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Integrating electronic components into 3D printed parts to develop a digital manufacturing approach

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Abstract. Digital manufacturing (DM) processes such as additive manufacturing (AM) technology, allow a high degree of integrability and functionality of printed parts. In this work, we present a proof of the DM concept focused on the integration approach where a product is developed and embedded with sensors. We also take this example one step further and introduce a method that allows 3D printing of heating elements into the specimens. The thermal characteristics of the developed heaters are investigated, and the results detailed. The novelty relates to a heater prototype injected and solidified into a curved 3D printed channel, which can produce a temperature between 23-46°C on the printed surface of the sample both in a dry and wet environment. This research demonstrates that it is possible to construct parts with embedded electrical structures using the described method.

Keywords: Digital manufacturing, stereolithography, sensors, conductive ink.

1 Introduction

This work uses complex methods, tools, and processes to demonstrate the possibilities of digital manufacturing (DM). The proposed approach combines the design and manufacturing information with the concept of functionalizing additively manufactured parts in various aspects. As a practical case study, we present an anatomical sweat glands module, which was developed with DM instruments, starting from design and conception to the direct fabrication by additive manufacturing (AM). This prototype will be further developed to optimize textile materials and to elaborate specific analysis of this industry.

The sweating glands are all over the human body surface within the first 3 mm of the skin. Their density is between 80 to 100 glands/cm² and they have 40 µm diameter. These reduced characteristics of sweat glands are not possible to be fabricated with standard AM machines. Due to AM limitations, we concentrated on considering the surface and the sweat rate. Thus, an anatomical module was designed that offer the possibility to bring the same amount of liquid to the required surface. The armpit area

was selected to develop a complex sweat glands module [1]. Regarding the AM possibilities, various scientific papers shown that 3D printing technologies can produce complex prototypes for different applications under the “layer by layer” principle [2-11]. Comparing with conventional manufacturing methods [12-14], 3D printing provides reduced time to market, lower product development costs, and improved design process [15]. Emerging technologies such as 3D printing and robotics [16] accelerates a sustainable developing of Industry 4.0 with DM. Analyzing the literature recommendations, the actual sweat glands module can be manufactured by stereolithography (SLA) technology. This AM process can produce directly accurate parts with good surface quality. A sweat glands module was designed according to AM requirements. To design the sweat glands module, boolean and CAD operations were developed using Creo Parametric and Meshmixer software. Boolean operations offer a versatile tool for editing or modifying the STL format, adding artificial constructions [17, 18]. With the design freedom afforded by the SLA process, atypically channels networks were developed for liquid flow. The designed and printed part is illustrated in Fig. 1. This module contains more than 600 outlet glands on the anatomical shape of the armpit. All the parts from this study were fabricated using a Form2 SLA system and a standard photo-polymer (Clear Resin-Formlabs).

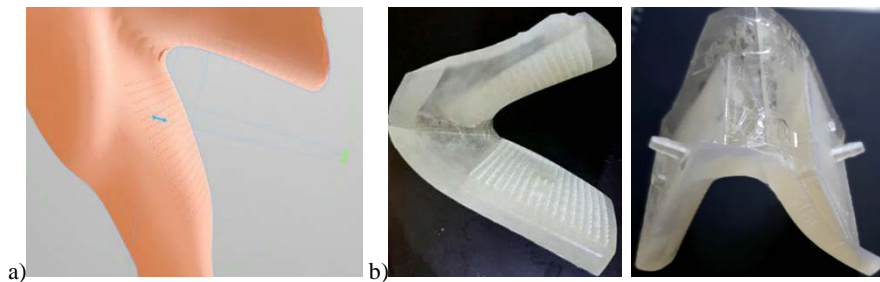


Fig. 1. Sweat glands module of armpit: a) Virtual model, b) SLA manufactured

To add functional requirements to the actual sweat glands module, the study was focused on embedding electronic components into the 3D printed parts. This work combines additive polymer printing with liquid metal infiltration for use in potential practical applications. The novelty of this study relates to a heater prototype developed by injecting a silver conductive ink into a curved channel, which can produce a temperature between 23-60°C on the printed surface of the sample.

2 Integrating electronics in SLA parts

AM technologies offer the possibility to integrate electric components and sensors in complex parts. Various applications of 3D printed sensors were reported for measuring the following: strain, pressure, ultrasounds, gas detection, food quality, biosensor, or even brain activity [19]. This paper describes two practical examples of how electronic components could be integrated into a sweat glands module. The first method is a

straightforward one, where traditionally manufactured electronic components and sensors are integrated into pre-designed holes in the printed part. After the part was SLA manufactured, additional sensors were integrated into the pre-designed holes. The concept is presented in Fig. 2, where humidity and a temperature sensor are connected. The humidity sensor is Honeywell HIH-4000-003 and has the following features: near linear voltage output versus relative humidity, laser-trimmed interchangeability, low power design, enhanced accuracy, fast response, and low drift performance and chemical resistant. The temperature sensor is a PTF type produced by TE Connectivity. It combines a resistance temperature detector using a platinum resistor in the thin film as a sensing element. This sensor contains a structured platinum film on a ceramic substrate, passivated by glass coating [20]. The main features of it are the following: resistance tolerance $\pm 0.12\%$, application temperature $\pm 200^\circ\text{C}$, and silver wire. As shown in Fig. 2, a specially printed circuit board (PCB) was designed, equipped with an ARM controller (STM32C476), which controls the electronics. This board enables the connection of various sensors and actuators and controls the integration of the components. After setting up the controller via an ST-Link (Nucleo-F103RB), the first data from the sensors (temperature and humidity) were read (Fig. 2b). Furthermore, this sweat glands module, and electronics will be implemented in a mechatronic system, which will allow us to simulate the sweating process in various conditions.

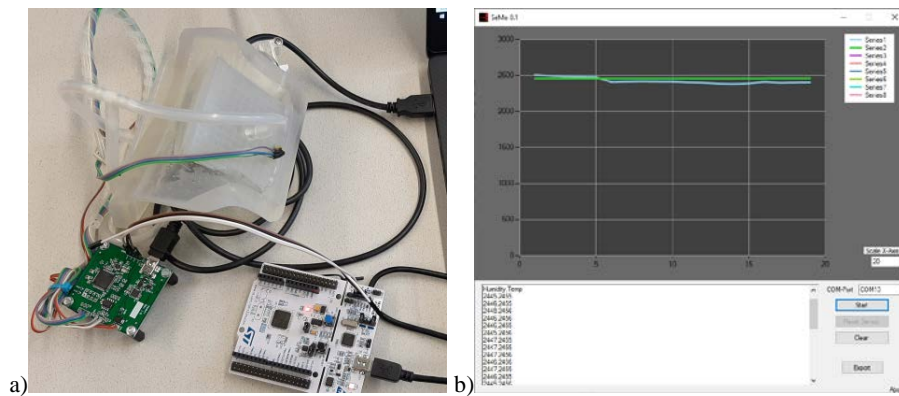


Fig. 2. Sweat glands module with integrated sensors: a) setting up the controller b) sensors data

The second example is based on a previous report focused on 3D printed microelectronics for integrated circuitry and passive wireless sensors [21]. In this method, some channels are left intentionally hollow in the part, and after manufacturing, they are filled with conductive ink. In this manner, interesting components such as micro-electro-mechanical-systems (MEMS) could be developed [22]. Using this technique, we produce integrated paths in the 3D printed sample, which can be used for actuating, in this case, thermal regulation, or even sensing purposes. Several samples were SLA manufactured with “U” channels (Fig. 3b). Each sample has three channels with a 1.00 mm diameter and 26 mm length. The SLA parts were post-cured with $1.25 \text{ mW}/\text{cm}^2$ of 405 nm LED for 60 minutes at 60°C . For these conditions, the heat deflection of SLA parts is approx.

58.4°C for 1.80 MPa load value (according to ASTM D 648-07). Using a normal syringe, all the channels were injected with a conductive liquid (Fig. 3a). The material used is based on silver conductive element and has a volume resistivity of 0.001 Ω cm (product code RS PRO 186-3600). According to the material data sheet, this conductive ink contains 50-75% silver, 10-25% 2-methoxy-1-methyl ethyl acetate, and 10-24% n-butyl acetate. In general, this conductive ink is used to repair circuits on printed circuit boards or to make electrical connections to non-solderable surfaces. Fig. 3b shows a sample developed using this procedure, which contains three resistive elements.

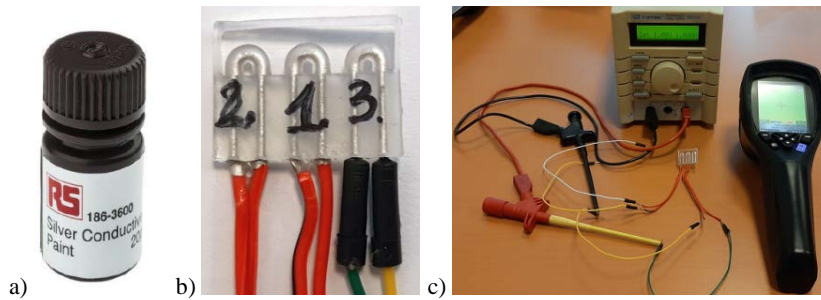


Fig. 3. a) Silver conductive ink used, b) 3D printed heater: SLA sample where the “U” channels injected with silver conductive ink, c) Instruments used for temperature sensitivity experiment

To investigate the heating behavior of these elements integrated into the SLA part, they were characterized for temperature sensitivity. In this step, we analyzed their suitability as heating elements. To undertake this work, a programmable DC power supply from Instek PSS-3203, and an infrared thermal camera from Flir i7 was used (Fig. 3c). The power was varied from 0 to 300 mW and the surface temperature of SLA parts was recorded. Typical temperature maps at different power values are shown in Fig. 4. Moreover, Fig. 5 shows the temperatures measured in air and with the elements immersed in a liquid with respect to increasing power. The results presented are the mean values recorded on the surface. All the measurements were made until the part was no longer conductive.

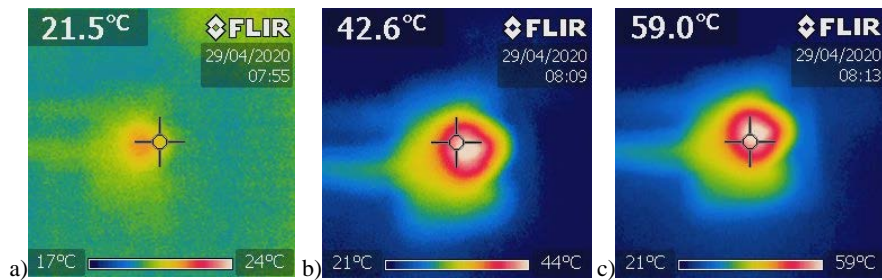
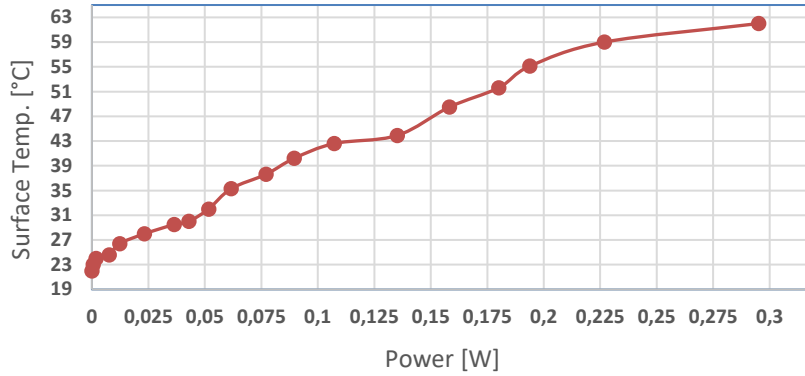


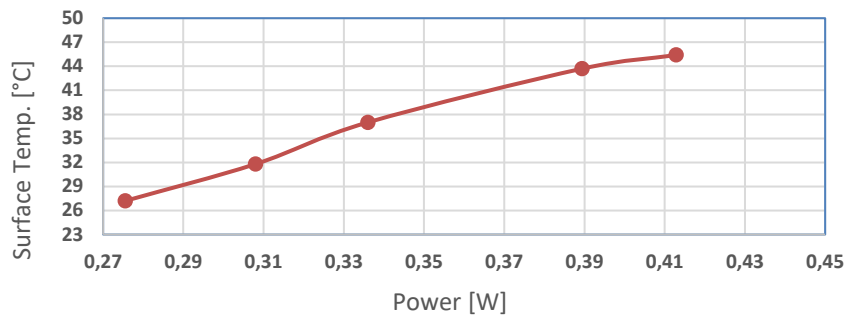
Fig. 4. Temperature maps at different values of power: a) 0.002 W, b) 0.107 W, c) 0.226 W

The interruption appears at maximum resistance, where a voltage supply of 1.15 V was applied (power of ~ 298 mW). The resistance of samples varied between 3.278 and

3.727 Ω . These results show that temperature from 31°C to 42°C can be achieved using a power input from 40 to 107 mW in a dry environment (Fig. 5a).



a)



b)

Fig. 5. Chart with surface temperature versus power: a) Dry environment, b) Wet environment

To investigate this system in a sweating environment, other samples were tested in water at room temperature (18°C). The results are exposed in Fig. 5b. In this case, the power was increased up to 420 mW. In a wet environment, temperature from 32°C to 44°C can be archived using an input between 310 and 390 mW.

For better mechanical and electrical properties, the conductive ink could be cured at 121-148°C for 5 to 10 minutes. To achieve this, another resin must be used for the printing process (e.g. High Temp Resin from FormLabs).

The measurements conducted above allow the determination of the thermal resistance (R_{th}) using the following equation:

$$R_{th} = \frac{\Delta T}{P} = \frac{(T_d - T_a)}{P} \quad [^{\circ}\text{C}/\text{W}] \quad (1)$$

where T_d is the device temperature (°C), T_a is the ambient temperature (°C) and P is the electrical power through the device (W).

The results of thermal resistance are shown in Fig. 6. Depending on the power supply, the thermal resistance varies from 34 to 142 $^{\circ}\text{C}/\text{W}$.

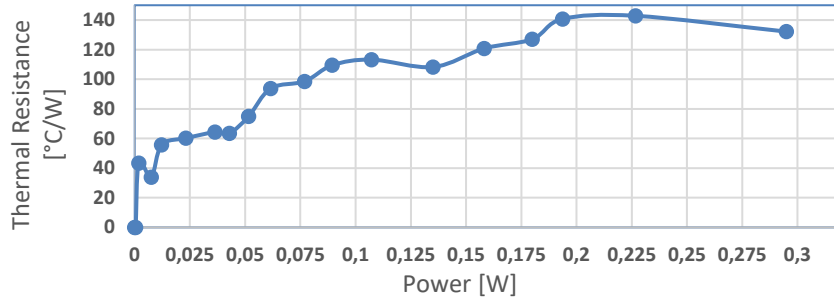


Fig. 6. Thermal resistance (R_{th}) versus power consumption

The presented results showed that this concept of resistive elements can be used as a heater. Future studies will integrate this heater concept into the anatomical shape of the sweat glands module, allowing us to simulate the sweating process at various temperatures in a dry or wet environment. To create an instrument, which combines both fluidic channels and sensing elements, the actual study shows a possible method to integrate electronic components into a 3D printed part.

The results reported brings a valuable contribution and useful reference for future applications of DM. The work was focused on functional design and the high levels of integration enabled by DM. In this study, the SLA process has been utilized to develop a sweat glands module with integrated electronic components such as temperature and humidity sensors, and a heating component made of silver conductive ink. Combining the 3D printing process and liquid metal paste filling method, a heater prototype was developed. The heating results show that it is possible to obtain a temperature from 36°C to 46°C both in a dry or wet environment using this heater. This preliminary study demonstrates that it is possible to develop an embedded heater into the SLA parts. From the manufacturing point of view, these findings suggest that a future heater can be constructed into the anatomical shape of the sweat glands module.

3 Conclusion

With the increase in the quantity and quality of computer systems in production facilities, the transition to a DM approach has become popular. DM concept refers to smart, networked methods, techniques, and tools that enable more flexible and customized manufacturing, increasing productivity and strengthening competitiveness [23]. In this study, a practical implementation of DM was developed which explores the benefits of 3D printing. Due to enabling to produce prototypes, tools, and final parts directly from virtual models, DM fosters dramatic reductions in delivery times and production costs while improving overall product quality. From our perspective, the technique described can be used to produce various electrical components with an atypical structure such as resistors, capacitors, inductors, circuits, and wireless sensors.

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