Functional Integration of Subcomponents for Hybridization of Fused Filament Fabrication

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***Abstract*—One of the main advantages of additive manufacturing by Fused Filament Fabrication is its wide variety of materials and cost-effective production systems. However, the resolution and tightness of the produced structures are limited. The following article describes a novel approach of the functional integration of stereolithographic produced subcomponents into the Fused Filament Fabrication process and the challenges during integration in terms of adhesion, taking into account different surface pre-treatments. Furthermore, it is investigated how conductive polymer composites could be used successfully for conducting mechatronic subcomponents automatically. With the help of these investigations it is aimed to extend the field of application of additive manufactured plastic components.**

***Index Terms*—stereo lithography, fused filament fabrication, hybridization, conductive polymer**

I. INTRODUCTION

Due to the development of new emission-free, electric powertrain concepts in the automotive industry, a change is taking place towards updated and upgradeable mobility concepts. The vision is an end-to-end digital production line for fast product development, but this also requires an adaptation of the associated production processes in order to enable a flexible but still economical fabrication. In consequence of the continuously rising speed of parts development, it is necessary to enable a fast and short-term adaptation of production lines with short set-up times [1]. However, the degree of complexity of novel vehicle components is also increasing due to the requirements for installation space, weight and additional functionalities. This leads to the need for new concepts and processes for future production technologies.

Additive Manufacturing (AM) offers great advantages in terms of geometrical design freedom and fast development cycles and hence seen as an innovation driver for flexible production of future mobility concepts [2–4]. The basic principle usually consists of a layered build-up of the components [4]. Especially Fused Filament Fabrication (FFF) systems have become widely used in recent years due to its large and diverse range of thermoplastic materials and its rather easy handling. The application in an industrial context, however, is limited and mostly used for prototypes and production aids [5]. On the one hand, this is due to the anisotropic material behaviour and the resulting typical structural failure between the build-up layers under load. On the other hand, caused by a low resolution and porous structure, there is usually insufficient accuracy to implement functional interfaces, such as threads, fits, sensors or fluid-carrying areas. Complementary to this, stereolithographic (SL) manufacturing processes offer the possibility of producing highly precise and sealed structures, which however, due to their limited mechanical properties, are again mostly only used in the field of prototyping [6].

Therefore, this study will investigate the hybridization of both processes to exploit synergy effects and is compared with conventional metallic inserts as reference. In this context, hybridization means the intrinsic integration of subcomponents (metal / plastic parts) during the printing process. The aim of this study is to investigate the adherence properties of integrated metal and SL manufactured subcomponents and the possibility to include mechatronic subsystems by conductive polymers.

II. BASICS AND STATE OF RESEARCH & TECHNOLOGY

In additive manufacturing, beside Selective Laser Sintering (SLS), two plastic processes have become established.

A. Fused-Filament Fabrication (FFF) & Stereolithography (SL)

As in Fig. 1, FFF is a manufacturing process in which a workpiece (3) is built up layer by layer from a fusible plastic filament (2). A thermoplastic material is transported to a heated nozzle (1) and is melted there. The melted polymer filament is applied to a heated building platform (5, 6). Depending on the component complexity, support structures are used to create overhangs (4).

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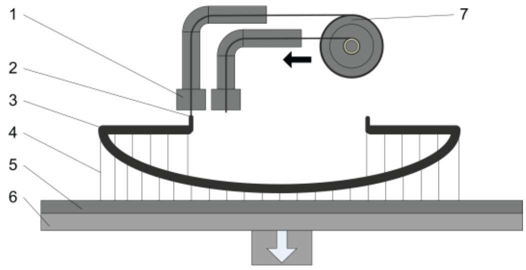

Figure 1. Fused Filament Fabrication (FFF) process and its components [7].

The main advantages and disadvantages of the FFF process are listed in the following Table I [6, 7].

TABLE I. ADVANTAGES AND DISADVANTAGES OF THE FFF PROCESS.

Advantages:	Disadvantages:
Cheap	Ribbed surface
Mechanically resilient parts	Medium accuracy of production
Wide variety of materials	Porous structures

According to Fig. 2, with SL objects (5) on a building platform (8, 9) are created from a liquid photopolymer resin (6) by curing this resin layer by layer with a laser or LED (2). Fresh resin is distributed on the building platform in layers with the help of a recoater (1). The exposure beam is directed to the target area by means of movable mirrors, so-called galvanometers (4) or Digital Micromirror Devices (DMD). Exposure can be performed from above (Top-down), as shown in Fig. 2, or from below (Bottom-up). Depending on the irradiation intensity and dose, the resin polymerizes in the exposed areas (3). Also here, depending on the component complexity, support structures are used to create overhangs (7).

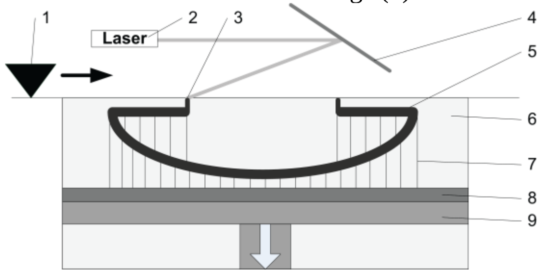

Figure 2. Top-down stereolithographic process and its components [8].

Characteristic advantages and disadvantages of the process are listed in the following Table II [6, 9].

TABLE II. ADVANTAGES AND DISADVANTAGES OF THE SL PROCESS.

Advantages:	Disadvantages:
High accuracy of production	Only UV hardenable polymers
Complex shaping	High production costs
Mechanically resilient parts	Necessity of post-processing step
Liquid and airtight	Removal of support material
Transparent components	Unicolored models

Component hybridization of both manufacturing processes can produce low-cost components (FFF) with locally adapted properties (SL). For example, the basic substrate of a plastic housing of a small electric motor can be manufactured at minimum cost using the FFF process. Parts with increased requirements for low surface roughness, liquid and airtightness as well as high manufacturing accuracy can be realized by integrating SL-manufactured sub-components with the help of a state-of-the-art machine concept. However, in order to transfer forces and moments into the housing, the interface, especially the adhesiveness, of both component partners must be investigated.

B. Conductive Polymer

Conductive Polymer Composites (CPC) are formed by combining conventional polymers with conductive fillers such as metal powder, carbon black and graphene.

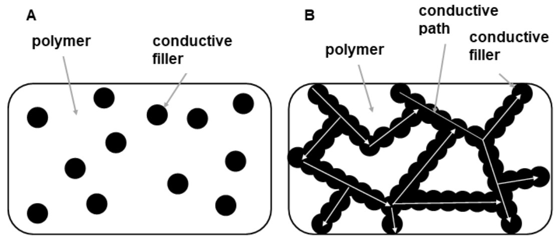

Figure 3. Additive concentration in polymer, (A) low concentration, (B) high concentration [10].

Soot: Soot is a finely dispersed solid consisting of spherical individual particles with diameters between a few dozen and a few hundred nanometers that have melted together to form aggregates. Soot is the most widely used conductive filler due to its low density, predominant electrical properties and low cost. However, the percolation threshold for carbon black is relatively high. The high carbon black content has a negative effect on the mechanical properties of the composite. [10]

Graphene: Graphene is a two-dimensional carbon layer consisting of C6 rings arranged in a honeycomb grid. Each carbon atom has a free electron on the outer shell, which can move over the surface as a charge carrier. This results in the good electrical conductivity of graphene. Graphene is considered the thinnest, lightest and at the same time strongest material in the world. [10]

C. Intrinsic Hybridization Concepts for Metallic Inserts

The state of the art in research and technology already provides approaches to embed metallic inserts in component structures. The aim is to create a functional extension. For example, by integrating a load introduction element into the component structure, moments and forces can be introduced without damaging the component structure. Such load introduction elements can already be integrated during the manufacturing process. In this case we define intrinsic hybridization of the component. In the literature different methods for intrinsic hybridization are discussed. In [11], for example, metallic inserts are integrated into fiber-plastic composites produced by Resin Transfer Moulding (RTM) in order to enable load introduction into the composite while protecting the sensitive fibers. A major challenge is the connection of the integrated insert to the matrix and the fibers. In the area of additive manufacturing, a hybridization concept in the FFF process for the production of metal/plastic composites was presented in [12]. For this purpose, a metal grid layer of copper is integrated during the FFF process. Acrylonitrile-Butadiene-Styrene (ABS) was used as the building material in the FFF process. In tensile tests a maximum tensile force of approx. 2400 N was achieved depending on the lattice density of the metal. In [13], the insertion of metallic inserts, especially nuts, into the FFF process was investigated. Besides the manufacturability and the geometric accuracy between metallic objects and FFF structures, adhesion plays a decisive role for the successful integration of an insert. [13] investigated the adhesion with the help of the test specimen below (Fig. 4). The base substrate was printed up to the layer of integration and then the part was inserted. After insertion, the printing process was continued, i.e. the insert was overprinted with two layers of polymer. In the course of this investigation the screen angle, ribbon width and spacing were varied.

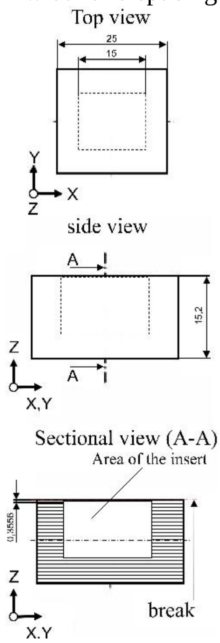

Figure 4. Test specimen for testing adhesion [13] .

Adhesion was evaluated on the basis of microscope images. A homogeneous inner grid without distortion leads to a high adhesion tendency when overprinting (Fig. 5 left). A high degree of adhesion was achieved by increasing the width of the strands. At imperfections, overprinting caused the molten filament to break off.

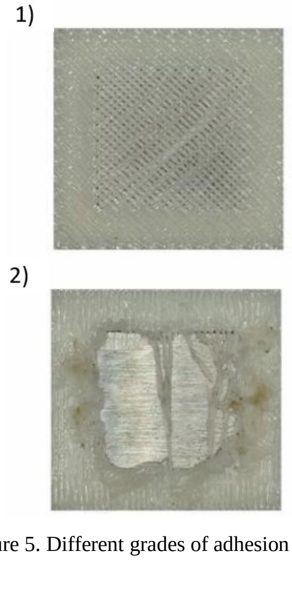

Figure 5. Different grades of adhesion [13].

In [13], a strand width of ≥ 0.60mm was specified. A larger strand width allows the nozzle to lay down a more robust strand and to deposit it more defined on the metal surface. The strand distance of 0mm should be avoided. If the strand distance is negative, the deposited strands may overlap and thus be torn off (Fig. 5 right). A strongly positive strand distance leads to a lower connection of the deposited strand on the metal surface. The screen angle has no influence on the adhesion. Another important factor influencing the adhesion tendency of the plastic is the ratio between the surrounding FFF surface and the area of the metal insert. Small surfaces can be compensated by the over stretchability of the polymer strand. For a high adhesion quality, the surrounding FFF surface should be at least 50% larger than the insert surface to be overprinted.

Numerous methods for increasing the adhesion properties between plastic and metal components are presented in the literature. On the one hand, adhesion can be achieved by mechanical surface treatment processes such as sandblasting or grinding. On the other hand, chemical processes use lyes or acids to increase the roughness of the surface. An increase of the surface roughness causes an increase of the surface energy which results in a better wetting of the active partners. In addition to chemical and mechanical processes to increase surface roughness, adhesion promoters, special coatings and adhesives are also used [14, 15]. In [15], an increase in tensile strength of 21.9 ± 1.1 MP was observed by using special coating systems for joining metal and plastic components produced in the FFF process. By using these binders, the tensile properties can be significantly increased compared to pure mechanical or chemical pre-treatment methods.

D. Research Deficit

The current state of research and technology includes some general approaches to significantly increase the adhesion properties between metal and plastic components. By using adhesion promoters, adhesives, special pre-treatment methods or coatings, the surface energy can be increased and thus an improvement in adhesion can be achieved. However, component hybridization between FFF and SL has not yet been investigated in the current state of research and technology. For this reason, the mechanical properties of thermoset acrylate SL inserts in FFF-manufactured thermoplastic polylactide (PLA) carrier components will be investigated in this study. A comparison with inserted metal strips in identical carrier components will be performed. In addition to the investigations described above, this study deals with the contacting of mechatronic subcomponents using conductive filaments. The main deficit here is the process investigation of three-dimensional printed conducting lines to reach the electrical requirements.

III. Experimental Setup

A. Adhesion Test

The tensile shear test according to DIN EN 1465 was chosen to investigate the adhesive effect between metal or SL-printed strips and FFF-printed plastic samples. This standard is mainly used to assess the usability and quality of adhesive systems. Since different types of failure occur between the samples, the maximum tensile force is used to compare the results. The sample geometries used are shown in the following Fig. 6.

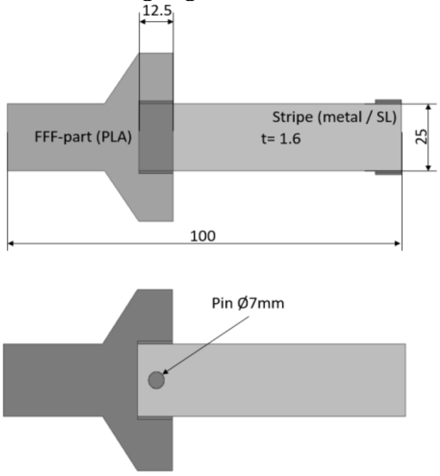

Figure 6. Test samples with adhesive (above) / form fit (below) connection.

The metal and SL strips were pre-treated mechanically and chemically according to Table III in order to investigate only the influence of the surface condition. In addition, the strip surfaces were measured with a mobile tactile measuring device (ATP HRT-W5) to determine the influence of the surface roughness on the adhesion effect. A form fit via pin was selected for the comparison of the substance-to-substance bondings (Pin diameter 7mm). The FFF samples were manufactured using an Ultimaker 2+. The following settings were selected: Nozzle diameter: 0.8mm; layer thickness: 0.2mm; printing temperature: 220℃; filling degree: 40%; printing speed 40mm/s; material: PLA (Ultimaker PLA); slicer: Cura. The process sequence for inserting the strips is shown in the following Fig. 7.

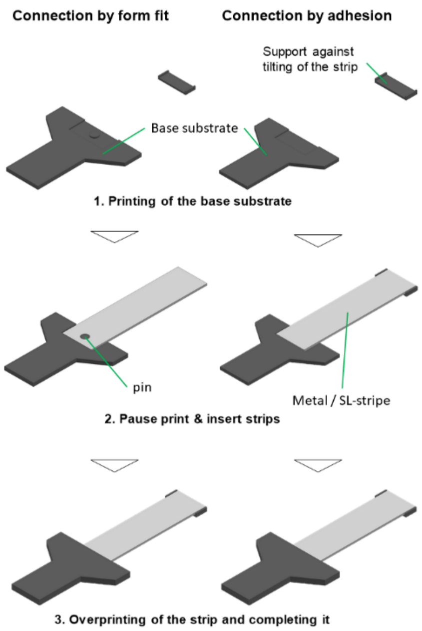

Figure 7. Process sequence for inserting the strips (metal / SL) into the base substrate (PLA).

First the basic substrate of PLA is produced in the FFF process. Once a previously defined layer is reached, the printing process pauses. During the pause, the prepared metal / SL strips are inserted into the cavity. After the strips have been inserted, the building job is continued and the printer overprints the strip surface (25 mm x 12.5 mm = 312.5 mm2).

TABLE III. PRE-TREATMENT OF THE METAL / SL SAMPLES

Type of joining connection	**Metal inserts**	**SL insert**
untreated	x	x
refined	x	-
pickled	x	-
uncured	-	x
sanded	x	x
sand-blasted	x	x
form fit	x	x

The structural steel strips are folded parts that have been cut out of a metal sheet according to DIN EN 1465. The SL inserts are manufactured out of the thermoset acrylate photopolymer Type D Standard from Druckwege GmbH (Hennef, Germany) with a D30II printer from Rapid Shape GmbH (Heimsheim, Germany) (Fig. 8 up). In order to investigate the influence of the residual reactivity and the resulting tacky surface of the photopolymer, a set of the samples was inserted into the FFF structure without post-exposure after the SL printing process (referred as “uncured”). This set has been post-exposed afterwards together with the FFF structure (Fig. 8 below). All other samples are exposed from each side with a dose of 5 J/cm inside the Opsytec BS-02 UV chamber (Opsytec Dr. Gröbel GmbH, Ettlingen, Germany) before inserted to the FFF component. The camber was equipped with 8 UVA mercury vapor lamps and was controlled via calibrated RM 12 radiometer sensors to a total radiation intensity of $6.7\ mW/cm^2$. This results into a tensile strength of 36.6 MPa, Young’s modulus of 1.28 GPa and 4.5% elongation at break according to the manufactures datasheet [16]. In order to investigate the influence of surface pre-treatment, one set each was treated by means of sandblasting and sandpaper (grain size 200). A form-fit connection was examined by adding a hole with 7 mm diameter, which was already included during the printing process (Fig. 7).

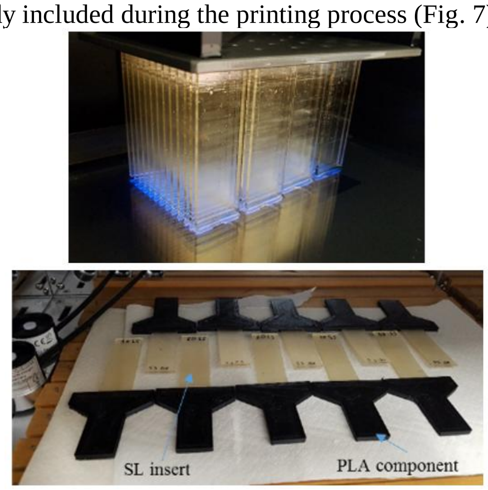

Figure 8. SL insert sample production. Up: UV-light based production of the initial samples. Below: Post-processing in UV camber to reach fully curing.

The tensile tests were performed using a tensile testing machine from Zwick/Roel (Load Cell Xforce K 20kN). A test speed of 2 mm/min and a preload of 1N was selected.

B. Experimental Setup to Investigate the Conductive Polymer

To evaluate the conductive materials for function integration of mechatronic components a test series was introduced. Aim of the test series was to investigate which parameters drive to the best conduction of sensors. The electrical resistance between temperature sensor and contact pin must be below a certain limit R_{max} for the sensor to work. This is determined by calculation and the result is verified by a test.

A solid connection must be made between the filament and the metallic components so that they are conductively connected. In order to develop a contacting strategy, the influence of the printer settings and direction of installation on the conductivity between the temperature sensor and the contact pin as well as the mechanical load capacity of the contacted components must be investigated. The electrical conductivity of a printed conductor is largely determined by the material used, the conductor cross section, the processing temperature, the resolution and the direction of build-up. These influences are investigated in the following and the results are evaluated. Proto-Pasta Conductive PLA was used as the electrically conductive filament in all experiments. In a partial factorial test series the following parameters were changed: Layer thickness, print temperature, bed temperature, material feed.

IV. Results

A. Adhesion Test

The surface roughness values were determined for the pre-treatment methods listed in Table III. Fig. 9 shows the averaged roughness (R_z) of the metal and SL samples. For metals, the highest roughness was produced by pickling. A treatment by cleaning causes a minimal reduction of the roughness, because this process step leads to a smoothing of the surface. If the roughness values of metal and SL are compared, the values of the SL samples are at a higher level due to the softer material after sanding and sand-blasting.

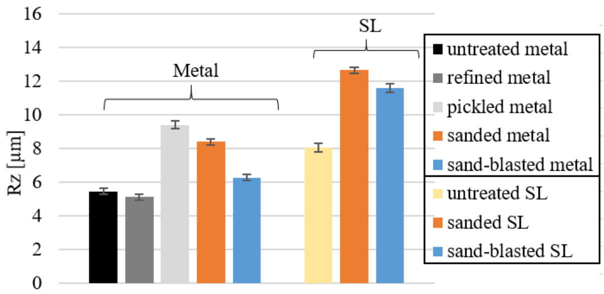

Figure 9. Comparison of roughness values of metal an SL insert samples.

With increasing roughness of the metal samples, a small increase of the maximum tensile force can be observed (Fig. 10). However, the differences between the untreated metal insert and the four surface treatments (refined, pickled, sanded, sand-blasted) show no statistically significant difference because of the high variance, except for the refined sample. The maximum tensile forces are between 35.45±8.37 N and 72.00±26.13 N. The metal form-fit shows a much smaller variance of the results with 47.20±1.95 N, but only a higher maximum tensile strength than the refined sample. All metal samples failed due to a pull out of the insert, which indicates a bad adhesion to the PLA.

If an SL-printed insert was used instead, a significantly higher tensile force can generally be achieved. Even for the untreated SL sample a tensile force of 314.94±9.91 N can be observed. Also a greater influence of the increased surface roughness can be seen compared to the metal inserts. If the surface was roughened by sanding and sandblasting, the maximum tensile force is up to 509.12±13.45 N and 498.52±8.99 N, respectively. The initially uncured specimen allows an increase to 396.88±14.32 N, but, like the form-fit variant, it is significantly lower than the sanded and sand-blasted specimens.

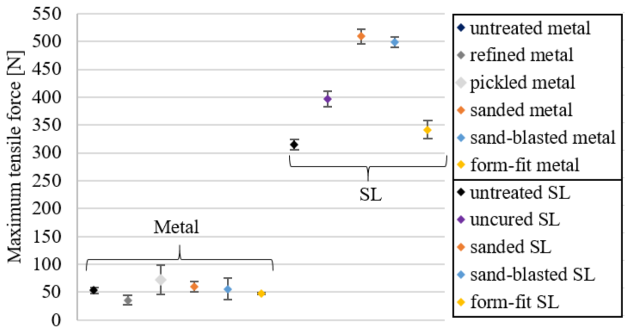

Figure 10. Results of lap shear tests with different pre-treated metal (left) and SL (right) inserts in combination with PLA during FFF process.

It is notable that the fracture of the FFF/SL specimen has always occurred within the SL component. For the untreated, uncured and form-fit samples this occurred mainly in the transition region (Fig. 11a and b). In the case of sanded and sandblasted specimens, a fracture usually occurs within the clamping jaws. By means of a pulled out SL specimen the traces of the FFF nozzle paths can be identified on the surface (Fig. 11c). This shows that there are micromechanical changes in the surface structure, which improves the adhesion.

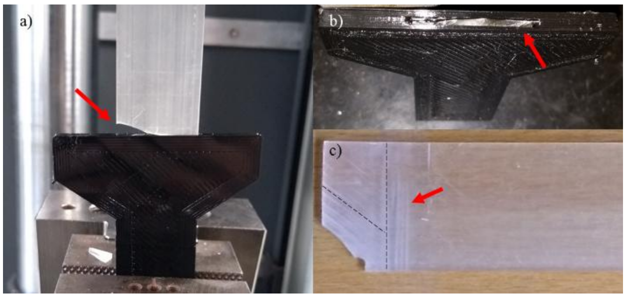

Figure 11. Lap shear specimens after tests. a) and b): PLA/SL specimen with fracture plane in SL component at transition between both materials. c): Traces of FFF nozzle on SL surface.

By considering the cross-sectional area of the SL insert, the sanded sample achieves a tensile strength of approximately 12.73±0.34 MPa. This is approx. 1/3 of the tensile strength of the purely printed polymer [16]. It is noticeable that the elongation at break was only 0.73±0.11%. According to the manufacturers specification, the elongation at break should be 4.5% [16]. This indicates that the interface would have been capable of withstanding a greater tensile load. This can be explained by early SL material failure due to stress concentrations at the transition between the two materials and the superposition of compression and tensile load with early crack formation in the clamping jaws.

B. *Electrical Contacting*

In Fig. 12 the final test object is displayed. A temperature sensor was directly in the additive manufacturing process automatically conducted by black coloured conductive polymer (PLA). After the test series the connection was investigated and verified.

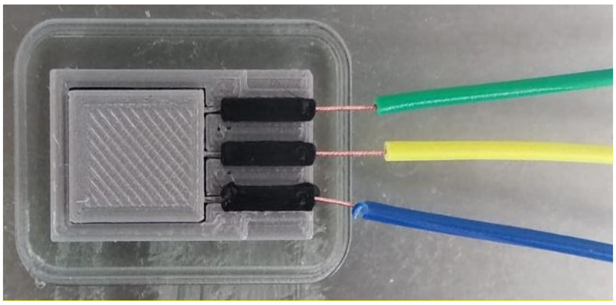

Figure 12. Imprinted sensor contacted in negative form.

The material is to be selected depending on the requirements for the electrical resistance of the conductor path. The conductor cross-section should be as thin as possible. The maximum temperature specified by the manufacturer must be selected as the processing temperature. If possible, the conductor track should be installed horizontally. Conductor tracks should be printed with the largest possible nozzle diameter and layer height (Table IV).

TABLE IV. PRINTER SETTINGS.

Printer Settings

Nozzle [mm]	0.8
Layer thickness [mm]	0.15
Print Temp. [℃]	225
Bed temp. [℃]	60
Material	Proto-Pasta Conductive PLA

Fig. 13 shows the almost linear increase of the electrical resistance with increasing measuring length. The specific resistance of the individual samples is approximately constant.

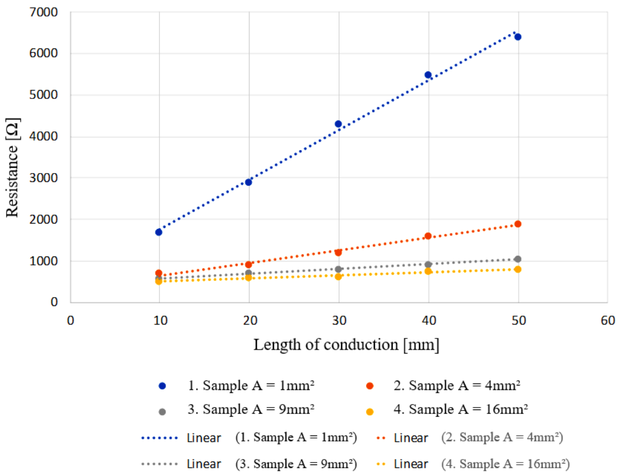

Figure 13. Graphical representation of the measured resistance values.

The specific resistances of the conductors are at the upper temperature limit during printing. T1 = 225℃ is always better than the pressure at the lower temperature limit T2 = 195℃. At a sample length of 20 mm the influence of the build-up direction is not significant. In contrast, the difference of the mean horizontal and the mean vertical resistivity at a sample length of 40 mm is 23 Ωmm.

V. CONCLUSION & OUTLOOK

The conducted study shows the feasibility of a FFF structure hybridization by integration of SL printed inserts. This enables the synergy of material properties, e.g. fluid-carrying cooling channels made of tight and resistant SL materials in combination with low-cost FFF housings, and hence allows an extension of the application spectrum of additively manufactured plastic components.

For optimum adhesion, the investigations have shown that the surface of the thermoset acrylate SL material should be mechanical treated with sandpaper or sandblasting to produce a significant increase in roughness. In direct comparison to metallic inserts, SL inserts generally offer better adhesion to thermoplastic PLA, whereby the mechanical surface treatment has a much greater influence than the form-fit. This allowed up to 1/3 of the maximum tensile strength of the SL material to be applied before premature failure in the clamping jaws occurred. Future studies should therefore perform material testing using additional force introduction elements on the specimen or a more ductile SL material to identify the maximum transmittable forces. When contacting mechatronic subcomponents, the described investigation showed that in principle, automated contacting was achieved using electrically conductive filaments. However, it turns out that the process management and precise temperature control have a considerable influence. Furthermore, the choice of filament content is important. Further investigations in printing three-dimensional complex conducting paths are focused.

Another further research aspect is the fully automatic insertion of the SL components to achieve an increase in production efficiency. In this context, special challenges of control engineering as well as the accuracy of robot and kinematics have to be solved. Especially when combining complex shapes, such as multi-bent cooling channels, high accuracy during placement is required. This should be tested in the next steps on component level, considering the influence of warpage on insert integration and the usage of subtractive surface pre-treatments.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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