Printed Strain Sensor

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TPU-substrate

Abstract

In this paper, information is provided on a printed strain sensor that enables in-situ strain measurements in an elastic fixture used for 3D molding of carbon fiber mats. The research is taking place as part of the DIREKT project (Digital Reconfigurable Manufacturing of Fiber Composite Components in an Elastic Production Environment) funded by the German Federal Ministry of Education and Research (BMBF).

The aim of DIREKT is to develop a reconfigurable, self-monitoring and sensor-supported production environment for components made of high-performance fiber composites. The basis is formed by low-consumption lay-up processes for carbon fiber-based semi-finished products as well as shape-adaptive tools that make the time-consuming and cost-intensive production of component-specific molding tools superfluous. Various sensors are integrated into the production environment at the Institute of Aircraft Design (IFB) in Stuttgart to continuously monitor the process.

The sensor presented here, which was developed by the HdM, is a single use (it will most likely be destroyed during the forming process), extremely low-cost strain sensor that can detect strains of up to 100 %. The sensor is screen printed on a TPU substrate and uses stretchable conductive silver tracks. A four-point resistance measurement is used to improve the measurement accuracy.

1 Introduction and background

In this paper, a screen-printed sensor is described that can measure very high elongations during a 3D forming process of carbon fiber mats. The sensor is developed within the scope of a project that is funded by the German Federal Ministry of Education and Research (BMBF). The project is called “Digital

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Reconfigurable Manufacturing of Fiber Composite Components in an Elastic Production Environment", with the acronym "DIREKT". In DIREKT several partners worked on the goal to develop and test a reconfigurable, self-monitoring and sensor-supported production environment for components made of high-performance fiber composites. The basis is formed by low-consumption lay-up processes for carbon fiber-based semi-finished products as well as shape-adaptive tools that make the time-consuming and cost-intensive production of component-specific molding tools superfluous. Various sensors are integrated into the production environment that is prototyped at the Institute of Aircraft Design (IFB) at Stuttgart University to continuously monitor the process. The sensor described here is intended to measure the strain of carbon enforced fiber mats during draping and the subsequent (adaptive) forming process. Figure 1 shows such a forming tool. The tool is called double dome and is used throughout the whole investigation. Figure 2 shows a close-up with a formed carbon fiber mat. The pictures in Figures 1 and 2 can be found on the IFB website[1].

Figure 1. *Forming tool "double dome" at IFB*

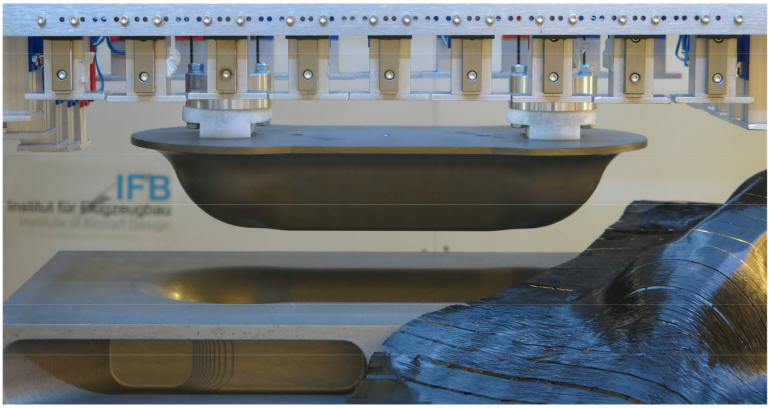

Figure 2. *Forming tool close-up with formed carbon mat*

Since the carbon fiber mats are anisotropic a delamination or rupture between the fibers can likely occur. The strain sensor should be able to detect the onset of these failures and it is possible to have a kind of early feedback where defects are likely, and the forming tool can be adapted. Such an adaptive forming tool that has been developed in parallel during the project by the company Cikoni (www.cikoni.com) is shown in Figure 3. Each piston can be adjusted in height individually.

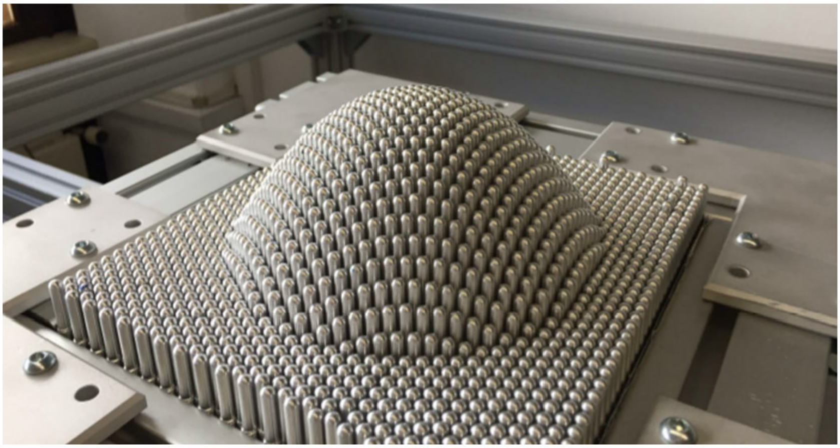

Figure 3. *Adaptive forming tool at IFB developed by Cikoni.*
Image source: www.cikoni.com.

2 Methods

Sensor Concept

The idea of a printed strain sensor is very basic. It can simply be a conductive path, as shown in Figure 4, whose resistance increases when the material is stretched under longitudinal stress. The change in resistance is caused by the decreasing contact between the conducting particles..

Figure 4. *Conductive path with contact pads at both ends.*

In the beginning we worked with a printed path of conductive ink in the dimension (rectangle) 200mm x 4mm. Material candidates were silver and carbon black. Although silver is more expensive than carbon black, it turned out that silver has the better performance for high strain. The most important requirement is the monotonous increase of resistance vs. strain. The tested carbon black not always showed such a monotonous behaviour. Since silver has a low resistance, a few ohms at the start of stretching, the electrical supply line required from the sensor inside the mold to the resistance meter in a control station outside the mold (see Figure 5) begins to affect the resistance reading. When the mold is set up, it is impossible to avoid that the supply lines themselves are affected by changes in stretch or temperature.

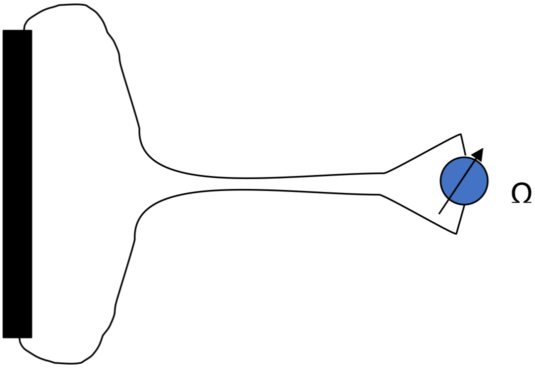

Figure 5. *Conductive path (sensor) with supply lines to the resistance measurement tool*

In electrical engineering there is a well-known way to eliminate the influence of the supply lines. Instead of a 2-point probe a 4-point probe measurement is used, which is shown schematically in Figure 6.

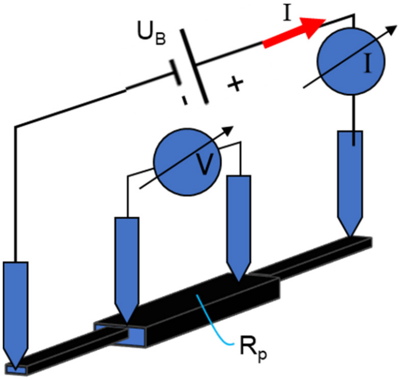

Figure 6. *Conductive path (sensor) with supply lines to the resistance measurement tool.*

The schematic drawing in Figure 7 now depicts the setup and the unknown resistance of the sensor probe Rp is determined by applying a known current I and measuring the voltage drop Up over the resistance Rp.

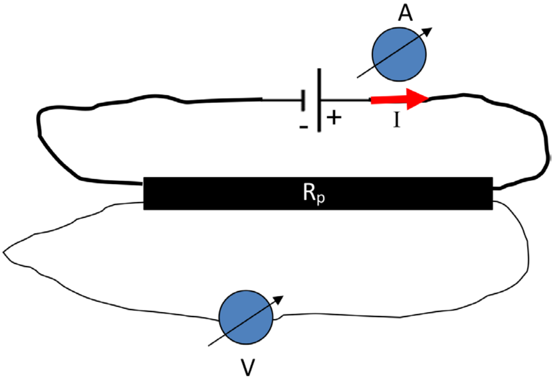

Figure 7. *Schematic drawing of the 4-point probe setup.*

According to the equivalent circuit diagram shown in Figure 8 under the assumption that $R_M >> Rp$ the unknown Rp can be found with $R_P = U_M / I$.

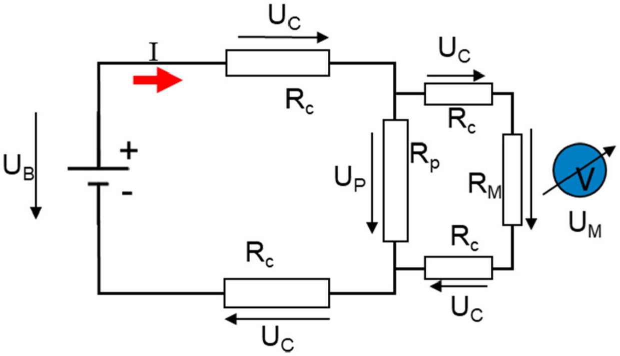

Figure 8. *Equivalent circuit drawing of the 4-point probe setup.*
Symbols drawn according to European standard

It is
R_C = resistance of connector supply lines
R_M = inner resistance of voltmeter
U_B = supply voltage
U_C U_M U_P = corresponding voltage drops

Figure 9 shows a printed sheet with six copies of the sensor, each with 4 supply lines. During the tests, the length of the actual sensor was reduced from 200 to 40 mm and finally to a length of 24 mm. This allows more sensors to be placed in different directions on the carbon fiber mats. It was found that the original sensor length does not play a significant role. The important change in resistance is independent of the length when properly normalized.

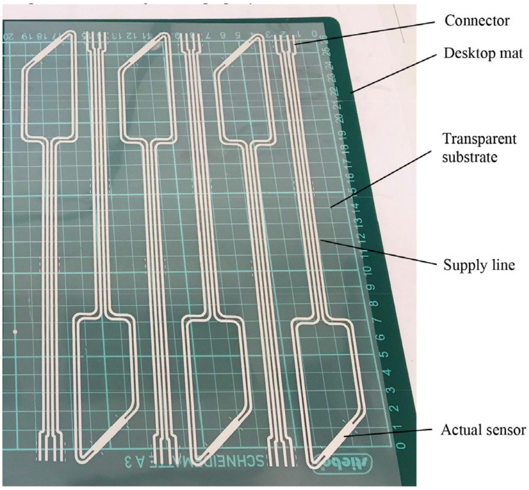

Figure 9. *TPU sheet with 6 copies of the sensor including the supply lines.*
The sensors are laser cut for applying onto the carbon mats

The high strains that can be expected lead to the fact that the sensor is single use only. During the forming process in the mould, it has undergone an irreversible change in dimension and will not regain its initial length when the stress is released. Therefore, the sensors must be absolutely low cost. To save material and resources six copies are printed at the same time. Later they are laser cut. The connection to the system environment is done outside the mould using standard ZIF-connectors (zero insertion force).

Inks

Small particles are advantageous for the highest possible conductivity of the print layer. Larger particles, however, maintain contact with each other longer during the slip process and maintain conductivity. Therefore, for large strains in combination with high conductivity, bimodal flake-like particles are promising (Mohammed 2016). In the last years commercially available screen-printable silver inks, usually referred to as polymer thick film (PTF) inks, were brought to the market that are specifically designed for stretching. Two types, both from SUN Chemical, were used: CRSN2442 and AST6400. After printing and drying, the inks were treated at 120°C for 30 minutes to achieve optimum conductivity. With the AST6400, maximum elongations of up to 100% were observed almost independent of track thickness. The CRSN2442 showed less maximum detectable strains (50 to 80 %) depending on trace thickness. The trace thickness was varied by using different meshes (made of PET), namely 54 - 64, 77 - 48 and 120 - 34, the first number representing the mesh count (threads per cm) and the second number representing the thread diameter in microns. In the forming tests performed later, it was found that the elongations usually do not exceed 50%, unless a crack occurs. The sensors therefore work reliably and faultlessly during the forming processes.

Substrates

As the substrate TPU (Thermoplastic Poly Urethane) is used. TPU has a quite low modulus of elasticity, thus it is stretchable very easily and therefore has a neglectable influence on the deformation process.

To provide good adhesion of the ink to the substrate different pretreatments have been evaluated to optimise performance. It turned out that atmospheric plasma treatment which usually yields superior adhesion in the case of TPU is causing a large scatter of the measured resistances. A preheating at 120°C of the foil was helpful. Another extremely helpful feature of the substrate is that it is not conductive at all since the carbon fibre mat is conductive and therefore would infringe the measurement.

Two foil thicknesses were evaluated 60 and 25 µm, both from Gerlicher industries. The 25 µm TPU foil for stability reasons comes on a BOPP carrier foil. This turned out to be very helpful for handling and thus this foil was used. The carrier foil is removed when placing the sensor onto the carbon fibre mat. For the in-situ measurements the endings of the sensor are attached to fibre mat by gluing or welding (ultrasonic).

Strain Testing

Thorough testing of the sensors was performed at our partners IFB. Therefore, test rigs were built that are shown in Figures 10 and 11. With this equipment curves could be recorded force vs. strain and most important the resistance over strain curves.

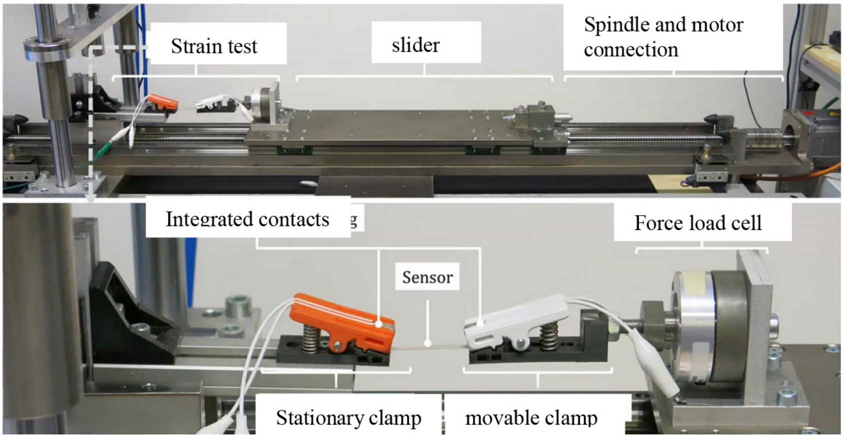

Figure 10. *Test rig for measuring the behavior at longitudinal stress (Ring 2020)*

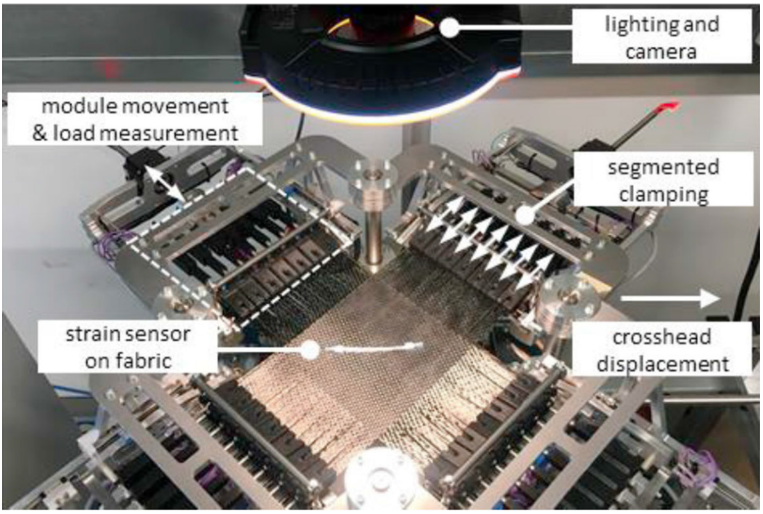

Figure 11. *Test rig for measuring the behavior at shear stress (45°) (Fial et al.2020)*

3 Results

The characterization of the change in resistance due to applied strain was done with the test rigs shown above and the recorded result for the 200 mm sensors are shown in Figure 12.

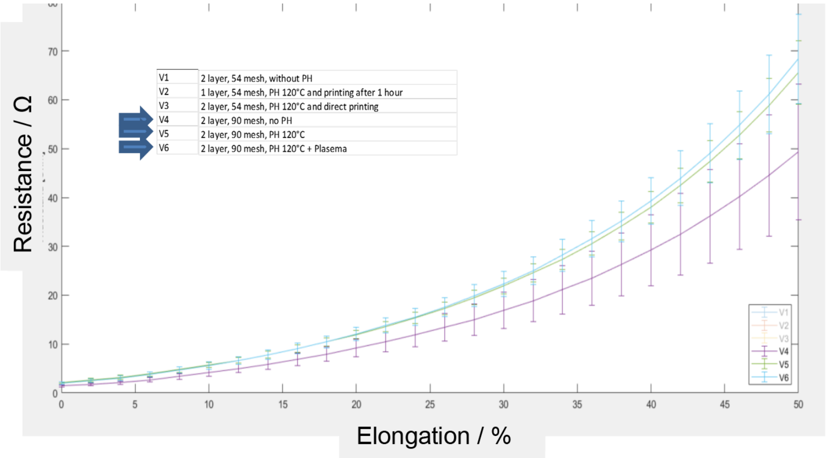

Figure 12. Resistance vs. elongation measured on TPU 25 micron foil with different pretreatments and different screen meshes

As can be seen in Figure 12 the 54 mesh (54 threads per cm) that produces a higher silver layer thickness shows a higher change in resistance than the mesh with a mesh count of 90 threads per cm.

Different pretreatments were used in this experiment. PH stands for preheating. The atmospheric plasma pretreatment of the substrate (curve V6), which normally improves adhesion very well, seems to be counterproductive because the scatter of the measured data, represented by the error bars, is the largest. Thus, the preheating was chosen for further procedures.

In another investigation carried out during a bachelor thesis the stretching behavior of the silver inks was examined. Figure 13 shows SEM images of the conductive paths before and after stretching.

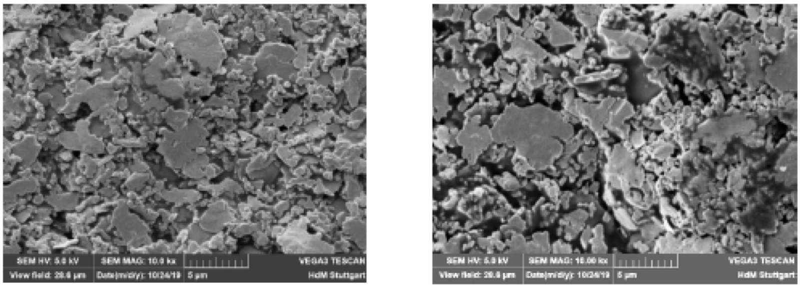

Figure 13. *SEM images of conductive silver path. Left before, right after stretching (Genz 2019)*

It can be clearly seen that the conductive particles become more and more separated from each other as they are stretched.

Conclusions

In this project, it was shown that the printed strain sensors work well and thus help to optimize the production process of 3D forming of lightweight components from draped carbon fiber mats. Figure 14 shows the carbon fiber mat prepared for the double-dome forming process. Two screen-printed sensors are mounted on the mat and the connection to the remote control system (data acquisition) with ZIF connectors can be seen.

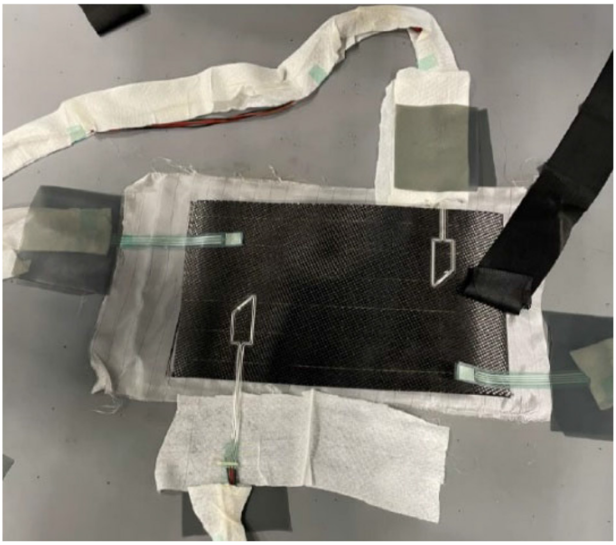

Figure 14. *Two printed strain sensors attached to the carbon fiber mat prepared for the forming process*

The low-cost sensor performed so well that the project partners IFB (application), Balluff GmbH (electronics and system environment) and HdM (printing) decided to apply for a patent. Currently the patent is pending.

Acknowledgements

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