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To cite this article: I Dani 2019 IOP Conf. Ser.: Mater. Sci. Eng. 480 012016

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Abstract. Smart components are key technologies for industry 4.0 as well as the Internet of Things. The application areas include e.g. systems for sustainable production, automotive, smart agriculture, and smart home. In order to integrate intelligence within a component, a sensor or actuator system typically needs to be embedded within the component itself during fabrication. Additive manufacturing has been extended to more and more industries and is now being used not only in toolmaking, but also in the series production of components. Geometric functionalization for conformal cooling is already state of the art in tool making. Despite the great potential of function-integrated parts, publications on sensor integration into parts fabricated by additive manufacturing are still rarely found. First approaches address multi-material printing by using insulating and conductive materials as well as the integration of smart elements during the printing process. Laser beam melting (LBM) is an additive manufacturing technology for geometrically complex parts based on the layer wise and selective melting of metal powders. As proof-of-concept of the developed integration concept, based on LBM, the functionalization of tools and medical implants will be presented.

1. Introduction
In the last years, a significant increase in applications of additive manufacturing technologies for production of direct metal parts occurred, especially in the medical and aerospace industry but also in engineering. Additive processes are characterized by outstanding geometrical flexibility and lack of tooling. Manufacturing of geometrically complex parts with additionally embedded sensors and actuators potentially enables the customization of products or real-time monitoring of engineering systems also in harsh environments. Additive manufacturing is especially suited for the production of smart structures with structurally integrated components due to its layer-by-layer fabrication process. Applications for sensor or actuator integrated smart parts include sophisticated biomechanical devices monitoring the interface between implant and bone and smart tools to monitor the process conditions or to predict maintenance. An extensive literature review on additive manufacturing of smart parts is contained in [1]. In particular, the powder bed based laser beam melting (LBM) allows a precise spatial energy input to fully melt metal powders to dense structures with mechanical properties comparable to those of conventionally manufactured parts. LBM enables a materially bonded embedding of functional components to obtain a maximum sensitivity of the adaptronic system. Further benefits include the complete encapsulation of the sensor within the metallic component and the utilization of far-field inductive energy transmission for wireless operation [2].

Tool and die making faces the challenge of producing molds for complex and high quality injection molded parts. The molds have to be equipped with a multitude of functions, such as locally defined heat conductivity, ventilation of the cavity, individual tempering options, toughness, strength, wear resistance, sliding, and demolding functions. By using additive manufacturing processes, some of
these functions can be implemented in the smallest possible space. Approaches for linking fluid-carrying functions in mold inserts with the application of temperature and pressure sensors for process monitoring were developed and are described in this paper.

Potentially, tool manufacturing for different sheet metal forming technologies can also benefit from the advantages of LBM. The focus is on incorporating a conformal cooling system to reduce cycle time into a tool for press hardening. To compare the simulation results with the real forming process tool, integrated sensors are applied - the position and the type of integration in the tool are crucial aspects for reliable measurements. Design and manufacturing of the tools are explained in the paper and the results of first forming tests are presented.

The integration of sensors and actuators into artificial joints has been discussed for several years. Integrated sensors or actuators for monitoring of osseointegration, for detection of implant loosening or for in vivo implant load monitoring substantially improve the functionality of the implants. Especially for an acoustic stimulation, actuators placed on or near the surface are not able to create useable structure-borne acoustic waves. A structural embedding and materially bonded integration of the actuator is favored. A concept for integration of an encapsulated actuator system was developed and is presented.

2. Manufacturing concept and materials

2.1. Technology

Laser beam melting is a very versatile additive manufacturing technology and in this paper is used as base process. The starting point is a 3D CAD model, which is virtually sliced into thin layers with a layer thickness of about 45 µm. Based on this data the physical part is built. A thin layer of metal powder, stored in a dose chamber, is uniformly distributed across the working area by a coater blade (Figure 1). The light emitted from an ytterbium fiber laser system at the wavelength of 1070 nm is directed by a galvanometer scanner across the powder layer according to the cross section of the part. The machine used, a M2 LaserCUSING® from Concept Laser, applies an island exposure strategy, i.e. the segments of each layer are irradiated in stochastical succession. Upon irradiation the powder melts to form a melt pool, covering not only the top powder layer, but also the already solidified layer below. After laser exposure of the first powder layer, the build platform is lowered, the next powder layer is applied and the exposure process starts again. These steps are iterated until the part is completed. Then, the unmelted powder is removed and the part is separated from the build platform and from the support structure.

![Figure 1. Scheme of the laser beam melting (LBM) process.](image)

To integrate a sensor in a metal part, the outer part is manufactured by LBM (Figure 2). From the cavity, designed to house the sensor, the unmelted powder is removed and the sensor (incl. the wiring) transferred. Subsequently, the LBM process continues, i.e. the next powder layer is applied and selectively melted.
2.2. Selection of Sensors and Actuators

The sensors and actuators to be integrated in parts manufactured by LBM have to meet special requirements. The measuring element and the wiring must have a high temperature resistance in order to withstand the very high local thermal load during laser beam melting of the surrounding material and a subsequent heat treatment of the part. Further aspects such as low costs, small installation space, good availability and good accuracy are noteworthy. Sensors to be exploited include thermocouples, resistance strain gauges and capacitive differential pressure sensors. Industrial applications studied in this paper include tools for injection molding and for hot forming of metal sheets.

In the injection molding process the material is plasticized in an injection unit at temperatures of up to 300 °C; during injection into the mold the temperature reaches still about 250 °C. Thus, for the intended application of thermocouples in injection molding tools a measuring range from room temperature up to 250°C is required. Thermocouples were produced from a nickel-chromium wire connected to a nickel wire (type K) and insulated by a double layer of glass fiber. The measuring range is between −200 °C and +1250 °C.

To monitor the pressure in the mold cavity of the injection molding tool resistance strain gauges and capacitive differential pressure sensors can be applied. To avoid contact between the sensor surface and the mold, the pressure is measured indirectly via a membrane. The thickness of the metallic membrane is a crucial parameter and is determined by FE simulations. Main advantage of using the membrane and a fluid medium is that the pressure exerted on the surface of the pressure sensor is significantly reduced, allowing the application of a sensor with a smaller maximum operation pressure. Simulations show a pressure in the active fluid medium (hydraulic fluid) of max. 250 bar for a membrane thickness of min. 2.7 mm and an assumed pressure of 2000 bar at the injection nozzle. An electronic differential pressure transmitter (PU5401, ifm electronic GmbH) with a measuring range up to 250 bar was selected.

Also, the alternative measuring system, a strain gauge, is covered by a metal top layer, in this case with a thickness of 0.3 mm. If a force acts on the surface of the sample, the top layer and the strain gauge deform and the resulting voltage is amplified by a bridge circuit, at the same time compensating temperature deviations. For this integration method, the strain gauge has to withstand the temperature necessary to melt the surrounding steel, so only relatively expensive high temperature strain gauges are suitable. Inconel 600 encapsulated strain gauges (KHCD-5-200-G11 C2M, Kyowa) with a maximum operation temperature of 800 °C were selected.

For the medical implant application, a pre-fabricated actuator system described in [2] and [4] was used (Figure 3), ensuring a materially bonded connection between the actuator system and the surrounding implant, a complete encapsulation of the system, and a wireless energy and data transmission. The primary objective of the actuator system with a total weight of 2 g and size of 28 mm x 6 mm x 6 mm is the generation of oscillations between the two interfaces of the actuator with calculated forces in the millinewton range.
2.3. Materials
The injection molding tool and the specimen for the pre-tests were additively manufactured by LBM from maraging steel powder (1.2709). The functional part of the hot forming tool was also manufactured by LBM from steel powder (1.2709) on a base part made from hot-working tool steel (1.2343). The medical implant was made from Ti6Al4V titanium alloy powder.

3. Results and discussion

3.1. Smart Tools for application in injection molding
In injection mold making, additive manufacturing technologies are increasingly applied for conformal cooling [5], avoiding inhomogeneous temperature distributions in the tool due to optimized cooling channel geometries. Application of conformal cooling channels is reported to reduce the cooling phase up to 50% [6]. Monitoring of the complex process of injection molding leads to increased controllability and effectivity of the process. Main parameters influencing the process include mold temperature and cavity pressure [7].

Application of an intelligent monitoring and control system by integration of thermocouples and pressure sensors into additively manufactured molds allows implementation of innovative and highly productive injection molding technologies. A mold concept adapted to additive manufacturing including conformal cooling channels, a near surface thermocouple, and a pressure sensor is shown in Figure 4. This paper describes a first approach for integration of the selected sensors into test specimen and their functional qualification.

Thermocouples described above were threaded into additively manufactured steel specimens after loose powder material had been sucked off (Figure 5). Since the space conditions usually are very limited, different geometries of these specimens were tested (Figure 5a). At the lowest foot height (this sample is indicated with “*” in Figure 5), placement was possible only with the help of a threading
aid. After threading, the specimens were finished with additively manufactured top layers with a thickness of 1 mm.

The functionality of the sensors after integration was confirmed on a heating plate with a set temperature of 200 °C. After 10 minutes, the temperatures given by the thermocouples show values from 70 °C to 106 °C. Origin of this variation may be the inhomogeneous temperature distribution of the heating plate, deviations in the height of the top layer and in the bonding of the thermos wires to the surrounding material.

The integration concept for the strain gauge is similar to the concept used for thermocouples. The base part is prepared by LBM using steel powder. After finishing the cavity for the strain gauge, the manufacturing process is suspended, the powder sucked from the cavity and the strain gauge placed horizontally in the cavity, flush to the surface of the part. The cable is routed down the prepared channel. Finally, the next powder layer is applied and the LBM process continued until the top layer with a thickness of 0.3 mm is finished.

For the high temperature strain gauges only the integration concept was proved so far using dummies made from chromium-nickel steel. After additive manufacturing of the basic bodies, the strain gauges are welded in the LBM machine onto the basic body (Figure 6). Number and size of the welding spots were varied (Figure 6 c, Table 1). The distance between two adjacent welding spots is 1.5 mm. In the samples with smaller welding spot width (samples 1 and 3) the strain gauge is completely connected to the base body.

After welding, the additive manufacturing process is continued and the cover layer prepared. The cross-section of sample 3 demonstrates the successful integration of the strain gauge (Figure 6d).

The integration of the capacitive differential pressure sensor using an active fluid medium is shown in Figure 7. To verify the integration concept housings were built by LBM. The membrane thickness of the as built housings varies from 3.7 mm to 4.1 mm. After separation from the build platform the defined membrane thickness of 2.7 to 3.2 mm is reached (Figure 7b). Each specimen is then threaded with a 6.35 mm (1/4 inch) bore diameter (Figure 7c). The flange surface is polished (Figure 7d). Then
the active medium is filled into the cavity of the housing. Finally, the pressure sensor is screwed in. The pressure acting on the surface of the membrane of the housing is transformed by the medium into hydraulic pressure and measured by the pressure sensor.

**Table 1.** Overview on samples for embedding of strain gauges.

| Sample | Joining design according to Figure 4c | Welding spot size |
|--------|----------------------------------------|------------------|
| 1      | Type A                                 | 500 µm, 250 µm   |
| 2      | Type B                                 | 500 µm, 500 µm   |
| 3      | Type B                                 | 1000 µm, 250 µm  |
| 4      | Type A                                 | 1000 µm, 500 µm  |

For verification of the measuring principle the manufactured test specimen are characterized in a universal compounding machine (PROMESS) with force-distance monitoring. The force was varied from 10 kN to 40 kN for each sample and the voltage of the pressure sensor recorded. A nearly linear relationship between the applied force and the measured voltage was verified (Figure 7e).

![Figure 7](image.png)

**Figure 7.** Design of the pressure sensor test specimen (a), housings: as built (b), threaded (c), polished (d), result of the force-distance monitoring: applied force and corresponding voltage in dependence of the time for a membrane thickness of 2.9 mm [8] (e).

### 3.2. Smart Tools – Embedding of thermocouples into hot sheet metal forming tools

Automotive parts made from high-strength steels formed by press hardening offer enormous potential for lightweight design. By use of this technology, the sheet metal is heated above 900 °C, the austenitizing temperature, and subsequently quenched during the forming operation to below 200 °C, forming a martensitic microstructure.

A tool for forming of gear pans from coated heat-treatable boron steel (22MnB5) was designed and an innovative cooling system developed using thermal and forming simulations [3]. For comparison of the simulated results with the forming process the embedding of thermosensors was necessary to enable a close positioning near to the contour and therefore showing short reaction times.

To find the optimum position of the thermocouple in the tool preliminary experiments were conducted. The additively manufactured specimens contained two curved channels with large radii for feeding the wires into the tool. To encapsulate the thermocouple, a top layer is manufactured by LBM. Powder application immediately after the embedding is critical, because the measuring tips of the wires must not protrude the surface of the solidified part. Therefore, the channel end was recessed to integrate the thermocouples as flush as possible (Figure 8).
Figure 8. Integration of a thermocouple into a test specimen: base body with inserted thermocouples (a), detail of the thermocouples (b), additive manufacturing process of the top layer (c), temperature profiles of the two thermocouples inside the specimen (d) [3].

For proof of concept the temperature profiles of the two thermocouples inside the specimen were monitored on a heat plate. Small temperature differences between the sensors may be explained by the quality of the joint between the thermocouple and the additively manufactured part. Characterization of the joints shows a material bonding of the thermocouple to the surrounding material.

To produce the punch for forming tests, a thermocouple was integrated 3 mm below the contour of the punch of the tool (Figure 9). During additive manufacturing of the top layer, the temperature was recorded for functional qualification. The peaks in Figure 9d clearly show when the area above the thermocouple is exposed to the laser in each layer. The measured maximum temperature is 815 °C and well below the melting temperature of the steel (about 1400 °C), due to the short exposure time to the laser and the limited thermal conductivity of steel. During manufacturing, the part heats up to about 135 °C. To minimize the residual stress and to adjust the mechanical properties of the tool a heat treatment completed the manufacturing process.

Figure 9. Design of the punch (a), thermocouple inserted into the punch (b), embedding of the thermocouple by LBM (c), measured temperature during additive manufacturing (d) [9].

To confirm the results of the simulation and of the pre-tests, extensive forming experiments were carried out under production-like conditions. Holding and cooling times were varied, starting at 10 seconds, a typical value for press hardening, and reduced to only 3 seconds. The thermocouple detected a tool temperature difference of just 10 K between the start of cooling at maximum tool temperature (closing of the tool) and minimum temperature at extraction of the part (opening of the tool). The entire process reached a steady state temperature after only 10 forming cycles (Figure 10).

Using the optimized, additively manufactured tooling, the cooling time could be reduced by up to 70% from 10 s to 3 s, for this type of component.
3.3. Smart implants

Important attributes of endoprosthesis are biomechanical and material properties as well as the realization of a stable implant-bone-interface. The latter can be characterized by imaging technologies (e.g. X-ray) or functional diagnostics. However, these are not regular examinations and an implant loosening is often detected too late. A routine monitoring by means of an implant-embedded system would be useful. This paper describes the integration of a materially bonded, hermetically encapsulated actuator in a hip implant for a defined vibrational excitation within the implant and the surrounding bone for monitoring implant loosening and structural health. Variations in the implant-bone-interface lead to a shift in the natural frequencies, which can be detected by wireless data transmission.

The hip stem (Figure 11) was additively manufactured by LBM from Ti6Al4V titanium alloy powder. For this material, a heat treatment is necessary for adjusting micro-structural and mechanical properties and to relieve residual stresses. However, conventional post-process heat treatments cannot be applied due to the embedded temperature-sensitive actuator system. Therefore, in a first step only the base body of the hip stem including a cavity for incorporation of the actuator system is manufactured, cleaned and subsequently heat-treated. After the heat treatment, the alloy contains alpha and beta phases. The encapsulated actuator is then placed into the cavity flush to the top surface. Afterwards, the part is positioned in the LBM machine and the additive process is continued till the part is finished. After support removal, the cone for fitting the ball head and a mounting hole for the impactor was machined and the unmachined areas are shot-blasted. The finished part is shown in Figure 11b.

Computer tomography verifies the material bond between the actuator system and the hip stem (Figure 11c). Static properties of the completed hip stem correspond to the properties of the volume fractions of the heat-treated and the as-build parts.
next investigations. The analysis of the dynamic response of the implant was carried out using a 3D laser scanning vibrometer to measure the surface velocities in three spatial directions. The experimentally determined frequencies inducing the largest displacement and velocity at 2135 Hz and 3416 Hz deviate slightly from the simulation values. The maximal surface velocity at the stem tip reaches about 15 µm/s and 7 µm/s, respectively [2].

![Figure 12](image)

**Figure 12.** Result of the FE-model based modal analysis (a), functional qualification by laser scanning vibrometry (b).

4. **Summary and conclusion**

Additive manufacturing technologies constantly widen the scope of their economic viability and increasingly answer the requirements of smart devices. In this paper, a general methodology for the integration of sensors and actuators into metal parts was successfully applied. Due to the material bonding between the functional component and the surrounding material short reactions times and high sensitivity were ensured even under harsh process conditions. The direct embedding into the structural component enables monitoring of main process parameters near the surface of the tools without weakening the mechanical properties. Functional qualification of the embedded sensors and actuators verifies the usability of the integration concept.

For an industrial application of the integration principle, the reproducibility of the performance of the functional components and the automatization of the process chain have to be improved. Application-oriented development of smart products is intended together with machine manufacturers and end users.

**Acknowledgments**

The results presented in this paper are based on several funded projects. The author sincerely acknowledges funding from the Manunet project HiperFormTool (02PN2000) by the German Federal Ministry of Education and Research (BMBF) within the Framework Concept “Research for Tomorrow’s Production”, from the project FunGeos by the BMBF under the grant mark 03ZZ0208A, and from the Fraunhofer Lighthouse Project “Theranostic Implants”. The responsibility for the content of this publication lies with the author.

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