# Thin Film Sensors for Condition Monitoring in Ball Screw Drives

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**Summary:** The development of sensor pins which can be easily integrated into ball screw drives for preload measurement is described in this paper. The sensor's base body consists out of a steel pin with a special shaped load region. This complex surface is coated and structured with a sensory thin film system based on a hydrogenated carbon layer. The layer shows an excellent tribological stability combined with piezoresistive behaviour. It is shown, that the sensor pins can be used for preload measurements during the mounting and for dynamic load detections during the movement of the ball screw drive. Hence, measurement results are presented, that show the dependency of resistance changes to the preload forces.

**Keywords: Piezoresistive, Thin Film Sensor, Condition Monitoring, Ball Screw Drive.**

## 1. Introduction

Due to their high feed force and positioning accuracy ball screw drives are commonly used in machine tools for the generation of feed motion [1, 2]. In many cases preloaded double nut systems are utilized to increase the axial rigidity and power transmission of the feed drive. Because of inherent rolling friction ball screw drives are subjected to wear processes. Loss of preload caused by friction leads to a changing dynamical behavior of the feed axis. The induced malfunctions of the ball screw drives lead to high expenses in consequence of the resulting production downtimes [3, 4, 5].

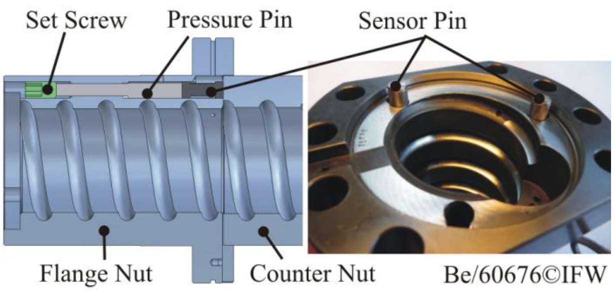


**Figure 1.** Sensor integration concept in ball screw drives.

A concept for sensor integration is developed for direct measurement and monitoring of the pretension in double nut systems of ball screw drives (Figure 1). Steel pins with thin film sensor system deposited in the load region are integrated in three additionally drill holes in the flange nut with a distance of 120°. The pretension can be adjusted and increased by pushing the sensor pins against the face of the counter nut with the set screw and the pressure pin.

Below the development of force sensors with integrated piezoresistive layer is described and the sensor characteristics are identified. Moreover the measurement results are discussed for the integrated monitoring application in ball screw drives.

## 2. Sensor Design

### *2.1. Mechanical design and optimization of the pin*

The specified requirements for the application of the sensor pin in ball screw drives are shown in Table 1. Based on these requirements different pin geometries are designed (Figure 2). At the IFW the mechanical structure of the pins is designed with the finite elements method in varied load scenarios. The analysis leads to the optimized mechanical sensor substrate geometry with slope of 30°. For this reason the sensor pin is optimized to high sensitivity with the largest pressure area and minor mechanical stresses.

**Table 1.** Requirements for the force sensors.

| *Requirement* | *Value* |
|---|---|
| Base Geometry | Ø 8 mm x 20 mm |
| Measurement Range | 0…10 kN |
| Material | Hardened Steel |

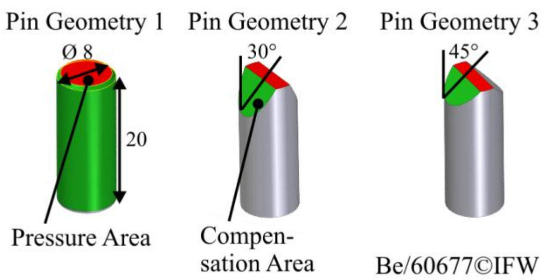


**Figure 2.** Sensor designs und FEA result.

### 2.2. Integration of sensory thin film system

A challenge is the deposition of the sensory thin film system on top of the complex shaped steel pin. The three dimensional structuring of the chromium electrodes needs special techniques. The application of this sensor system directly in the main load region is possible, because of its multifunctionality. It combines piezoresistive behaviour with an excellent wear resistance.

The composition of the layer system is shown in Figure 3. The polished surface of the pins is at first coated with the piezoresistive hydrogenated carbon layer in a plasma assisted chemical vapour deposition process PACVD. The homogeneous thickness of this sensory layer is about 6 µm. The surface hardness of the layer is between 15 and 30 GPa in conjunction with a young modulus up to 270 GPa [6, 7]. This piezoresistive layer is contacted by a chromium layer, deposited in a physical vapour deposition process (PVD). Its thickness is approximately 400 nm. The metallization is structured by photolithography and chemical wet etching in order to fabricate electrode structures and contact pads, as it is shown in Figure 4. The electrode area, the underlying piezoresistive layer and the substrate are forming the actual measurement element. For the purpose of electrical isolation and wear protection the layer system is covered homogeneously with a hydrogenated carbon coating, modified with silicon and oxygen. This top coat is deposited in a thickness of 3 µm in a PACVD process.

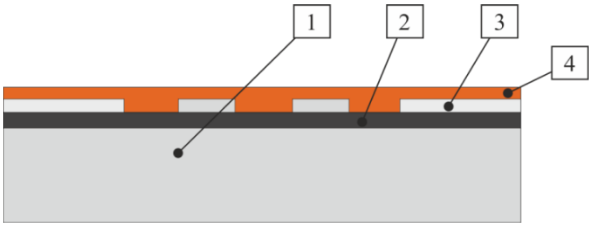


**Figure 3.** Design of the sensory thin film system: 1-substrate, 2- piezoresistive sensor layer (6 µm), 3-structured chromium layer / electrodes (400 nm), 4-insulating, wear resistant layer (3 µm).

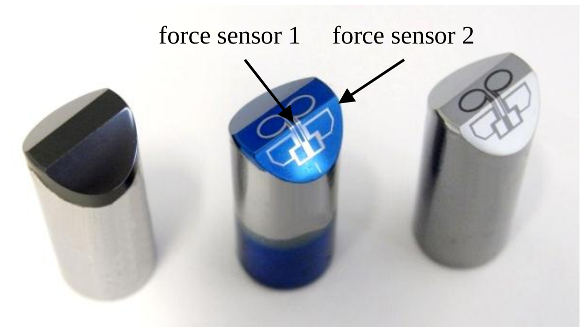


**Figure 4.** Steel pin with piezoresistive layer (left), chromium layer (middle) and structured electrophoretic resist (before wet etching) and structured chromium electrodes (after wet etching, right).

Until now this thin film sensor system is successfully integrated directly in the track of inner bearing rings for the detection of load distribution, unbalance and the beginning of pitting [6]. Also sensor modules are deposited with this layer system as a control and optimization tool for deep drawing processes [7]. Sensory washers are also in development as an universal insertable measurement system for screw joints [8, 9].

## 3. Characterization and calibration

### *3.1. Characterization results*

The piezoresistive behavior of the sensory pins was characterized in a test bench at the Fraunhofer IST. Three load-unload cycles were applied by the polished surface of a counterpart directly onto the load area of the pin and simultaneously the resistance change of each sensor system was measured. The measurement results are shown for both sensor systems (force sensor 1/2) of a pin in Figure 5. There is a linear dependency between the layer resistance and the applied force.

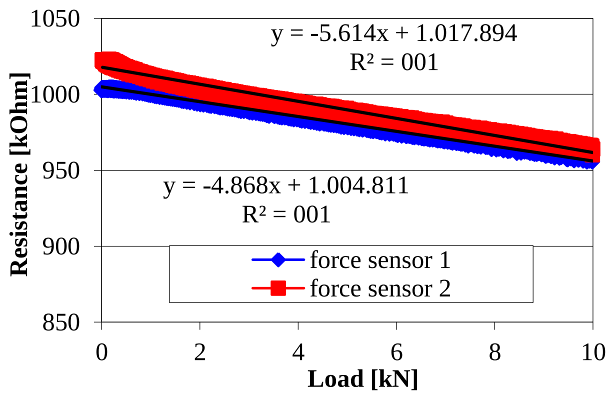


**Figure 5**. Linear dependency between thin film resistance and load of two sensor systems at a pin ($R^2$: coefficient of determination).

### *3.2. Calibration results*

Furthermore three sensor pins were calibrated with uniaxial stepped force profiles in the preferred measurement range up to 5 kN at a test bench at the IFW. Referenced by a piezoelectric reference sensor (Kistler, 9251A) the force characteristic was identified. The good correlation of the output signals between the reference sensor and the sensor pin is shown in Figure 6. The identified characteristics can be used for the determination of the corrections and thus for digital compensation of the measurement error.

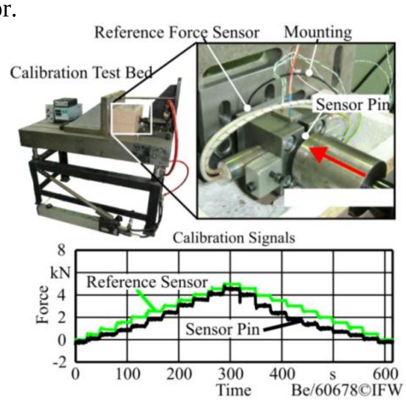


**Figure 6.** Test bench for sensor calibration and measurement results.

## 4. Measurement results

The uncalibrated sensory pins were attached into the double nut system of a ball screw drive (Figure 7). In a static test set-up the screws of the double nut system were tighten with a defined torque. The resulting load on the sensory pins was recorded simultaneously. The load application to the sensor surface as well as the re-attaching to the torque production is shown in Figure 8.

In a second set-up the preload forces were recorded dynamically during the motion of the ball screw drive at speeds of 1 m/min and 4 m/min. The results of the dynamic tests are shown in Figure 9. The measured changes in resistance are directly dependent on the variation of the preload force resulting from the tumbling motion of the two nut halves due to systematic manufacturing errors, as it is shown in [5].

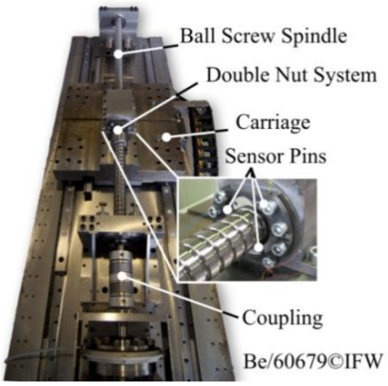


**Figure 7.** Test bench for ball screw drives.

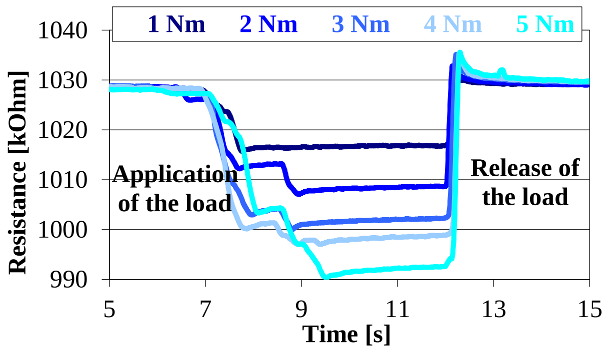


**Figure 8.** Static load measurements with thin film sensor systems.

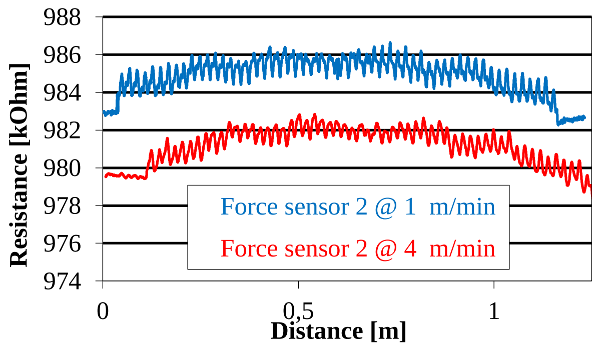


**Figure 9.** Dynamic measurements with thin film sensor systems during motion.

## 5. Results and Conclusion

The development of the thin film sensor system based on the piezoresistive hydrogenated carbon layer was successful in two ways. Through the introduction of electrophoretic resist it is possible to realize sensory coating on curved surfaces. With flexible masks the lithographic step was well done, as it is shown in the middle of Figure 4.

The sensory pins can be easily integrated in the double nut system of the ball screw drive as it is shown in Figure 1. The measurement of preload during the mounting is possible as well as the detection of the dynamic load change during the movement of the ball screw drive.

Due to the fact, that the thin film sensor developments on steel pins show good results in ball screw drives it should be a promising solution as an universal insertable sensory element. In the future it should be integrated in other machine components like bearings as a controlling and measurement system.

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