# Encapsulating Piezoresistive Thin Film Sensors Based on Amorphous Diamond-Like Carbon in Aluminium Castings

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**Summary:** The paper describes a new approach for the in-process integration of sensors into lightweight metal components made of aluminium and fabricated by casting. It examines the suitability of DiaForce® thin film sensors based on piezoresistive hydrocarbon layers (DLC) for integration in molten aluminium. In contrast to previous research, a technology is introduced which will allow real-time measurement of both dynamic and static loads for the detection of permanent deformation of cast aluminum parts. The results show that the DiaForce® thin film sensors maintain their sensory function in spite of contact with molten aluminium at a temperature of 700 °C. Thus a novel approach for series production of castings with embedded sensory function for health monitoring and detection of mechanical overcharge is established.

**Keywords: Casting, Aluminium, Sensor Integration, Dlc Thin Film Sensor, Casttronics.**

## 1. Introduction

### *1.1. Motivation*

To produce metal-based near net shape components, casting is one of the most important manufacturing technologies. Especially for large-scale series production of castings made of light metal alloys like aluminium, high pressure die casting is state-of-the-art because of its productivity. The enhancement of castings with electronic functional devices like sensors and transponders is a new approach grown up during the last years, to increase the added value of castings and to build up new unique selling points for the German foundry business. Such kind of smart and intelligent cast parts are able to sense their loadings, like compressive and tensile stresses, for real time health monitoring of their structural state. The widespread implementation of such monitoring systems for metal castings has so far failed because of a lack of appropriate sensor systems and joining techniques. Sensor systems such as piezoelectric sensors, or the widely used strain gauges (SGs), are well-established measurement systems that are cost effective on the market. But these solutions can only be applied to the surface of the components and require a permanent operational use of expensive protective measures against external environmental influences, adverse media such as oils, acids or alkalis, and against contaminations. Moreover, these conventional sensor systems offer no opportunity for condition monitoring directly in the component, at the point of impact and damage.

### *1.2. Preliminary work*

Preliminary investigations with piezoelectric sensors based on PZT ceramics have demonstrated the technical feasibility of an in-process embedding of sensory elements in aluminium castings [1, 2, 3].

All of these approaches used piezoelectric sensors in form of monolithic or multilayer stacks [1] or patches [2, 3]. These sensors have shown excellent properties for acquisition of dynamic load change at high frequencies in the cast component. The disadvantage here, however, was well-founded in two different aspects. On the one hand side, the piezo-ceramic material is not very temperature resistant, its usage temperature is restricted to 200-300 °C at the maximum because of the curie-temperature. On the other hand, piezoelectric sensors are not able to measure static loads and deformation, but can only monitor dynamic loads [4].

## 2. Piezo resistive thin film sensors (DiaForce®) adapted to the casting process

The present approach shows a new evolution step in Fraunhofer research for an in-process embedding of sensors into aluminium based castings directly during the casting process.

Instead of piezoelectric ceramics, thin film sensors based on piezoresistive hydrocarbon layers (diamond like carbon coatings – DLC) are investigated. These special thin film sensors of the DiaForce® type are developed and manufactured at the Fraunhofer Institute IST (Braunschweig). For the present investigation, samples were designed, coated, structured and sealed with the protective insulation layer SiCON® specifically for an existing experimental die cast mold at Fraunhofer Institute IFAM (Bremen). The casting experiments, namely high pressure die casting of aluminium, were subsequently performed at Fraunhofer IFAM.

### *2.1. Performance and advantages of piezoresistive thin film sensors*

A DiaForce® sensor is characterized by its multi-functionality, as it changes its electrical resistance under load and combines this capability with high tribological resistance. The hardness is about 24 GPa and the coefficient of friction against steel about 0.18. The overall thickness of a complete thin film sensory coating with DiaForce® is in the range of 9-10 µm and therefore DiaForce® allows embedding even in the main loading zones.

The expected advantage of using the DiaForce® thin film sensor is its excellent tribological resistance against mechanical loads as well as against high temperature impact. In comparison to the preliminary work [1, 2], the abolition of an additional insulation layer is facilitated. Furthermore, the geometric dimensions of a thin film sensor will be much smaller than those of conventional piezoelectric ceramic based sensor elements, a crucial advantage with respect to embedding sensors into thin-walled aluminium castings. Moreover, a piezoresistive measuring principal opens up the possibility to monitor even static loads and deformations in the castings.

*2.2. Design of the sensor structure*

For the integration experiments, an existing casting mold at Fraunhofer IFAM is used. Specific tailored sensor samples were prepared, build-up on 1 mm thick stainless steel sheets which are geometrically adapted to integration in the molding tool using a special fixing technique. To this end, the sensor design is following a T-shaped layout contour [see Fig. 1].

The horizontal bar will be poured directly in the aluminum and comes into contact with the molten metal. In this area the sensory electrode structures are placed for measuring compressive loads. The vertical bar is used to fix the specimen in the mold [see Fig. 3]. Electrodes and contact pads that have to be separated from contact with the molten metal are positioned here. After casting they are outside the aluminum matrix and available to be connected to the circuit analyzer. For better soldering of the measuring connections, the contact pads are additionally coated with gold. The state shown in Fig. 1 is before finishing with protective coating layer.

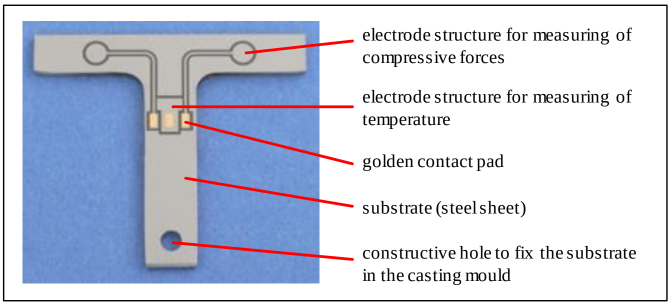


**Figure 1.** Layout of the structured thin film sensor.

The manufacturing process of the DiaForce® coating covers six production steps, performed at Fraunhofer Institute IST [cp. Fig. 2]. As first step, the basic body of the sensor sample (1), the substrate, is surface polished (2). Afterwards the piezoresistive sensor thin film DLC layer can be deposited (3). Subsequently, the sensing layer is coated with a chromium-electrode layer on top (4) and the described electrode structure is worked out (5). The finished sensor system is finally coated with a silicon-oxygen-doped SiCON® layer (6) which provides electrical insulation of the sensor layer on the one hand side and guarantees high tribological resistance on the other hand.

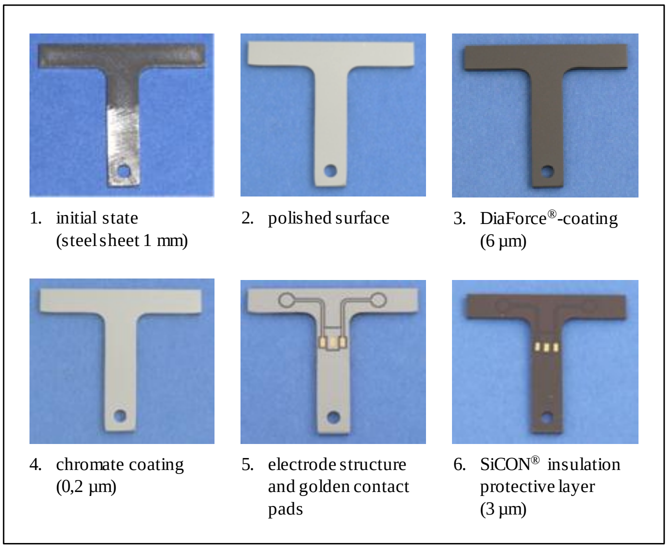


**Figure 2.** Process chain of coating and structuring the DiaForce® based thin film sensor for experimental work with casting.

Normally, the SiCON® layer serves as a friction-wear protection layer, but the present work has shown that SiCON® is also thermally very stable and resistant enough to serve as an insulating protective layer during the casting of aluminum.

*2.3. Characterization of the functional capability before casting*

With the method presented, various sizes and shapes of the sensor structure were realized. The sensor samples were tested for their sensor signal measured in the initial state and characterized. In the following, the results are shown based on the example of a sample with circular electrode design of 2 mm diameter. The other variants of sensor structures and samples show similar results.

The samples produced for experimental casting show the characteristic curves typical for DiaForce® thin film sensors. In the unloaded state, they have an output impedance of ~ 240 kohms. Under compressive loads, the thin film sensor responds with a decrease in its electrical resistance. Figure 3 shows a representative example of a force-resistance characteristic curve diagram. A linear dependence of the electrical resistance on the compressive load of approximately dR/dF ~ 15 ohms/N is recognizable.

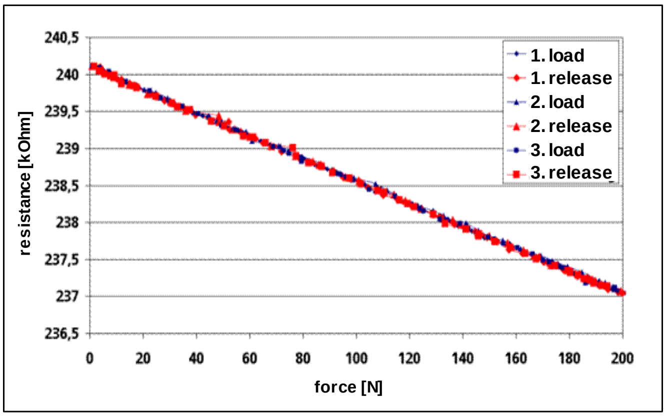


**Figure 3.** Measurement results before casting in aluminium.

## 3. Encapsulating the sensor in an aluminium casting

### *3.1. Experimental Work*

For the experimental work a real-time controlled die-cast unit ‘BÜHLER SC N/66’ was used with locking force of 6,616 kN. As molten metal aluminium melt type ‘AlSi9MgMn’ (Silafont-36) was used and teemed at 700 °C. The temperature of ejector die and cover die was set to 240 °C. The sensor pattern with thin film sensor coating was manually plugged into the casting mold and fixed in it with a patented, pluggable metal core developed at Fraunhofer IFAM, which was approved in previous encapsulation work for the integration of piezoceramic actuators [cp. Fig. 4]. After the casting process, the casting was ejected and quenched down in water.

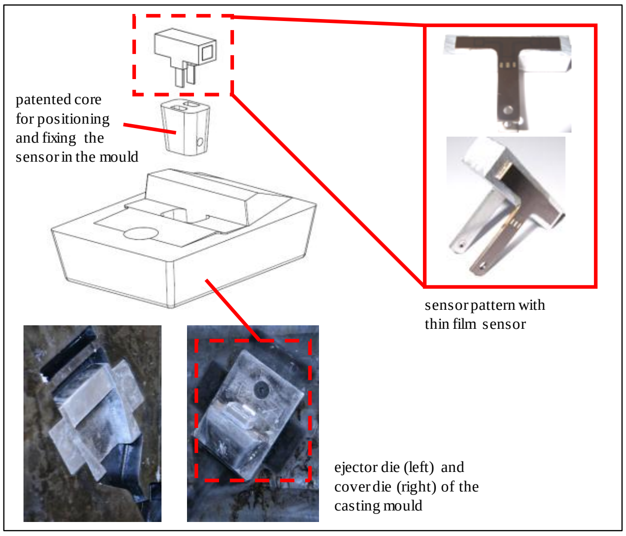


**Figure 4.** Positioning and fixing of the sensor in the mould.

### *3.2. Characterization of the functional capability after casting*

The encapsulated sensors were measured similarly to the procedure presented in 2.3 [cp. Fig. 5].

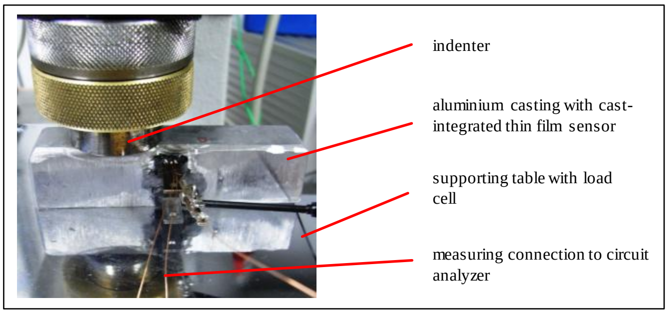


**Figure 5.** Measurement setup for characterization of the functional capability of the embedded thin film sensor after casting.

After direct contact of the sensor with the molten aluminium at 700°C a change is observed in the output resistance of the thin film sensor. After casting, the linear dependence is shifted to much lower resistance. In unloaded state, the sensors output impedance is about ~ 35.7 kohms. The resistance change is also reduced to approximately dR/dF ~ 0.06 ohms/N. However, the sensitivity of the sensor system (described by the relative change in resistance per Newton based on the output resistance of the uncompressed sensor system) remained unchanged. The resistance of the temperature sensor structure, which was located outside of the molten metal, remained unchanged as well. The linear dependence of the sensor resistance on stress level after encapsulation is shown in Fig. 6.

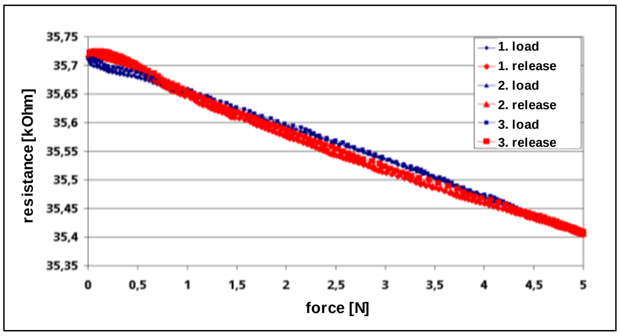


**Figure 6.** Measurement results after casting in aluminium.

## 4. Conclusions and Outlook

The experiments have shown that the DiaForce® thin film sensor characteristics decrease to lower output resistance when encapsulated in molten aluminum due to the thermal influence it is subjected to in the process. However, its general capability as sensor remains unchanged. The investigation indicates that the thin film sensor is affected by the thermal flux during casting, but its functionality is stable. Furthermore, providing the thin film sensor with a chromium-electrode structure and an electrically insulating coating with SiCON® results in a thermally robust solution for the embedding by casting of piezoresistive DLC sensor films in aluminium.

Future studies are planned to increase piezoresistivity by further optimization of the thin-film system and thus increasing its sensitivity. At the same time, investigations will follow that consider the thermal effects closer to the thin film sensor. Furthermore, the connection of sensor elements to the casted material structure can be improved. The aim is to apply the DiaForce® sensor for the casting of aluminum in other casting processes (e.g. gravity die casting).

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