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Additive manufacturing of sensors - printing of conductor paths in loaded structures

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Abstract

Saving energy for environmental protection and cost reduction are one of the most important objectives of our time. Topology optimizations and additive manufacturing make it possible to design complex structures with optimal stress distribution. This type of additive lightweight design will be one of the most important areas of research in the coming decades. However, due to the still high manufacturing costs today, additively manufactured components must offer further advantages, such as maximum functional integration, in order to offer an additional value compared to traditionally manufactured components.

The integration of sensors for monitoring the stresses and forces in heavily loaded structures such as cutting tools is a major focus of the developments. The application of foil strain gauges to determine force and torsion in a milling tool is very time-consuming and expensive due to the limited installation space and the necessary wiring. The Institute for Machine Tools at the University of Stuttgart, Germany developes additively manufactured milling tools in function-integrated lightweight design with the target to produce additively manufactured sensors in one process step with the production of a vibration damping plastic structure inside the tool. For this purpose, a non-conductive filament for an inner component geometry and a conductive filament for the creation of electrical conductor paths were used. A parameter study with different printing orientations, layer thicknesses, filling patterns, print head temperatures and printing speeds as well as different connection types or combinations between the materials provided the basis for the design of the special test samples with integrated sensors in the form of 3D-printed strain gauges.

Based on bending tests, new test samples were developed in accordance with the intended application in shell end milling tools. The additive and sensor integrative manufactured test samples were experimentally tested in a test bench specially developed for the typical combined loading of torsion and bending of milling tools.

Keywords: additive manufacturing, lightweight design, In-process measurement

1. Introduction

This paper describes the process development and the process optimization of additively manufactured electrical conductors using FFF (fused filament fabrication) also known under the brand name FDM (Fused Deposition Modelling) 3D printing. Conductor tracks in the form of strain gauges were additively integrated into an additively manufactured base body made of non-conductive material and subsequently tested. The combination of an additive damping structure with integrated stress sensors was investigated in further investigations for the direct integrability in tools.

After the selection of the electrically conductive material, the most important parameters of the FDM 3D printing were analyzed and optimized with the help of reference specimen regarding the electrical resistance. Strain gauges made of electrically conductive material were embedded in a carrier plate made of PLA in order to investigate the behaviour of the electrical resistance under bending loads. In extensive tests, the strain gauges demonstrated a high sensitivity to strain. As a result, four strain gauges were integrated into a cylindrical PLA test sample and additively manufactured. Connected as a Wheatstone full bridge, it was possible to compare the measured values for torsion loads with those of standardized strain gauges using a scaling factor. Finally, strain gauges produced with FDM 3D printer were bonded into a metallic test sample to compare the behaviour under torsion loading with standardized strain gauges.

1.2 State of the art

A review of 3D-printed sensors was given in [1] und [2]. These two papers, published almost simultaneously, presented a good overview of various additively manufactured sensors. Since there is already a large and constantly growing number of 3D printing processes in the development of additive technologies, almost 150 literature sources were cited in both papers from 2017. Both papers contain an extensive reference and overview table, in which [1] the sensor table is sorted according to the 3D printing process and [2] the sensor type, for example strain sensor, pressure sensor etc., is used as reference criterion. In a further table the processes with advantages and disadvantages as well as the possible 3D printing materials are presented.

An initial approach to 3D-printed strain sensors using the FDM method was presented in [3] in the form of printed conductor tracks. The authors from the University of Warwick, United Kingdom, produced an electrically conductive material made of 15 % Carbon Black and PCL (polycaprolactone) with the name "Carbonmorph". With application examples such as flex sensors, 3D printed glove, 3D printed capacitive interface device and 3D printed smart vessel, both the test objects and the measured variables of the applications were presented clearly. Preliminary research in the field of dynamic measurement of 3D-printed strain sensors has already shown the ability to measure frequencies up to 800Hz [4]. A similar material was used in the experiments for this paper.

The developments presented in this paper will be used in a smart milling tool after the basic investigations presented/performed, which, in addition to the tool presented in [5] and [6], also contains additively manufactured load-bearing structures in multi-material lightweight design in addition to the additively integrated tracks and strain gauges (see [7]).

2. Material and print parameters

For the development of printed strain gauges presented in this paper, we used an ECC filament (electrically conductive composite) already available on the market under the brand name of “Proto-pasta” with volume resistivity of molded resin (not 3D printed): 15 Ωcm. This is comparable to the filament presented in [3] and consists of a PLA (polylactide) enriched with carbon black. The conductivity of the filament depends significantly on the process parameters of the 3D printing process. The parameters extruder temperature, layer height and filling pattern in x-y layer were identified on the basis of a preliminary investigation. In addition, further dependences could be identified by the layered design in z-direction as well as the contacting of the conductive surfaces. Samples with three conductive areas were defined for comparable tests. Figure 1 shows an exemplary sample.

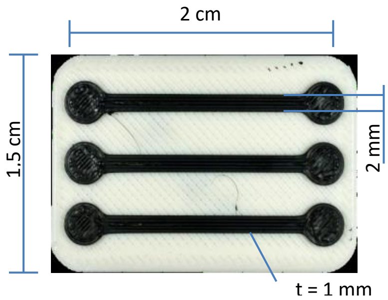

Figure 1. Sample with three conductive regions

2.1 Influence of extruder temperature

One of the main criteria for a successful 3D printing process is the extruder temperature. The temperature setting is important for the reliable material flow as well as for the conductivity of the filament. The minimum printable temperature without printing error is T_d = 200 °C. The maximum temperature without deformation of the printing lanes is T_d = 240 °C. For the tests, the extruder temperature was varied in 5 K steps. Figure 2 shows the measured resistance R as a function of the extruder temperature.

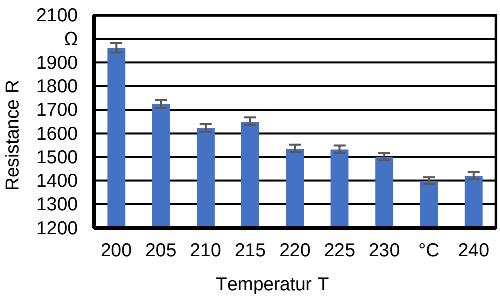

Figure 2. Resistance variation as a function of extruder temperature

The results shows a reduction of the resistance R with increasing printing temperature up to T_d = 230 °C out of a total of 22 %. This was due to an increasing adhesion of the individual layers. Macroscopically, the samples showed no clear differences. T_d = 230 °C was subsequently determined as the optimum printing temperature for the target of small circuit resistances.

2.2 Influence of the filling pattern

The filling pattern is a basic setting in FDM 3D printing and describes the travel path of the extruder inside a layer. In contrast to the conventional requirements of stability and optics, the filling pattern is to be examined with regard to the different conductivities. To avoid gaps, the filling density is kept constant at 100 %. The filling patterns "Grid", "Linear", "Triangles", "Concentric" and "Gyroid" were investigated. For the investigation, simple tracks in the size from 5 mm to 40 mm were used. Figure 3 shows the different resistances of the different filling patterns

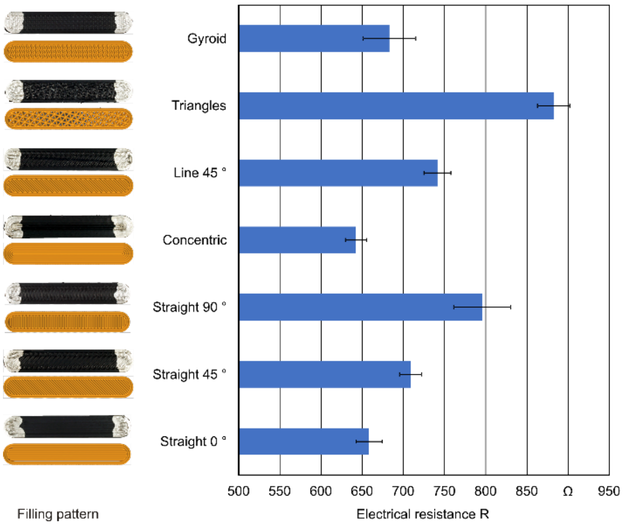

Figure 3. Results of the test series with different filling patterns

A closer look at the filling patterns revealed inhomogeneities of the electrically conductive layer. A parallel arrangement of the printing tracks showed an up to 21 % improved conductivity compared to vertical tracks. This was particularly evident in the comparison of the linear filling patterns in 0°, 45° and 90°. The concentric filling had the lowest resistance due to a very dense filling of the samples and was used for the further investigations.

2.3 Influence of the layer height

In classic FDM 3D printing, very small layer heights of 0.05 mm are used to achieve high accuracies. The basic principle is that the thinner the layer, the finer the component is dissolved. However, the electrical resistance of a conductor track behaves in the opposite direction. The smaller the conductor cross-section, the greater its resistance. The results in Figure 4 showed that the electrical resistance decreased with increasing layer height and layer thickness. Therefore several thin layers had a worse effect on the total resistance than one thicker layer.

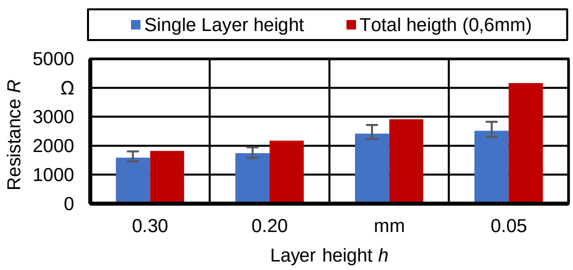

Figure 4. Influence of the layer height on the electrical resistance

2.4 Layer structure (angle dependence)

In addition to the influence of the layer height and the filling pattern, the component orientation and angular position during the printing process also influence the conductivity of the material. Tests of various samples with angles of 0° - 90° showed that the measured resistance in the z-direction increased by up to 37.5 %. Figure 5 shows the measuring results of the samples printed at different angles.

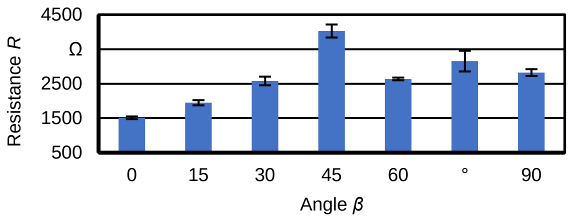

Figure 5. Resistance values at different printing angles

It is clearly visible that prints at an angle of 45° provided the highest resistance. A reduction in the inclination angle to 30° reduced the expected resistance by half.

2.5 Influence of the contact zone

The contacting of the printed conductors is another challenge. Depending on the contacting method, the resistance values can be noisy or stable. Various types of contacting such as panel-mount-sockets, solder, silver conductive lacquer and melted down wires were investigated. Figure 6 shows the different contact types.

Figure 6. Contact zone

For short-term resistance measurements with a multimeter, the silver conductive lacquer with a special contact resistance ρ_V of 0.1209 Ωm proved to be suitable. However, this is not suitable for permanent measurements. Melted wires in the contact zone provided more stable measured values with a specific contact resistance of ρ_V = 0.1281 Ωm.

3. Application of printed conductors

The additive manufacturing of embedded, electrically conductive filaments in non-conductive plastic base structures paves the way for highly integrable components and products. The main goal of this development was the application-oriented integration of conductive structures, in particular for stress measurement, in passively damping plastic structures. In a first research step, strain gauges were manufactured and tested for functionality. Figure 7 shows the first basic tests of an additive strain gauge in combination with a PLA base plate.

Figure 7. Printed strain gauge on base material

The structure was loaded with test weights of 200 g - 800 g and the measured values were recorded using a HBM Quantum amplifier. The load phases were repeated 5 times to identify deviations of the measuring signal. Figure 8 shows the result of an examination of a sample printed on the x-y plane.

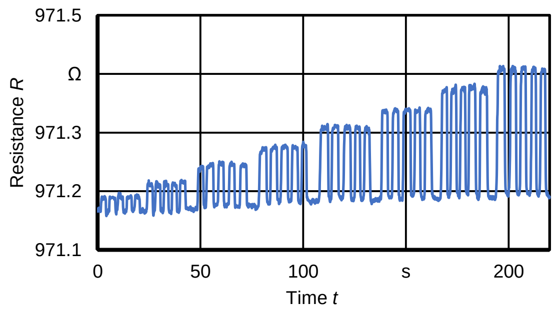

Figure 8. Measuring result of printed strain gauges:

The samples were printed in different directions and angular positions taking the influence of the printing orientation into ccount. The measured values of the different samples showed different changes in resistance for the bending test (the resistance of the samples is not constant due to the design) but with similar curves. Figure 9 summarizes the results of the investigations for four different pressure angle positions.

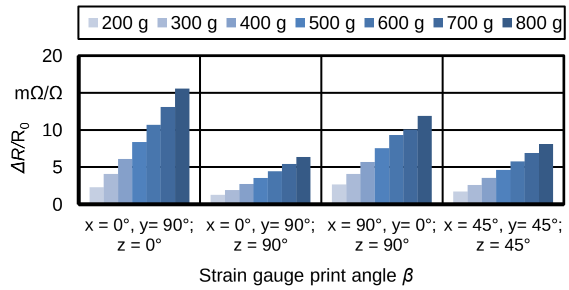

Figure 9. Comparison of the resistance change of samples for different printing orientations

The tests shows a basic functionality of additively manufactured strain gauges in polymer structures. However, the results of the printing orientation tests also showed that the behaviour of the strain gauges changed depending on the angular printing position. The investigation of this dependence, with the aim of producing cylindrical components for integration into tools, was carried out by comparing standardized strain gauges on a torsion test bench (see Figure 10 on the right). Several strain gauges were printed into the sample (see Figure 10 left) and connected as a full bridge.

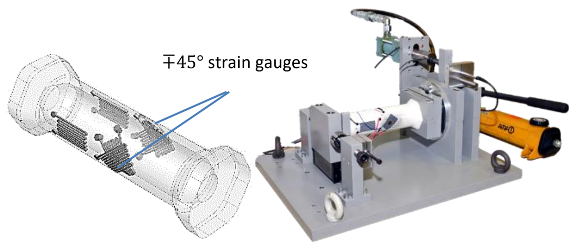

Figure 10. Printed model (left) and test bench (right)

Strain gauges with a resistance value of 120 Ω, type QFLAB-3-11 by Tokyo Sokki Kenkyujo Co. were used as reference. The samples were loaded and unloaded five times with 70 Nm. The force applied caused the sample to rotate by 2.3°. The results of the measurements in Figure 11 showed clearly low amplitudes of the printed strain gauges (orange) compared to the reference strain guages (blue). Using a scaling factor 30.71 (determined by the basic test bench Figure 7 & 9), the measuring results of the printed strain gauges are comparable with the results of the reference strain gauges (red).

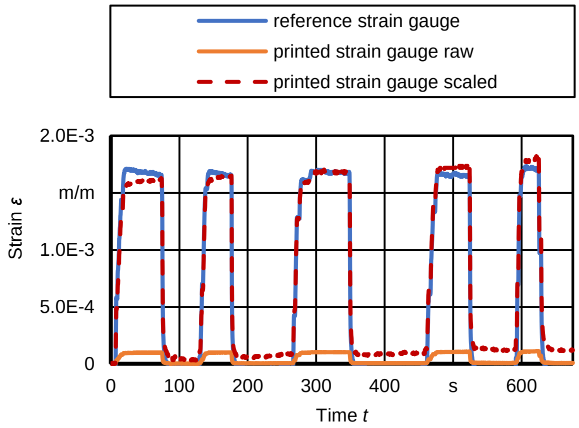

Figure 11. Torsion measurement printed strain gauges vs. bonded strain gauges

Figure 11 shows the small deviation of the measured values. The measured values of the printed strain gauges showed neither a temporal shift nor larger amplitude deviations. The maximum deviation of the tested strain gauges was 5 % for multiple loads. However, the large twist angle of the specimen also indicated large strains in the measuring region. For the integration into metallic bodies, which exhibit considerably smaller deformations, the behaviour of the additive strain gauges was investigated. Figure 12 shows the schematic structure and the interconnection of the sample with four printed strain gauges.

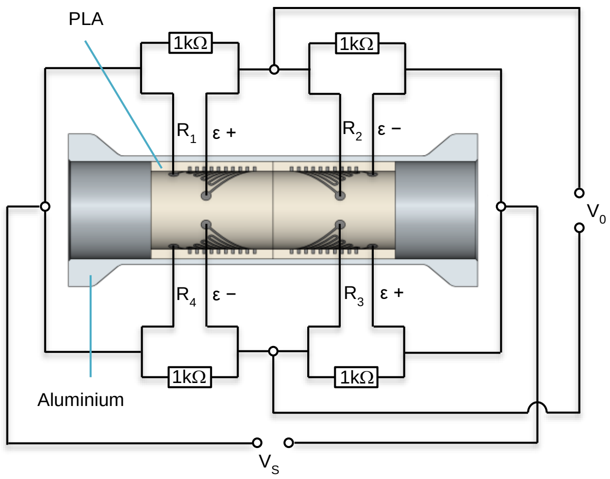

Figure 12. Connection diagram of printed strain gauges

The basic body was made of aluminium. The additive structures were bonded into the aluminium body with a two-component adhesive 9200FR by MG Chemicals. Four 120 Ω strain gauges of type QFLAB-3-11 were also used as full bridges for reference measurements. The additive structures had an outer diameter of 45 mm with a grid length of 20 mm and a conductor cross-section of 2 mm^2. The size reduction of the additive manufactured strain gauges leads to an increase of the basic resistance to 20 kΩ per strain gauge based on the experiences of the preliminary investigations. The evaluation of the printed strain gauges was therefore only possible with an extended bridge circuit consisting of parallel-connected 1 kΩ resistors. This reduced the maximum resolution of the bridge circuit. Figure 13 shows the results of the measurement with a load of 100 Nm and a maximum rotation angle of 0.3°.

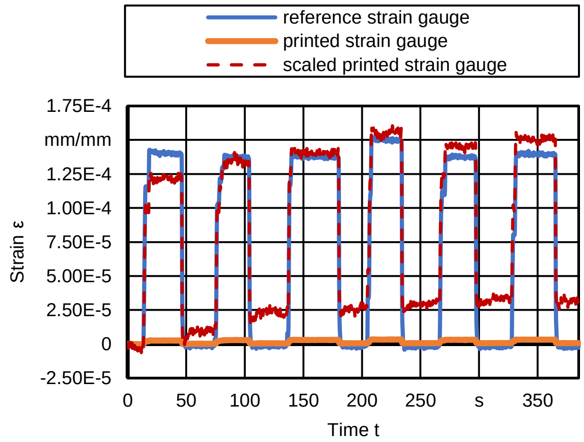

Figure 13 Sample comparison of standard strain gauges with printed strain gauges in a composite design under torsion stress

The results show clearly recognizable amplitudes of the printed strain gauges. Despite a longer transient response at the beginning of the measurement and the strong reduction in measuring resolution, repeated measurement values with low fluctuations could be generated.

4. Conclusion and outlook

The investigations shows that the additive manufacturing of rotationally symmetrical basic bodies with integrated strain measuring structures with the required accuracy is possible. The geometry to be printed at an angle of 45° and the resulting high basic resistances of 20 kΩ were considered to be problematic in this application. In addition, due to the angular position and the step effect, at least 1 mm thick conductor paths of the strain gauges were possible. For the integration of printed strain gauges in tool bodies, a reduction in the size of the strain gauges as well as a general reduction in the line resistances were therefore required. New conductive materials for FDM 3D printing are currently being tested at the Institute for Machine Tools in Stuttgart and validated for the application shown. In addition, new printing methods for reducing the step effect are being researched in order to reduce the print-angle dependence of conductive filament.

References

[1] Yujie Ni, Ru Ji, Kaiwen Long, Ting Bu, Kejian Chen & Songlin Zhuang 2017 A review of 3D-printed sensors, *Applied Spectroscopy Reviews*, **52:7**, 623-652, DOI: 10.1080/05704928.2017.1287082

[2] Yuanyuan Xu, Xiaoyue Wu, Xiao Guo, Bin Kong, Min Zhang, Xiang Qian, Shengli Mi, Wei Sun 2017 The Boom in 3D-Printed Sensor Technology *Sensors (Basel)* **17(5): 1166**, doi: 10.3390/s17051166

[3] Leigh S. J., Bradley R. J., Purssell C. P., Billson D. R., Hutchins D. A. 2012 A simple, lowcost conductive composite material for 3D printing of electronic sensors, *PLoS One* **7(11)**: 1–6.

[4] Maurizi M, Slavic J, Jerman M 2019 Dynamic Measurements Using FDM 3D-Printed Embedded Strain Sensors In: *Sensors 2019,2661*

[5] Maier W, Möhring H-C, Werkle K. 2018 Tools 4.0 – Intelligence starts on the cutting edge. *Procedia Manufacturing.* Volume **24:** 299-304.

[6] Möhring H-C, Maier W, Werkle, K 2018 Increasing the Accuracy of an Intelligent Milling Tool with Integrated Sensors. **18th** *International Conference & Exhibition, Proceedings* ISBN: 978-0-9957751-2-1: 235-236.

[7] Werkle K, Maier W, Möhring H-C 2019 Additive manufacturing for intelligent lightweight tools. In: *Production at the leading edge of technology.* Springer-Verlag, ISBN: 978-3-662-60417-5: 269-275.