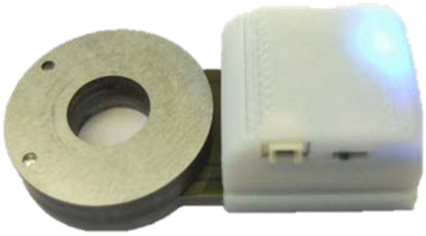


Figure 16: Sensory washer system with connected wireless Bluetooth Low Energy data transmission system.

The fully integrated system reaches an accuracy up to 1% FS (full scale) with a transmission range up to 40 m. In this case a standard tablet is used to receive and visualize the sensor data due to the Bluetooth 4.0 interface, as shown in Fig.17. Therefor an Android application was written to calculate out of the sensor signals the responding forces applied on the washer system.

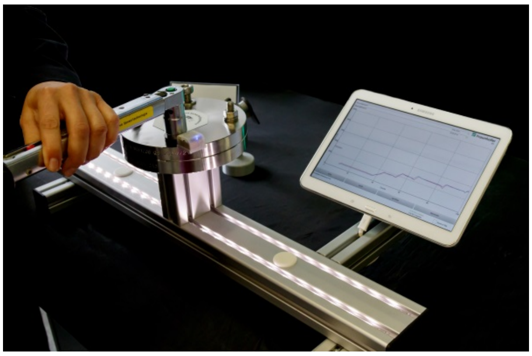


Figure 17: Test arrangement of a screw joint with integrated sensory washer system. Tighten of the screw can be directly observed on the tablet.

4 Conclusion

The integration of sensor systems in machinery for getting real time data about the load and temperature distribution is a very important theme for an optimized, flexible and costumer oriented production. Therefor multifunctional thin film systems directly coated on the tool surface can be one solution. Just 10 µm thin layer systems with integrated load sensor structures as well as temperature sensors even on complex shaped tools can be fabricated as shown on blank holder tools for deep drawing processes. The load sensor systems are based upon the piezoresistive hydrogenated carbon layer called DiaForce®. This coating has a negative temperature coefficient due to the fact that the electrical resistance is decreasing with increasing temperature. This effect is also mentioned in the introduction for the carbon nanotube layer used as new temperature sensitive film. Also meander structures out of Cr are integrated in the thin film system for the local temperature measurement. These sensor systems show a positive temperature coefficient like it is well known from metallic layer.

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