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Integrating sensors in castings made of aluminum – new approaches for direct sensor integration in gravity die casting

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Abstract

Structural health monitoring relies on mechanical and thermal measurements of the component. Whereas for a strain gauge on the surface of a component a structural model is needed to gain knowledge of the internal state at the point of interest, integrated sensors can measure strain and temperature directly inside the component without the influence of adhesives required to mount the sensor on the surface.

Integrating sensors in gravity die casting leads to certain requirements. The Sensors have to withstand the harsh conditions of the casting process at temperatures around 750 °C and a shrinkage of 1.1 % during solidification of the melt. The yield of embedded sensors can be increased, if the sensor-substrate is based on the same coefficient of thermal expansion, which reduces stress during the cooling phase and at the solidification point of the melt through shrinkage. Aluminum as substrate keeps the amount of foreign matter in the casting good at a minimum.

In this paper we present the first approach to integrate sensors on aluminum substrates during gravity die casting. The design, fabrication and embedding of screen printed thick-film sensors is shown. The embedded sensors are examined before and after their integration into gravity die-cast aluminum in terms of thermal behavior and diffusion.

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1. Introduction

There is a strong trend in industries towards intelligent components which can provide useful information about their physical condition [1]. Knowing temperature and strain values at critical locations of such a component can help to reduce material while maintaining the strength itself. Furthermore, an existing component with embedded sensors will allow to supply real-time data in operation mode. This information can be used to prevent failing or overload. Machine learning and artificial intelligence can help to optimize the operating parameters, for example, a good real-time chassis adjustment can minimize the emitted noise of a car if all necessary information is available. Autonomous cars will benefit from additional information to be aware of the environment and provide a safe operation [2,3]. Measurement data can either be generated by external sensors like surface-mounted strain gauges, or by internal material-integrated sensors, e.g. to measure strain in fiber reinforced epoxy [4-6]. Material-integrated sensors can measure directly at the point of interest and they are enclosed by the component. Besides, for external sensors, a model is required to derive physical quantities at the point of interest and a harsh environment requires additional protection against corrosive conditions, contamination or mechanical damage. To benefit from material-integrated sensors we have to get on top of new challenges. A material-integrated sensor is a foreign body in the component, which will change the properties in terms of mechanical strength and thermal conductivity. In production, sensors that are integrated in aluminum cast metal components have to withstand high temperature and pressure which vary depending on the casting method.

Until today there are only a few publications available which demonstrate the integration of different sensors in cast aluminum processes. In high pressure die casting (HPDC) thermoelectric generators and piezoceramic modules where successfully embedded [7,8]. The main characteristics of HPDC are the high temperatures at short dwell times, the process specific high pressure and rapid filling velocity of the aluminum melt. The focused casting process in this paper is gravity die casting (GDC). The characteristics of this process are a mechanical and thermal reversal of those observed in HPDC: while melt temperatures are about the same, dwell times are longer due to lower cooling rates. Thermal loads are thus increased, whereas the order of magnitude of the filling pressure, and thus the mechanical load matches atmospheric pressure. In [9], Kobilska et al. have shown, that it is possible to successfully embed thin-film sensors in cast aluminum using GDC. In this first approach with GDC, we wanted to find out if it is possible to integrate thick-film sensors on aluminum substrates and which changes occur regarding the sensor.

2. Thick-film sensor manufacturing

The main reasons why common sensors fabricated on silicon fail, when embedded in aluminum castings, is the great difference between different coefficients of thermal expansion (CTE) with $\alpha_{Si} = 2.6 * 10^{-6} K^{-1}$ and aluminum $\alpha_{Al} = 21 * 10^{-6} K^{-1}$, high compressive stress is induced in the silicon substrate during cooling phase and solidification of the melt [10]. Hence, the sensor is applied on AlMg3 aluminum sheets as substrate, this way stress through different elongation coefficients can be minimized, as well as the amount of unnecessary foreign matter in the cast good. The sensor is manufactured by screen printing directly on the aluminum substrate. The sensors outer shell consists of the dielectric glass ink to protect the sensor from a short. A resistive ink based on ruthenium and bismuth is used as sensor element, which is connected through an overlap with a conductor ink based on silver particles. The used ink system is adapted to aluminum and can be applied by screen printing [11]. After printing and levelling, each layer is dried for 15 minutes at 150 °C to remove the solvents. The dried layer is sintered at a peak temperature of 550 °C for two minutes with a dwell time of 30 minutes in a furnace. Three dielectric layers are used to avoid any pinholes between the conductor-resistor system and the substrate, as well as three layers on top, to insulate the sensor completely. Between the dielectric layers one conductive and one resistive layer is applied.

To examine diffusion two sensor designs are realized. Design A with a detached part of 1x3 mm as well as design B with a 1x1 mm detached part are applied, as can be seen in fig. 1. Trough high temperature materials lead to diffusion, while production in the sintering process and while embedding through the high melt temperature. If diffusion occurs, design B with 1x1 mm would change its properties faster, because it has less detached space and is therefore more vulnerable for diffusion from the conductor. The inner U-shaped line is a test for the conductor. Fig. 1 (a) shows, that the three insulating top layers omitted at the contact pads for later investigation.

In total, eight layers are individually printed and fired to build up a sensor, which can be integrated during casting. Each layer is 20 µm thick, so the overall sensor is 160 µm thick. This leads to a total foreign matter below 0.05 cm³.

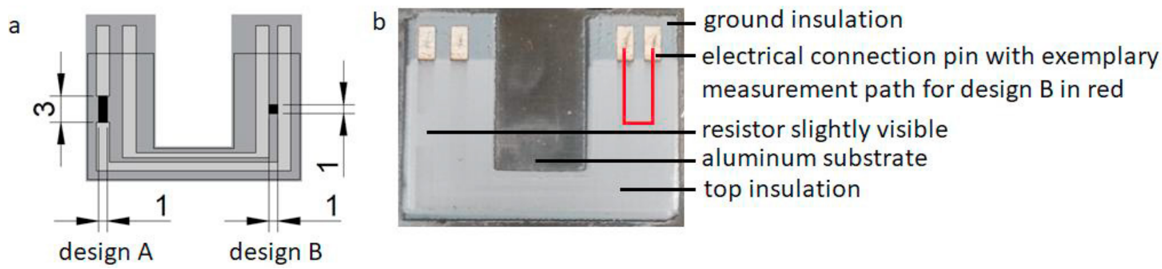

Fig. 1. (a) layout of sensor design A and B with different detached sensor geometries;
(b) picture of a fabricated sensor with contact pads for electrical measurement.

3. Embedding the sensors while gravity die casting

GDC is a permanent mold casting process where molten metal is poured from a vertical position into a mold at atmospheric pressure. The two mold halves are closed before the molten metal is poured in. After solidification of the melt, the mold halves are opened for releasing the cast component. Advantages of this manufacturing process are low amounts of trapped air or gas within the mold. It is a well-suited method for large and thick wall components as well as for components with a high degree of details. Components manufactured with GDC are typically of complex geometry such as cylinder heads or pistons [12].

3.1. Mold and sensor substrate

The permanent GDC mold used consists of two symmetrical mold halves with two inserts. The mold is designed to insert a plate (2 x 25 x 100 mm). Besides the runner there are four risers, two risers on each half. The manufactured cast component without runner and risers has dimensions of 34 x 34 x 205 mm with semicircular grooves along the long side on top and bottom. The component has a volume of approx. 0.185 dm³. For preheating the mold is equipped with heating rods which allow heating the mold up to 400 °C.

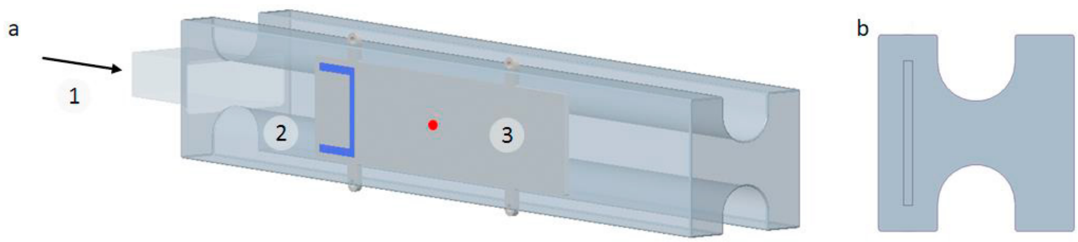

Fig. 2. (a) manufactured cast component with embedded sensor substrate used for experimental testing, schematic figure of flow in of aluminum melt (1), cast aluminum component (2), aluminum substrate with thick-film sensor on the left side and sheath thermocouple in the center (3); (b) cross section of the cast aluminum component.

The sensor was protected from direct contact with the 700 °C hot melt, because the sintering process takes place at 550 °C, pouring 700 °C hot melt directly on the sensor would lead to a viscosity of the inks which might lead to washing them away with the inflowing melt while the mold is being filled. Fig. 3 shows two protection variants, AlMg3 plates were used, with a glued bonded joint and a copper wire wrapping. Other variants consisted of wrapping commercial aluminum foil around the sensor or applying a layer of aluminum oxide on top of the sensor.

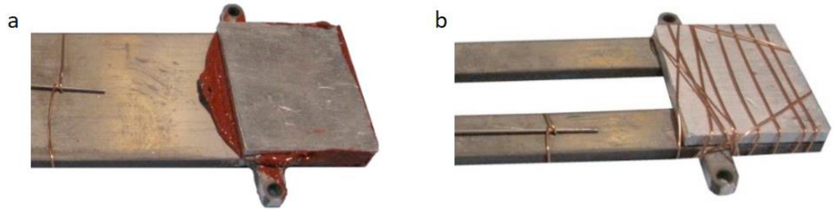

Fig. 3. (a) sensor substrates with contact pad protection plate glued onto the substrate with high temperature resistive silicone; (b) protection plate wrapped with copper wire; both sensor substrates with attached thermocouple.

3.2. Conducting of the casting experiment

It is a major challenge for embedding of sensors in aluminum to ensure that the sensors remain in position throughout the entire casting process. A series of pretests was necessary in order to estimate the ideal temperatures of the preheated mold and the aluminum melt. Evaluation and determination of the pretest results were entirely based on casting criteria such as complete mold filling and demoldability. The minimum acceptable pretest series results indicated the test temperatures for preheating and aluminum melt, thus the temperature profile for the embedding process.

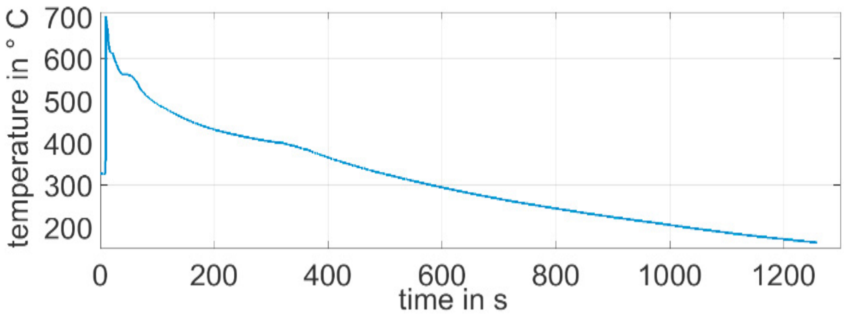

Fig. 4. Temperature over time profile of the casting process measured with a sheath thermocouple.

The cast aluminum used was Anticorodal 70 (AlSi7Mg0.3) and it was heated up to 750 °C. Each mold half contains heating rods controlled by type K thermocouples in a closed loop circuit, therefore the mold was stably tempered at 350 °C before casting.

The substrate with the sensor element was inserted inside the mold via four small insertion pockets in order to minimize the common contact area between substrate and mold. The distance between sensor element and wall of the mold is about 4 mm. A sheath thermocouple (Ø 0.5 mm) of type K was attached centrally onto the substrate (fig. 3) for measuring the temperature during the experiment in close proximity to the sensor element.

The filling of the cast aluminum into the mold with a ladle began when the temperature of the substrate reached about 325 °C. As the curve in fig. 4 shows the temperature of the substrate reached its maximum at 699 °C immediately at the beginning of filling. Cooling of the cast aluminum melt starts with an average (659 to 617 °C) cooling rate of 11.7 K/s, hence the melt remains in its liquid state for approx. 6.5 seconds before the solidifications sets in at about 618 °C. With progressive cooling and an average (602 to 563 °C) cooling rate of 2.8 K/s the solidification is completed at about 560 °C. Both begin and end of the solidification process go along with very high but short cooling rates. After 180 s since filling the demolding process began and was completed after 300 s. Cooling after completed solidification continues with an average (545 to 397 °C) rate of 0.56 K/s before and an average (397 to 163 °C) rate of 0.25 K/s after demolding.

3.3. Test results

The cast components were X-rayed afterwards in order to investigate the quality of the sensor embedding process. Due to the uneven ratio of thickness between the substrate and the cast component the generated images provide a rough overview only. Fig. 5 shows the X-ray image of an embedded sensor substrate. The contour of the substrate inside the cast component can be seen at the top and at the bottom, which means that the substrate remained in nominal position. The melting point of the AlMg3 substrate is approx. 600 °C [13]. During the experiment the dwell time above 600°C was about 14 s. No local melting of the substrate can be detected. One explanation can be, that during the sintering process of the thick-film inks the native aluminum oxide layer of the substrate increases, which protects the AlMg3 substrate from being fuzed.

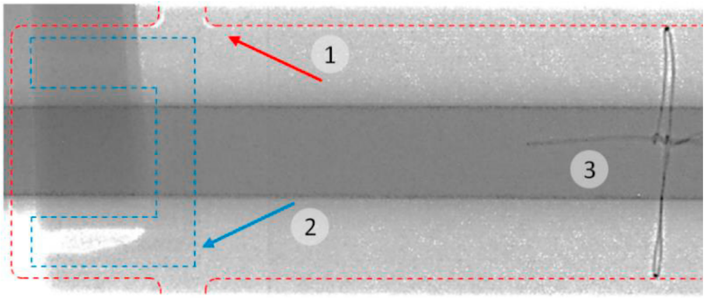

Fig. 5. X-ray image of the embedded sensor substrate in cast aluminum, contour of the substrate (1), conducting paths (2), thermocouple (3).

4. Sensor characterization

In fig. 6 a thermal characterization of the sensors is presented. It shows the linear relation between temperature and resistance for two states of both designs. The first state is the behavior right after fabrication, before casting.

The second state shows the behavior of the sensors after casting and baring. It can be seen that there is a difference between design A and B right after fabrication. Diffusion of silver from the conductor leads to a decreased slope even while fabrication, thus the temperature of 550 °C while sintering leads to diffusion. After the embedding process, it appears that there is a decreased slope in the temperature resistance behavior for both designs. The temperature exposure while embedding leads to further diffusion of silver particles into the resistor.

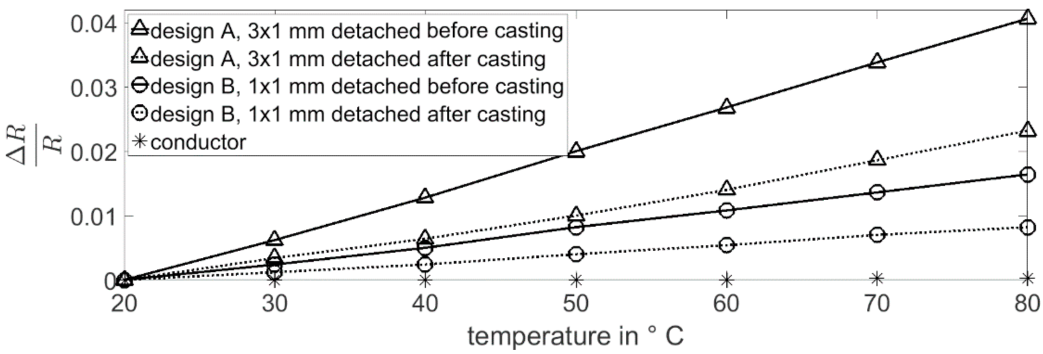

Fig. 6. Change of resistance with temperature for both sensor designs before and after embedding.

The conductor showed no significant change and its temperature resistance change behavior is three orders of magnitudes smaller than the one of the sensor, which can be seen exemplary near the x-axis of the graph.

For the measurement of strain, the sensor needs to be positioned at a specific point inside of a new mold to cast tensile specimens or specimens, which can be used to perform a 3-point bending test. In [14] we already showed, that the 3-point-bending test is an appropriate method for the characterization of casting embedded sensors.

5. Conclusion

We presented the fabrication of a screen printed sensor on an aluminum sheet which was integrated while gravity die casting. Based on the temperature-time integral, gravity die casting demands the highest requirements of a sensor caused by the highest overall heat exposure scenarios. The sensors are able to survive the embedding process, even though, the direct contact with aluminum melt was impeded through protection. The sensor survived the thermal shock while filling the cast aluminum and high compressive stress while cooling and solidification. Diffusion was observed while fabrication and casting. Further experiments have to focus on a material joint connection as examined in [15] and a feed line, which protrudes out of the casting good for direct examination without baring the contact pads. With adopted sintering parameters and longer detached sensor parts, the sensitivity of the sensor can be improved. By replacing the silver conductor with a material, which has a higher melting point and a lower tendency for diffusion an increased temperature resistance could be achieved.

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