In-Process Embedding of Piezo Sensors and RFID Transponders into Cast Parts for Autonomous Manufacturing Logistics

Dipl.-Wi.-Ing. Christoph Pille[1,2]

1) Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM), Dept. Casting Technology, Bremen, Germany
2) Chair in Near-Net-Shape Manufacturing Technologies, Faculty of Production Engineering, University of Bremen, Bremen, Germany

1 Introduction

Casting is the most important manufacturing technology for production of metal-based near net shape components. Their enhancement with electronic components for advanced functional abilities with additional assembling technologies is state-of-art for today's cast parts, but the conventional way of application is complex or costly, particularly for large-scale series production like in automotive applications. Such kind of smart and intelligent cast parts are able to sense their loadings, compressive and tensile stresses or vibrations for health monitoring of the structure, to control the distortion of their material actively or to retain and transfer product-related data, especially in autonomous manufacturing logistics. This approach shows a new technology method being investigated for an in-process embedding of electronic components into the cast part. The specific of this method is that the electronic functional components such as sensors, actuators or RFID transponders get integrated directly during the casting process. In this way the embedded electronic is protected from contamination, damage or loss – during subsequent mechanical machining processes on the casting, during assembly steps and in operational use. Furthermore, the connection of sensor and actuator elements to the material structure can be improved

2 Fields of application for function integrated castings

Integrated sensors detect mechanical and thermal stress or deformation as well as vibration inside the casting – right at the spot of appearance respectively impact. Embedded piezo sensors offer the determination of stresses to evaluate its live time cycle on schedule. The sensor data can be ascertained in real-time for a health monitoring to warn against current overstress and damage of assembly parts – especially for safety castings a crucial advantage. With their actuatory skills integrated piezo sensors additionally offer the ability of active vibration damping inside the parts structure for an active engagement in its behavior (Structure Health Control). Cast-in transponder allow part identification voidly intervisibility as well as wireless power and data transfer to store information within the part, e.g. a unique serial number, parameters of manufacturing orders or an electronic genuineness certificate for protection against plagiarism. These transponder are inseparable

ISBN 978-3-8007-3208-1

joined with the part due to casting integration and enable the communication as well as the data exchange between the casted part and the production process. Stored information about the life time cycle of a product can be used to optimize processes and quality assurance. Moreover, from the integration of communicative skills directly since ‘birth’ arises the opportunity for an autonomous routing of castings through a manufacturing process. The vision of autonomous logistics should give products the ability to adapt themselves to the actual production situation and to react to troubles within the process by using autonomous methods. Only an identification technology that offers unique identification of a product right by its emergence and the ability to add and save information throughout the production cycle can turn a common data bus between working stations and central control system down [1]. This is a precondition for the development of a local and autonomous production control.

Advantages and sample applications are shown by means of casted demonstrators. Inside the sample ‘function integrated pedal crank’ two integrated piezo sensors measure the compressive and tensile stresses being induced during operation. On the other hand another sample demonstrates the cast-embedding of a RFID transponder for product identification without an intervisibility required and technological basis for autonomous manufacturing logistics.

3 Motivation for development of cast-embedding technologies

Nowadays according to the state-of-art castings are enhanced with electronic components by using conventional joining technologies, e.g. by screwing or bonding. These conventional joining technologies, however, represent an additional production step, which in turn usually requires more preparation steps like special pretreatment of a surface or mechanical treatment of a screw connection. Through this the process chain is extended needlessly as well as the added value decreases. In some cases certain application methods are absolutely inexpedient for connecting electronics with castings. For example, a typical method for the connection of piezo sensors with the surface of a part is the application of an adhesive layer between them [2]. The adhesive layer can work as a buffer between sensor and the distortions or vibrations affecting in the part and falsify the measuring result. Besides, the measuring result can be affected negatively by ageing of the adhesive layer. A direct integration of the sensor in the part right to the spot where the stress should be measured and a positive fitting connection of the sensor to the material structure would offer three advantages compared to the state-of-technology: an improved connection of the sensor for optimal sensor signals, the prevention of variation of the sensor signal due to the ageing of an interlayer and the secure protection of the sensor against external damage. In research possibilities for integration of piezoelectrical components into castings are investigated, but so far there is no possibility for a well-directed, local integration of those elements without affecting the surrounding cast structure [3].

Embedded RFID transponders would likewise attain protection from external damage during machining processes as well as they offer a tamper-proof genuineness certificate. Such applications of casted parts, where it is essential that functional

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components and the part have a positive fitted integration, are rather complex or simply impossible to construct with common joining technology. To this the casting technology offers a wide and manufacturing technical potential to optimize the integration of electronic functional components. This is done during the emerging of the product by casting the components into the parts structure, like an implantation. This means the integrated components are placed inside the casting mold and become embedded by the conventional die-cast process. This provides an opportunity to produce intelligent casted parts in one production step.

4 Challenges to the in-process embedding during a die-cast process

The major challenge to the in-process embedding technology is to shelter the sensitive electronic components from the high temperature of molten metal and compression load resulting during the pressure die-cast process. Furthermore, the electronic component has to be fixed in position in the casting mold, useable for a large-scale series production. For developing a technology to cast-in electronic functional components some general, fundamental questions need to be taken into consideration:

- In which position inside the part should the functional component be integrated to function properly?
- What kind of electronic is suitable for the intention?
- How to protect the electronic component against high temperatures of the melt and what kind of insulation materials are suitable?
- How to ensure a positioning of the embedding component in place and to fix inside the casting mold to resist high casting rates and pressures during redensification.
- How to communicate with the embedded functional component?

The following contribution illustrates the development stage for the in-process embedding of RFID transponder and piezo sensors, each with the help of one exemplary demonstrator sample.

5 Technology development for in-process embedding of RFID transponders

In the manufacturing process chain for castings with afterwards machining specific demands to the identification of the cast part are made. The identification of must be guaranteed from the first production step, as soon as it leaves the molding tool. That means, „beginning just from the birth” of the casting a possibility to allocate the part to a manufacturing order is necessary. The conventional procedures of marking casted parts do not allow a unique marking at single-product plane as a result of their humble information density. The most widely used techniques for the identification of cast parts with a comparatively high information content are engraving or laser cutting of barcode and data matrix code (DMC) on the surface of the part. Due to their sensitivity and low robustness these techniques are only limited usable [4, 5].

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The identification mark must withstand over all manufacturing and machining processes being damaged. For example, on the surface applied information can be damaged or even completely destroyed quickly during blasting or varnishing. One possibility is the usage of RFID transponders which are widespread in the field of the animal identification and also belong to the state-of-art technology product marking, first of all in the field of logistics.

5.1 Functional principle of RFID transponders

The functional principle of the RFID technology is based on the transmission of information and energy via radio waves. At first an electro-magnetic field is generated with a reader. By placing a RFID transponder within the electro-magnetic field a current is induced in its antenna, which can be used as energy supply for the activation of a microchip located on the transponder. In order to realize the communication with the reader the received electro-magnetic field is modulated by the microchip. According to the changes of the field strength due to the modulation the transmitted signals can be detected by the reader and then decoded into the information stored on the microchip, e.g. the unique serial number or stored manufacturing parameters. During the metalliferous process these sensitive electronic transponders, which are mostly located on the surface of the parts, are heavily burdened due to the aggressive cooling lubricant or surface machining. Furthermore the working frequency of the transponder can be disrupted in the metallic environment, so that the radio frequency based technology is not suitable for the identification of the metallic cast parts innately. Within the low frequency band of RFID System (125 kHz) the lines of magnetic flux are deflected by the metal parts and induce a magnetic field with converse direction in the metal parts which is called eddy current. Due to the eddy current the transponder cannot be powered by the energy from the magnetic field [Fig. 1, left]. Within the high frequency band (868 MHz - 3 GHz) the radio waves are total reflected by the metal parts and interference with the arrival waves, so that the connection between the transponder and the reader malfunctions [Fig. 1, right]. Hence, some RFID transponder are not functional suitable for the integration in metallic cast components.

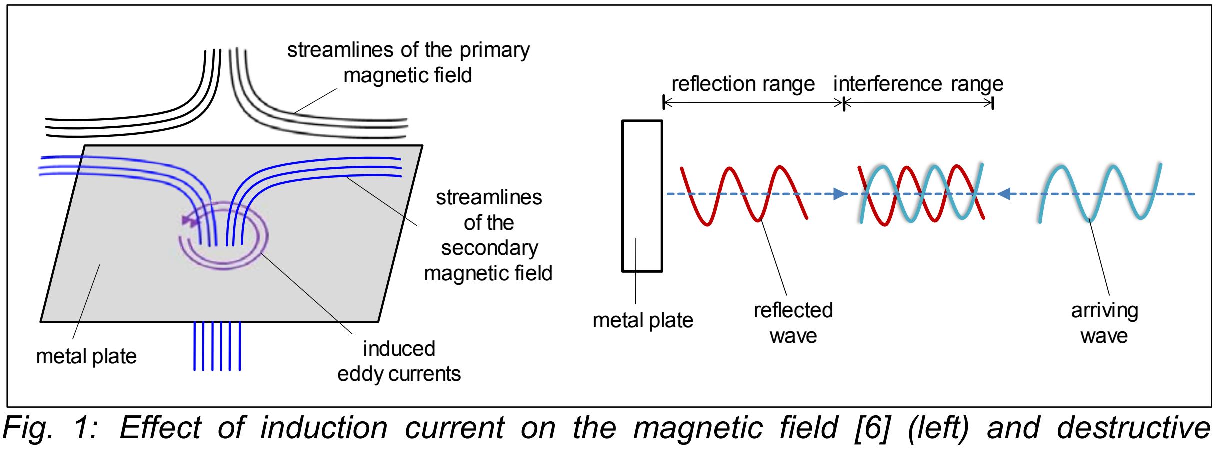

Fig. 1: Effect of induction current on the magnetic field [6] (left) and destructive interference by reflection of the electromagnetic wave (right)

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5.2 Characterization and evaluation of the transponder

In the first step a RFID transponder is to be selected being suitable for the cast intention. For the shown part a glass transponder ‘Sokymat SID153 Hitag S 2048 bit‘ was chosen [Fig. 2, left]. Its compact construction (2.12 mm of diameter and 12 mm length) is suited for the integration in thin walled casting structures. Its operating frequency is in the low frequency band at 125 kHz (±6 kHz) to hold disturbances by the metallic environment as low as possible [cp. 5.1]. Besides, its inductor is wrapped around a ferrite core to improve the performance in metallic environments. The peak temperature of the transponder is +120 °C for max. 100 h storage or max. +85 °C for operational use. Additional the SID153 shock vibration class is certified for IEC 68.2.6 / .29.

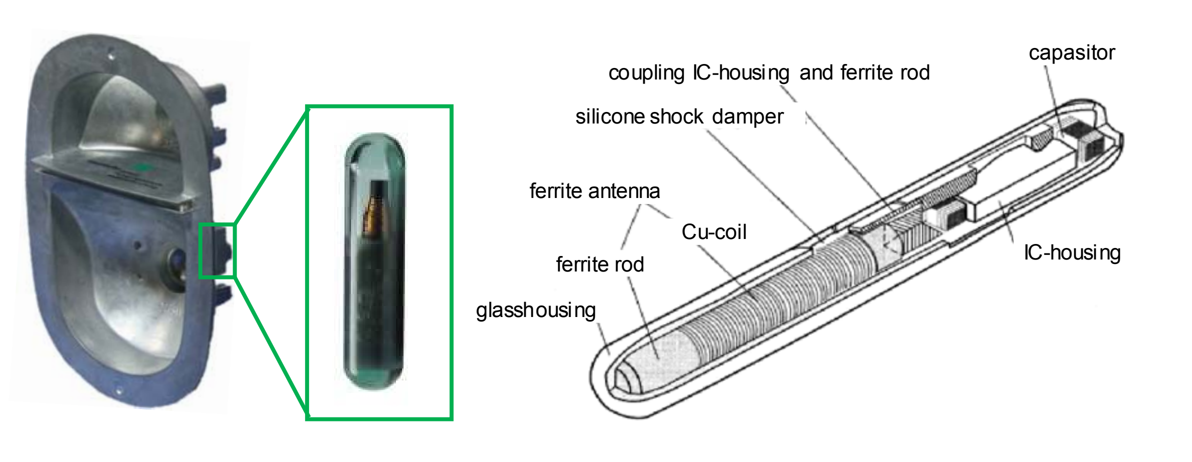

Fig. 2: RFID cast part with integrated RFID transponder (left) and design of a glass transponder [7] (right)

5.3 Designing of insulation layers

A direct contact of the RFID transponder with liquid metal melt would destroy the transponder because thermal energy would exceed the thermal endurance of the electronics. Hence, the research work concentrates on verification and development of suitable insulation materials resist high thermal-mechanical stresses during the process in aluminum-, magnesium- or zinc-based die-casting and prevent a thermal shock of the transponder. In the focus are basically polymers and polymer-based compounds. Therefore, with assistance of numerical simulation heat input into the functional component is calculated first during mold filling and next during solidification of the molten metal. So that from expected temperature level and maximum thermal endurance of the transponder a temperature difference can be determined, that must be cushioned by a suitable insulation layer. This process is exemplary illustrated in Fig. 3.

ISBN 978-3-8007-3208-1

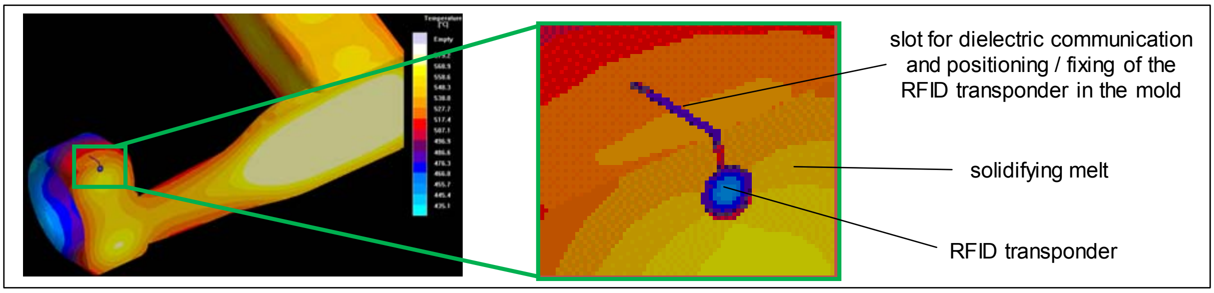

Fig. 3: Numerical simulation of the heat input into the RFID transponder during filling of the mold and solidification of the melt (without insulation encapsulation)

On the basis of this knowledge an insulation layer can be designed to cover the RFID transponder and to protect it during the die-casting process. In order to prevent damage to the transponder during encapsulation with polymer injection molding by a too high heat input of the molten polymer, the heat input impacting on the electronics are measured with the help of experimental researches. If necessary the insulation layer is adapted accordingly to fall below the maximum thermal endurance of the transponder in this step. The material of the encapsulation as well as its wall thickness are to be adapted in each case in dependence of the surrounding volume of molten metal, the wall thickness of the casting and the duration of the solidification period.

5.4 Positioning and fixing within the die casting mold

Besides the insulation layers main function of thermal protection it can be used for positioning and fixing of the functional component inside the molding tool during the die casting process. Due to these functions the insulation material not only needs to resist the molten metal but also has to provide a mechanical protection for the transponder. On the one hand it has to resist high pressures during redensification caused by the die casting process. On the other hand it needs to hold the functional component inside the molding tool in a fixed position. Furthermore the encapsulation must have good dielectric properties so that the RFID based communication between reader and embedded transponder surrounded by metal can be ensured. Fig. 4 illustrates the usage of the encapsulation for thermal-mechanical protection as well as positioning and as dielectric using the example of an automotive tail-light.

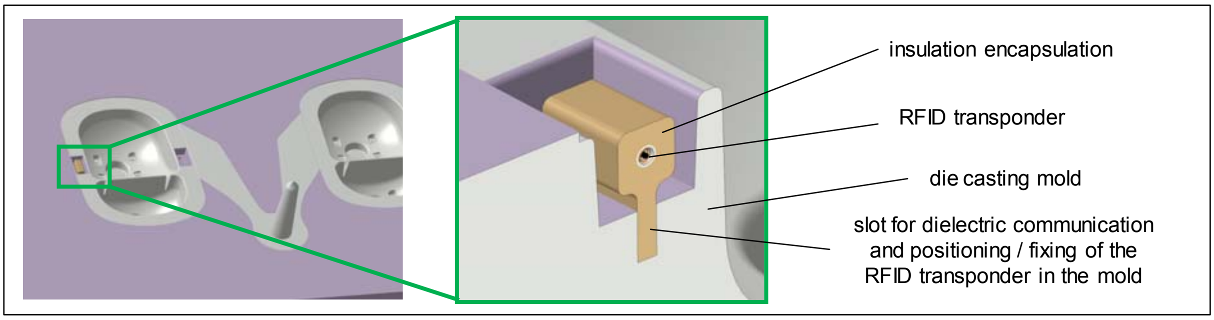

Fig. 4: Positioning and fixing of the RFID transponder with insulation encapsulation in the die casting mold

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5.5 Casting experimental work

For the experimental work a die-cast unit 'FRECH DAW 315' with a closing force of 3150 kN was used [Fig. 5]. As molten metal a zinc alloy type ZL0410 was teemed by 420° C. The temperature of ejector die and cover was set to 250° C. The encapsulated RFID transponder was plugged into the casting tool manually and automatically ejected with the casting due to positive fitting inside the part afterwards. The metal weight of one reflector (without gate) is 325 g. After ejection the castings were cooled down by water as well as by air at room temperature. Indeed, the zinc alloy used in this experiment has a clearly lower processing temperature with a difference of 290° K in comparison to molten aluminum (approx. 710° C). But with a wall thickness of approx. 1 mm and the resulting volume it is comparable to aluminum concerning the heat capacity for that a comparable heat energy having impact on the electronics. This comparison was confirmed by comparative numerical calculations.

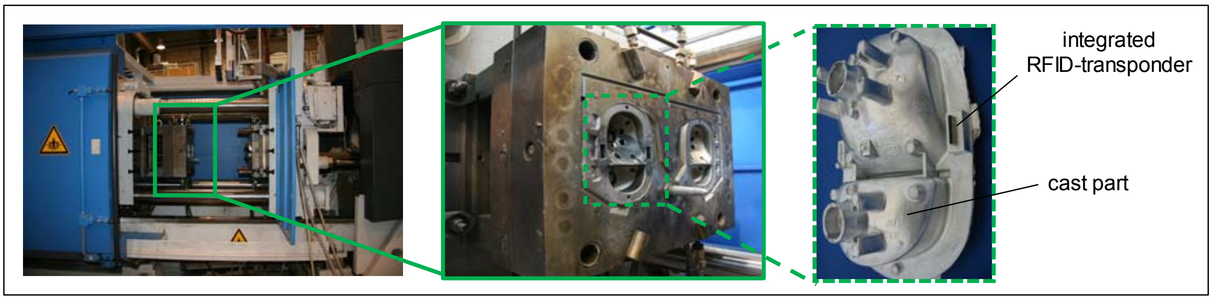

Fig. 5: Die-cast unit FRECH DAW 315 (left), die casting mold (center) and final cast part with integrated RFID transponder (right)

6 Technology development for in-process embedding of piezo sensors

The in-process embedding of piezo-ceramic sensors into cast parts is illustrated alongside the production process of a further demonstrator sample. Inside the 'function integrated pedal crank' two integrated piezo sensors should be able to ascertain compressive and tensile stresses are induced into the casting during handling or result inside the material structure.

6.1 Functional principle of piezo sensors

The technical functional principle of piezo sensors is based on the piezoelectric effect. Electric charges in the crystal structure of piezoelectric materials are generated from mechanical distortion, e.g. through compressive and tensile stresses or vibration. These electric charges can be derived as a sensor signal for the corresponding loads of pressure / tensile forces or vibration. Besides, extremely low response times of a few microseconds are feasible. In a reversal of this effect piezoelectric materials can be actively deformed by investing an electric potential.

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6.2 Characterization and evaluation of the piezo sensors

Before some specific sensor elements are selected for application the expected loads on the part should be calculated by a structural-mechanical simulation in order to identify the critical locations on the casting for sensor positioning. Afterwards the suitable sensor element will be selected and construction of the part will be adjusted in consideration of the structural-mechanical embedment of the functional elements. For the demonstrator sample a load of 1800 N on the pedal crank was assumed [Fig. 6].

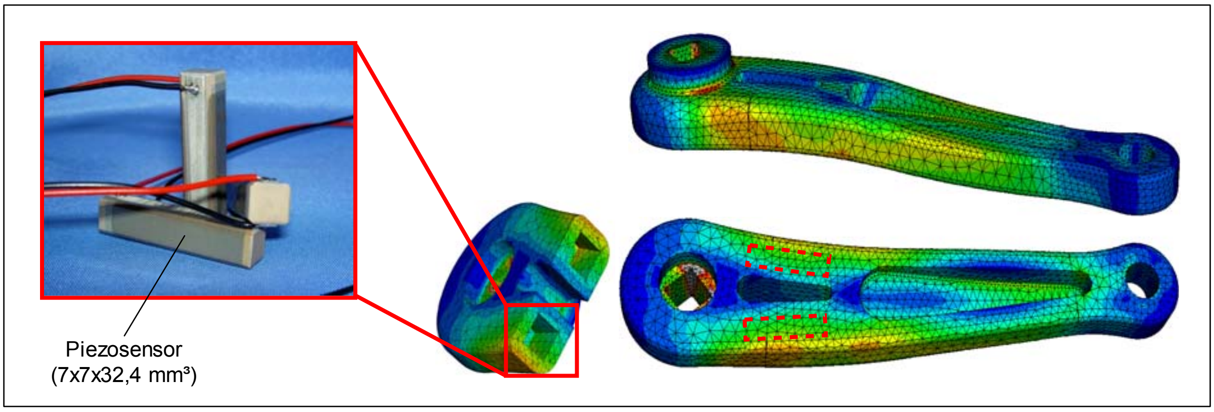

Fig. 6: Piezoelectric sensor of type SP505 7x7x32.4 mm³ (left) and structural-mechanical calculation of a load of 1800 N (right)

The piezo-ceramic stack actuator type 'CeramTec SP505 7x7x32.4 mm³' was selected for the application due to the robust machining properties and high ability in generating the sensor signals. The latter is caused by the size of the piezo-ceramic stack that voltage generation acts in proportional dimensions to the mechanical deformation. The type SP505 offers a storage and usage temperature from 40 up to 120°C. But the feature of piezoceramics is a higher maximum thermal endurance, the so-called curie temperature (CT). By heating above the storage temperature the piezoelectric structure will lose polarity and therefore its functionality. By the use of repolarization the polarity can be restored. The curie temperature (CT) is the level at which the depolarization of piezoceramic elements cannot be undone. The curie temperature of the type SP505 amounts to C_T 205 °C.

6.3 Designing of insulation layers

In order of protection of the piezo sensor from thermal damage and exceeding of the curie temperature the expected heat input of molten metal is calculated firstly, analog to the embedding-procedure of RFID transponders. Belonging to the example 'function integrated pedal crank' the piezoceramic sensor is encapsulated with a high-heat resistant polymer based insulation layer of 2 mm thickness. In addition to the thermal insulation the protection layer shields the sensor from the mechanical damage which is caused by process based high redensification compressions up to

2,000 bar during solidification. In order to measure compressive and tensile stresses inside the casting by reason of axial deformation the embedded piezoelectric sensors are not completely covered with insulation, but only radial - in contrast to the approach from Chapter 5.3. As the front ends are left, is made a positive connection between the sensor and the metallic structure [Fig. 7, center]. It should be noted that thus is an increased heat input to the functional ceramics on the sides of the front ends which must be compensated on the applied side insulation layer.

6.4 Positioning and fixing within the die casting mold

A special, patented construction technology was developed for positioning and fixing the piezo sensors within the casting mold of the pedal crank. This fixing-construction builds the basis for an electrical contact of the embedded piezo sensors at the same. The mechanical stabilization is realized via 1 mm V2A steel plates for electrical contacting and positioning, which are bounded with a specific selected two part adhesive onto the piezoceramics. This adhesive offers high mechanical stabilization along with sufficient flexibility, so adequate warping and deforming of the sensor stack is enabled during later operations. An electrical contact to the electrode surfaces of the piezoceramic works via bonding of copper folding plate with electrically conductive adhesive. This is followed by the sheathing with insulating protective layer [Fig. 7, left].

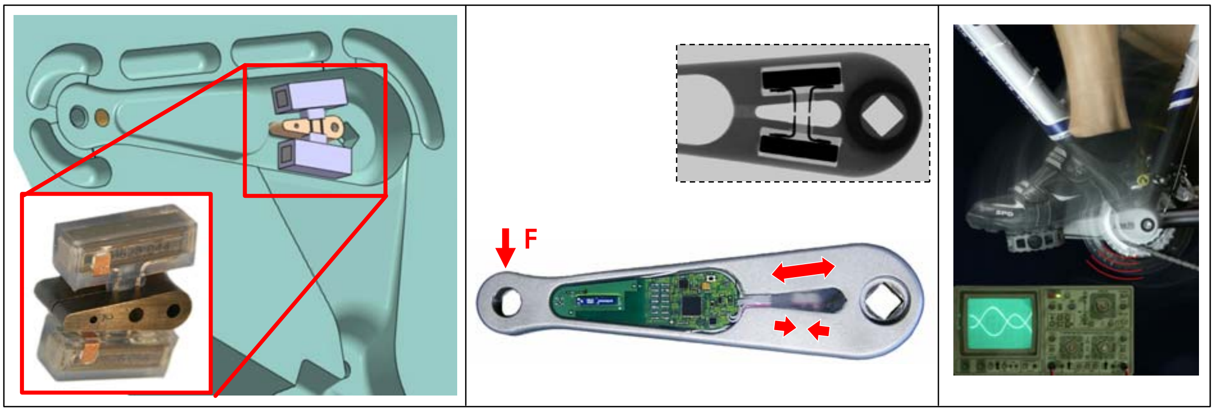

Fig. 7: Encapsulated piezo sensors fixed in die-cast mold (left), casted pedal crank with embedded sensors and x-ray image (center) and analysis of the sensor signals (right)

6.5 Casting experimental work

For the experimental work a real-time controlled die-cast unit 'BÜHLER SCN/66' was used with locking force of 6,616 kN. As molten metal an aluminum melt type 'AlSi9Cu3 (226)' was used and teemed by 710° C. The temperature of ejector die and cover was set to 200° C. The encapsulated sensor system was manually plugged into the casting mold via a patented, pluggable metal core that will be closed automatically by locking force of the die-cast unit [Fig. 7, left]. The casting weight of

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the pedal crank (without gate) is around 290 g. After ejection the casting parts were cooled down in oil.

7 Conclusions

The works presented have shown that the in-process embedding of electronic functional components such as RFID transponders for component identification and data storage as well as piezoceramic sensors for measuring of mechanical loads into castings via die-cast process could be implemented. In a first step, the thermal and mechanical loads to the embedding component are determined in relation to the casting geometry, the alloy and casting parameters. Subsequently, the functional element is sealed with an application-specific thermal-mechanical protective insulation layer and fixed within the casting mold with the help of positioning techniques. Based on two examples the technology could be shown successfully to provide the in-process embedding of functional components into castings in zinc and aluminum die-cast processes.

8 Acknowledgement

The parts for integration of RFID transponders were supported by the German Research Foundation (DGF) in subproject C1 “Integration of RFID in Die Casting” of the Collaborative Research Centre 637 “Autonomous Cooperating Logistic Processes”.

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