INTELLIGENT MACHINE PARTS WITH SURFACE EMBEDDED SENSORS UNDER WEAR RESISTANT COATINGS

T. Schönberg[1], *K.P. Almtoft*[4], *M.K. Hansen*[4], *B.H. Christensen*[4],
M. Svensson[1], *N.P. Østbø*[2], *H. Ronkainen*[3], *L.P. Nielsen*[4]
[1]Acreo, Kista, SWEDEN
[2] SINTEF ICT, Oslo, NORWAY
[3] VTT Technical Research Center of Finland, Espoo, FINLAND
[4]Tribology Center Danish Technological Institute, Aarhus, DENMARK

ABSTRACT

A surface embedded temperature sensor has successfully been fabricated on a customized industrial bolt. The aluminum substrate of the bolt was electrically isolated by plasma electrolytic oxidation followed by the fabrication of a type T thermocouple and finally covered by a wear resistant DLC coating. This bolt is part of our work to develop smart machine parts that are capable of reporting their current physical status under real working conditions enabling both new tools for condition based maintenance and information gathering for process optimization. By adding intelligence to the surfaces of machine parts we also reduce the need of traditional packaging of discrete sensor components.

KEYWORDS

Surface embedded sensor, bolt, thermocouple, intelligent machine parts, wear resistant coating.

INTRODUCTION

Industrial relevance

Industrial tools need maintenance and there are many different maintenance approaches, philosophies, strategies, methologies and policies described in the literature [1]. Some of the most common practical maintenance approaches are:

- Failure based maintenance which is based on actions initiated by failures and where the main objective is to put the equipment back in working condition as fast as possible.
- Preventive maintenance which is planned and optimized actions using statistical methods to reduce the number of failures and their economical consequences.
- Condition based maintenance which determines the best time for intervention by monitoring the condition of the component and thereby utilizing as much as possible of its life and at the same time avoiding unnecessary maintenance stops.

Intelligent machine components with surface embedded sensors enables early detection of deviations from normal running conditions. Such deviations can be damage initiations that can lead to failure. With continuous monitoring of the machine components, maintenance can be optimized and the number of failures can be reduced.

Process optimization is another key area for using surface embedded sensors where economical benefits are found through increased process control. A clear example is a process with fixed time cooling cycles of the substrate, e.g. metal or plastic forming. With temperature sensors embedded at the interface to the substrate, the cooling process time can be optimized by adapting it to the measured substrate temperature.

Sensor fabrication

Thin film sensors are traditionally fabricated by deposition of metal layers and isolation layers with subtractive or additive patterning using conventional photolithography and cleanroom processing techniques. However, these processes requires flat and smooth surfaces which in MEMS and microelectronic applications are handled by using substrates with perfect flatness, e.g. silicon, quarts or glass wafers. We focus on sensor fabrication on normal industrially machined parts and components going beyond traditional cleanroom processing where such patterning is no longer applicable.

The fabrication of surface embedded sensors under wear resistant coatings on three-dimensional (3D) machine parts and other high-tech components require new technologically demanding approaches. The present trans-Nordic COSMOS project (Components and Smart Machines with Micro-Nano Surface Embedded Sensors) has earlier shown successful fabrication of surface embedded sensors on a 2D polished steel substrate [2] and have now successfully fabricated surface embedded temperature sensors on 3D industrial aluminum bolts.

Similar work on 3D substrates is shown by Mihara et al. [3] and Lüthje et al. [4] where thin-film sensors were developed for engine bearings and cutting tools. Our work is based on other deposition techniques for the insulating layer and has a beneficial DLC overcoat.

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3D substrates

There are several difficulties to address in order to fabricate working sensors on traditionally 3D machined metal parts:

1. The metal needs to be electrically isolated which sets new demands on the insulating layers since the surface roughness is typically higher (Ra > 0.1 µm) than for traditional MEMS substrates and therefore has much higher risk for defects and subsequent shortcut of the sensor structure to the substrate.

2. The sensor structure is patterned and fabricated on the surface which requires handling of 3D objects and conformal deposition techniques.

3. An electrically isolating wear resistant coating is required to protect the sensor from mechanical damage under real working conditions.

EXPERIMENTAL

Our device is a customized industrial bolt made of an aluminum alloy on which we have removed two sections of threads leaving flat surfaces along the bolt, as seen in Figure 1. The complete bolt was electrically isolated by plasma electrolytic oxidation of the aluminum alloy forming a porous base layer of amorphous Al_2O_3 with a thickness of approximately 45 µm. To obtain a smoother surface for deposition of the thermocouple the bolt was mechanically polished. An Al_2O_3 base layer has also been synthesized by reactive pulsed DC magnetron sputtering where post-polishing is unnecessary. To reduce the risk of pinholes to the substrate, a multi-layer structure was made in the deposited Al_2O_3 by intermediate back-etching of the deposited film to re-nucleate the growth of the film. Figure 2 shows a SEM image of such a multilayer Al_2O_3 where the lower 1.5 µm is a TiAlN binding layer followed by three layers of Al_2O_3 with intermediate etches. The structure can be seen to go from a clearly columnar to a more homogeneous growth.

Another way to avoid pinholes in the insulating layer is to modify the substrate bias voltage (controlling the ion bombardment) during the deposition process. Altering the bias voltage results in different material morphology, from columnar growth at a negative bias of 30 V to a more homogeneous morphology at 100 V.

A thermocouple type T was fabricated by depositing a 1 µm thick Cu wire from the bolts head along one of the flat surfaces to the top of the bolt using PVD techniques (Figure 1). A second wire of CuNi was subsequently fabricated along the other side of the bolt overlapping the Cu wire at the top. Both wires were patterned using shadow masking technology which offers a simple processing technique suitable for the industry.

The thermocouple structure was buried under Diamond-Like Carbon (DLC) by Ion Beam Assisted Deposition (IBAD) leaving contact holes for the wires at the bolt head (Figure 3 and Figure 4). The DLC coating (Figure 5) has several advantageous physical properties for industrial use, e.g. ultra low friction, fair hardness and excellent wear resistance. The IBAD-DLC is made by evaporation of silicone oil which is decomposed by bombardment of Ar^+ ions with energy of approximately 50 keV.

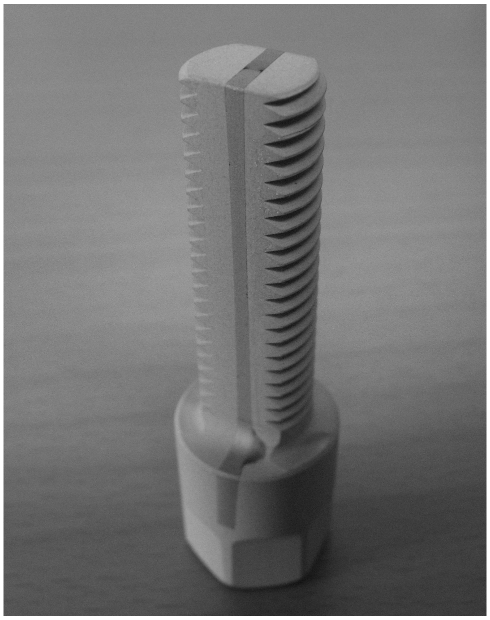

Figure 1: Industrial M10 bolt with a plasma electrolytic oxidized insulating layer and patterned Cu/CuNi wires from the bolts head to the top forming a thermocouple type T sensor structure.

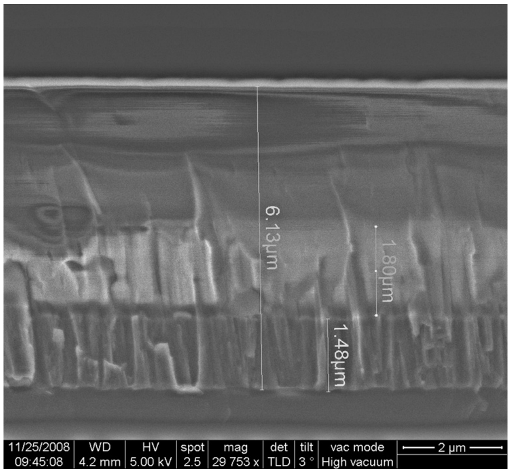

Figure 2: SEM picture of an insulating film of Al_2O_3 with intermediate etches resulting in morphological changes through the film. The lowest 1.5 µm is a TiAlN binding layer followed by three layers of Al_2O_3.

Figure 3: The same bolt as in Figure 1 with a wear resistant DLC coating covering the complete sensor structure except for contacts at the bolts head.

Figure 4: The bolt seen from another angle.

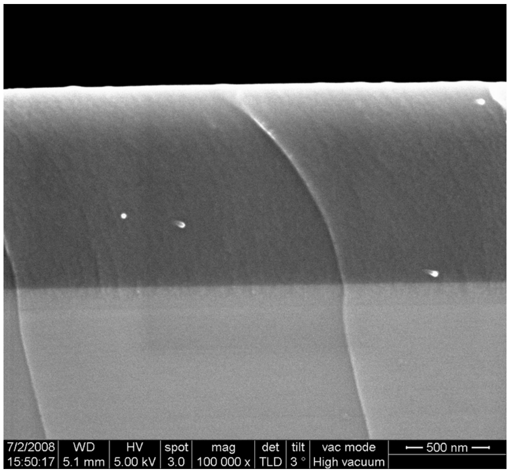

Figure 5: SEM picture of the DLC wear-resistant coating.

RESULTS AND DISCUSSION

Such a type T thermocouple, processed the same way as the bolt, was placed in a convection oven with Cu/CuNi wires soldered to the corresponding open metal contacts on the bolts head. The wires were lead outside the oven where the electrical signal from the bolt was measured using a multimeter. The measured signal is directly related to the temperature difference between the point where the two metals overlap at the top of the bolt, usually called the “hot point”, and the point where the signal is measured, called the “cold point”. To get a correct temperature difference between the hot and cold point we monitored the temperature inside the oven with the ovens built-in mercury thermometer and the room temperature using a conventional liquid thermometer. As the temperature inside the oven increased, the room temperature close to the outside of the oven where the thermocouples cold point was placed also increased. The oven temperature was let to stabilize after each temperature increment to ensure a correct reading of the built-in thermometer.

The temperature response was measured at two occasions to examine the repeatability of the sensor and due to the slow cooling of the convection oven the second measurement was done the following day. The measured oven and room temperatures together with the sensor voltage can be seen in Table 1 and Table 2.

The measured sensor response can be described with a well fitting slightly parabolic curve as a function of the temperature as seen in Figure 6. The measurements from day 1 is seen as solid black squares and from day 2 as black squares with white dots. The complete measurement range from day 1 and 2 shows a very good repeatability of the sensor.

Table 1: Measured temperatures and voltage day 1 [°C, mV].

Oven Temp	23,5	66	100	132	147	164
Room Temp	23,5	23,5	23,8	24,3	24,8	25,1
Temp diff	**0**	**42,5**	**76,2**	**107,7**	**122,2**	**138,9**
Measured voltage	0	1,7	2,8	4,5	5,1	5,8

Table 2: Measured temperatures and voltage day 2 [°C, mV].

Oven Temp	48	60	104	135	156	173
Room Temp	22,0	22,5	24,0	24,9	24,5	24,5
Temp diff	**26,0**	**37,5**	**80**	**110,1**	**131,5**	**148,5**
Measured voltage	0,6	1,1	3,4	4,8	5,9	6,5

There are two error sources that should be considered in our measurements. First we have a poor resolution of reading the convection ovens built-in mercury thermometer. Having a major unit of 5°C we estimate the reading accuracy to be ±1 °C. The second error source, and probably more relevant, is the placement of our thermocouple structure inside the oven. Convection ovens have generally some vertical temperature deviation following the basic physical properties of cold air being heavier than warm air. Depending on the height difference between the thermocouple and the built-in thermometer, there might be some discrepancy between the thermometer read out and real temperature response of the sensor.

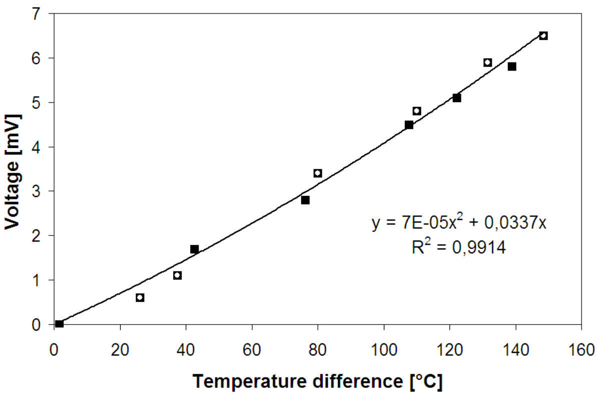

Figure 6. Sensor response for surface embedded thermocouple under wear-resistant coating placed in a convection oven. The temperature difference is measured between the oven and the room temperature.

CONCLUSIONS

The temperature response from our sensor shows the same parabolic characteristics as commercial type T thermocouples. The seemingly systematic measurement error is very likely dominated by limitations in the experimental set-up and not the actual sensor.

We have successfully developed a 3D surface embedded sensor fabrication technology that will clearly benefit the industry by enabling machine parts with built-in sensors. Intelligent surfaces of machine parts allows better process control which can be used for process optimization and as a new tool for condition based maintenance. Adding intelligence to the surface also reduces the need for traditional packaging and placing of discrete sensor components. Not only will such machine parts open up for higher productivity and reduced downtime through on-line control of tools and processes but also enable development of completely new ranges of products based on intelligent surfaces.

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CONTACT

Tommy Schönberg
Acreo AB, Electrum 236, SE-164 40 Kista, Sweden.
Phone: +46-(0)8-632 77 00
E-mail: tommy.schonberg@acreo.se