STRAIN SENSING USING SINGLE CARBON FIBRES

T. Mäder*, D. Nestler, B. Wielage
Institute of Materials Science and Engineering, Composite Materials Group,
Chemnitz University of Technology, Germany
* Corresponding author (thomas.maeder@mb.tu-chemnitz.de)

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Abstract

The use of embedded sensors and actuators for condition assessment of machines and structures is on rising demand. Composite parts with high requirements on safety and a long economic life-time, e.g. parts in airplanes and blades of wind turbines, will be equipped with strain- and impact-sensitive sensors in the future to monitor their load history. The diameter or size of all available strain sensors is bigger than that of the fibres in composite materials and thus these sensors influence the structure and distort the strain measurements [1]. Therefore, the aim of this work is to develop a strain sensor with a diameter equal to that of the reinforcing fibres. Carbon fibres (C fibres) show piezoresistive properties. This effect can serve as strain- and tension-sensitive microsensor technology capable of supporting health and safety monitoring functions in parts made of composite materials. A fabrication method for single C fibre sensors based on thin-film deposition technology (magnetron sputtering) has been developed.

1 Introduction

The non-destructive in-situ structural health monitoring (SHM) of highly loaded composite parts, in particular with a spatial resolution of strain down to fibre size, is still an unfulfilled quest. Marketable sensor solutions cannot be found. However, for some prototypes, different physical effects are used to realise embedded sensors for the macroscopic strain measurement in composite materials. Embedded sensors guarantee an artefact-free, lasting and, related to the cross-section of the part, representative strain measurement. Furthermore, these sensors are protected against external mechanical impacts [2]. Therefore, embedded sensors are more reliable than resistance strain gauges and should be favoured. There are different strain sensor principles allowing an embedded application based on different energy transformation effects. Piezoresistive [3], piezoelectric [4] and magnetostrictive materials [5] are commonly used. Furthermore, optical fibres with and without engraved gratings (fibre Bragg grating - FBG) are used to detect strain [2, 6]. The minimisation of the sensor diameter is a goal for fibre-based sensor development. A significant reduction of the diameter of optical sensors has been achieved in Japan [6]. The Japanese FBG sensor has a diameter of only 52 µm and is the smallest of its kind. Embedding this sensor reduces the notch effect evoked in the surroundings compared with common FBG systems. The change of the electric resistance of carbon-fibre-reinforced plastics can also be used as a measure for strain shifts. Carbon fibres are electrically conductive and comprise a graphitic microstructure of high order. Loading and changes in strain therefore induce a shift in the electric resistance within the fibres [7]. Carbon fibres show piezoresistive properties. Single carbon fibres are currently not used as strain sensors. Embedding of strain-sensitive wires by stitching (e.g. constantan) is another possibility to realise piezoresistive strain sensors [3]. Wires with a diameter of less than 25 µm are not commonly available. An artefact-free strain measurement cannot be guaranteed with thick wires.

Summarising literature studies, the development of a strain microsensor is necessary to fulfil the above-mentioned demands – in particular artefact-free and space-resolved strain measurements. The goal of the present project therefore is the development of a strain-sensitive sensor which can be integrated into composite parts with a minimised influence on the composite structure. A minimum influence can primarily be realised by minimising the sensor dimensions.

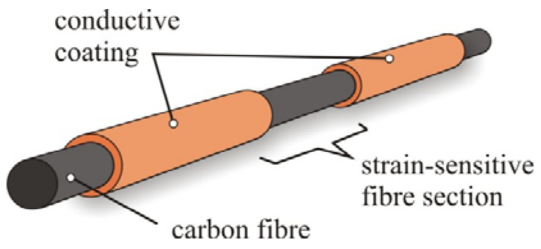


Fig. 1: Functional model of a strain-sensing piezoresistive carbon fibre sensor

At a diameter of less than 10 µm, stress peaks, notch effects and damaging influences of the sensor on the composite structure can be omitted.

One approach chosen to reach this goal is the use of partially coated single C fibres. A conductive coating on the fibres serves as a signal guide to the sensitive structure. The coating also facilitates an easier contacting of the sensor compared with the naked fibre. The uncoated part of the C fibres is then used as strain-sensitive section (cf. Fig. 1). By measuring the change in the electrical resistivity along the uncoated fibre segment, the strain in a limited composite volume can be sensed.

2 Experiments

The deposition of conductive layers on carbon fibres was carried out using the magnetron sputtering technology. For the production of sensor fibres, aluminium layers were partially deposited. Chromium was used as a coupling agent to increase the bonding of the layers. The coating process was done by means of a rotating fibre holder. This device allows the continuous rotation of the substrate fibre above the sputter magnetron while plasma deposition runs to guarantee an even coating. The deposition was carried out at a power of 400 W using a DC generator. The process regularly lasted 20 min. After that, the layer microstructure was investigated using the focused ion beam sample preparation and the electron microscopy (SEM, STEM). To determine the mechanical properties of aluminium layers, single-fibre tensile tests were carried out with coated fibres. Therefore, single fibres were completely coated for 30 min or 60 min with the same parameters achieving layer thicknesses of about 700 nm or 1400 nm. For each type, 10 tensile tests were made to ensure statistic validation.

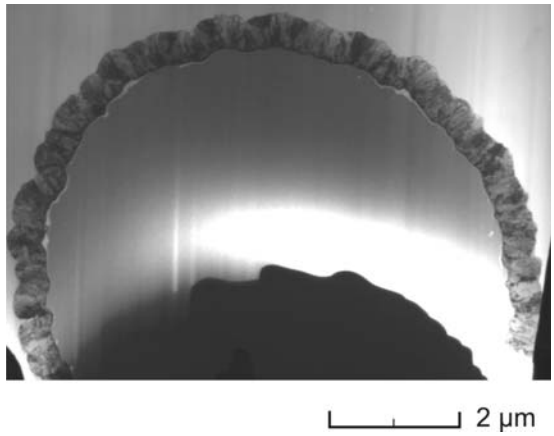


Fig. 2: STEM image of a FIB-prepared cross-section of a single carbon fibre Al-coated via PVD

The electrical resistivity of coated and uncoated carbon fibres was measured. Additionally, the resistivity of the partially coated fibres was tested in the non-loaded state to collect data of the transition resistance. Connecting the fibres and the Cu wires via silver-conductive glue leads to a sometimes varying transition resistance. It was important to record the contact resistance to ensure constant current transition. These tests were followed by single-fibre tensile tests in combination with simultaneous resistivity measurements. The strain-dependent resistivity was recorded using the two-terminal sensing. Doing so allows the evaluation of the signal strength and the calibration of the sensors. The tests were carried out using HTA 5241 C fibres (PAN, Toho Tenax) in the described way.

To investigate the influence of the embedment process to the coating of single C fibres, fibres with conductive layers were embedded into fibre-reinforced polymer matrix composites (FRP).

In the last experiments, sensing fibres were integrated into a glass-fibre-reinforced polymer composite (GFRP). Standard tensile test specimens with the integrated strain sensors were then loaded in a tensile testing machine. The monitoring of the sensor signal was recorded simultaneously.

3 Results and discussion

3.1 Deposition results

The coating experiments, i.e. the deposition of aluminium on a carbon fibre surface, were really successful in terms of layer quality, morphology and

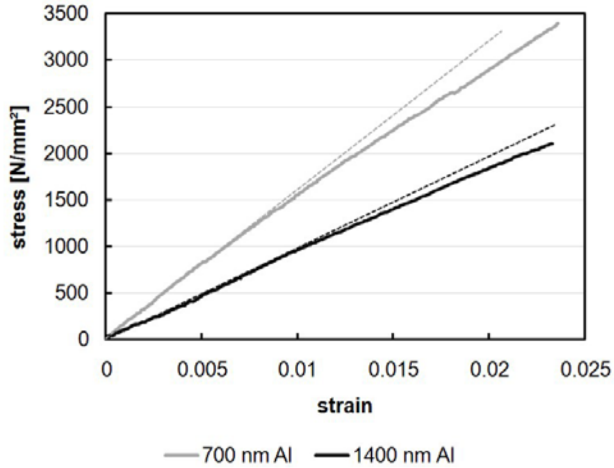


Fig. 3: Typical stress-strain curves of aluminium coated C fibres with 700 nm and 1400 nm coating thickness

layer adhesion. The scanning transmission electron microscopic (STEM) investigations of the so produced layers demonstrate a homogenous distribution of the layer microstructure. The layer comprises an even thickness around the whole circumference of the surface. The layers are compact and no voids or defects are visible (Fig. 2). They also show an excellent bonding to the surface of the fibre.

Single-fibre tensile tests were carried out to investigate the mechanical properties of coated C fibres. Two different thicknesses of Al coatings were tested to figure out if the coating thickness influences the mechanical properties. The results of the tensile tests clearly indicate that Al-coated carbon fibres have a limited elastic deformation compared with plain fibres (Fig. 3). Independent of the coating thickness, the elastic limit has an average elongation of 0.7 % (cf. Fig. 4). The breaking elongation is fibre-dominated. The average value is about 2 %. Low elastic limits of the conductive layer can possibly reduce the number of load cycles under alternating load. This could result in a conductivity drop due to fatigue fractures of the coating.

For C fibres with aluminium coatings, the only influence of a changing thickness can be found in the strength. Thicker coatings tend to decrease the yield strength and the tensile strength of coated fibres. This is because the aluminium coating comprises a lower strength than plain C fibres (cf. Fig. 5).

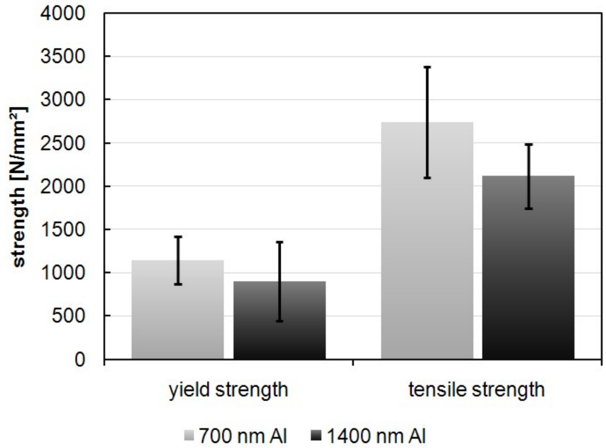


Fig. 4: Comparison of yield strength and tensile strength of coated C fibres with a coating thickness of 700 nm and 1400 nm Al determined in single-fibre tensile tests

To assure a long sensor life-time with a high number of load cycles, it is of vital interest to find more elastic alternatives to aluminium as a conductive coating for C fibres used as elongation sensors. For this purpose, the capability of copper-beryllium alloys will be determined in following investigations. Furthermore, it is necessary to develop an elastic coating with isolating properties. The electrical isolation is important for the sensor embedment into C-fibre-reinforced plastic to eliminate side effects caused by the conductivity of the surrounding C fibres.

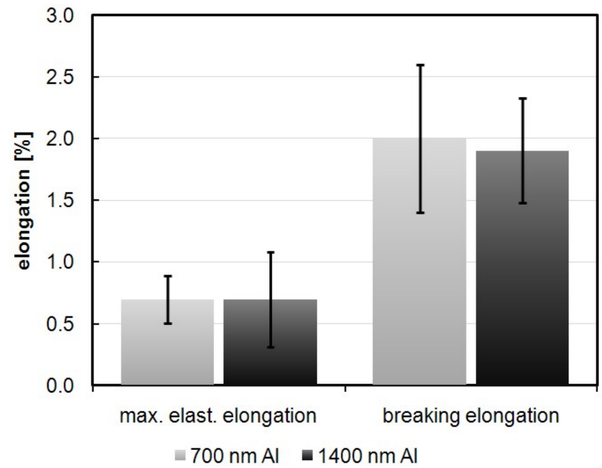


Fig. 5: Comparison of maximal elastic elongation and breaking elongation of coated C fibres with a coating thickness of 700 nm and 1400 nm Al determined in single-fibre tensile tests

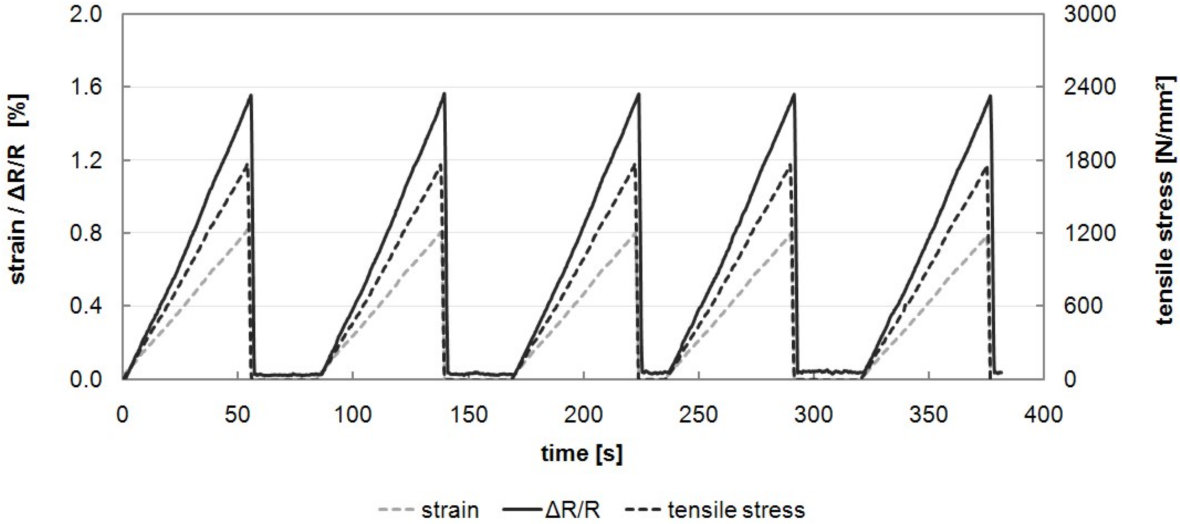


Fig. 6: Load cycling of a HTA 5241 single C fibre under combined measurement of elongation, load and electrical resistivity of the fibre

3.2 Electrical resistivity measurements

PAN-based C fibres of the type HTA 5241 clearly show a resistivity change in accordance with strain changes. Repeatedly carried-out load cycles display a constant resistivity change for this fibre type, which can be seen in Fig. 6. The change of the electrical resistivity ΔR of C fibres dependent on the applied stress is a combined effect. The whole amount summarises one portion due to the change of the measurement length Δl; one part results from the variation of the cross-sectional area Δd, and the last one is caused by the piezoresistive effect $\Delta\rho$. Equation 1 displays this composition.

$$\Delta R = \frac{\delta R}{\delta l} \cdot \Delta l + \frac{\delta R}{\delta d} \cdot \Delta d + \frac{\delta R}{\delta \rho} \cdot \Delta\rho \qquad (1)$$

In order to investigate the contribution of the different parts to the resistivity change of HTA 5241, the portion caused by the geometric changes $R_{f(\Delta l, \Delta A)}$ was calculated using Equation 2 (where ρ_0 is the specific resistivity of HTA 5241 fibres, l_0 and A_0 are the starting length and area, and Δl as well as ΔA are the absolute change of both geometric fibre parameters due to strain).

$$R_{f(\Delta l, \Delta A)} = \rho_0 \frac{l_0 + \Delta l}{A_0 - \Delta A} \qquad (2)$$

The specific resistivity of HTA 5241 fibres was calculated out of a simple four-terminal measurement and has a value of 0.0157 Ωmm. Assuming that HTA 5241 fibres have a Poisson's ratio of 0.27, which is typical for PAN-based C fibres [8], this produces a linear contribution of about 83 % of the overall resistivity change for this fibre type. In accordance with Equation 1, the remaining portion results from the piezoresistive effect. Fig. 7 illustrates the strain-dependent overall relative resistivity change and its comparison with the calculated relative resistivity change due to geometric variation of the fibre.

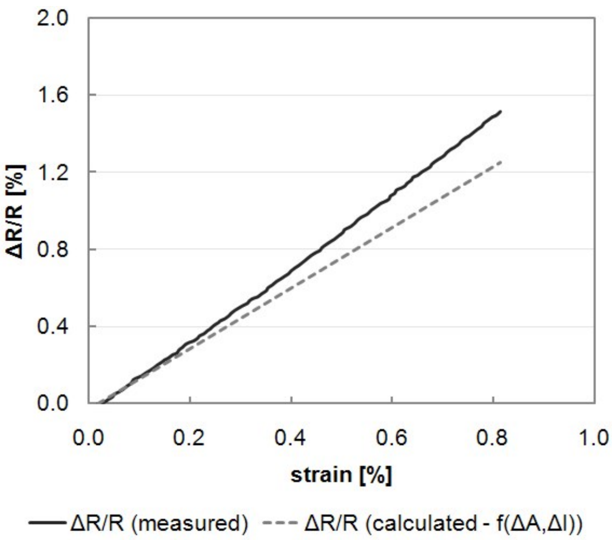


Fig. 7: Strain-dependent overall relative resistivity change of HTA 5241 fibres compared with the calculated relative resistivity change due to geometric variation of the same fibre

The coefficient of strain sensitivity k can be deduced out of Equation 3 (where ΔR is the absolute resistivity change, R_0 is the absolute resistivity without load, and ε is the strain).

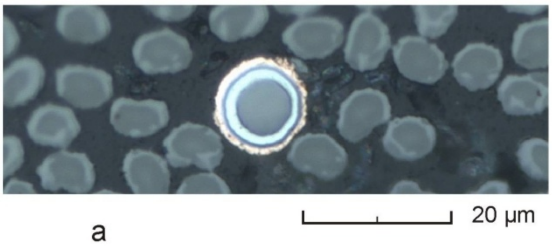
$$k = \frac{\Delta R}{R_0 \varepsilon} \tag{3}$$

The average strain sensitivity k of HTA 5241 C fibres is 1.86.

3.3 Embedment of coated C fibres into polymer matrix composites

The embedment investigations for aluminium-coated C fibres are going on at the moment. The results of the embedment of a comparable material system will be given here as an example. Copper-coated C fibres were embedded into C fibre reinforced plastic. The hardening process of the woven prepreg material with the coated fibres inside was done in an autoclave at a temperature of 120 °C, a gauge pressure of 5 bar, and lasted 3 hours.

When viewing the microscopic image b in Fig. 8, one can see that the coating of the C fibre has been deformed by the reinforcing fibres due to the hardening pressure. This deformation has only occurred for the crosswise orientation of the coated C fibre (cf. Fig. 8 a). Because the longitudinal orientation of the sensor is preferable to measure true fibre strain, the embedment results can be seen as a success. Furthermore, the coated fibres lie close to the reinforcing fibres and no resin nests occur. Out of this result, it can be deduced that a good load and strain distribution is guaranteed in the contact zone of reinforcement and potential sensor. This ensures an excellent sensor response and is a pre-condition for a long sensor life under alternating load with numerous cycles.



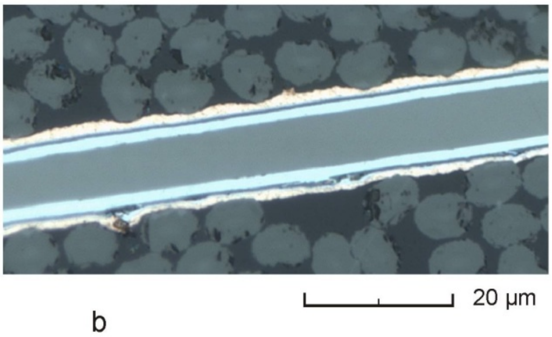


Fig. 8: Light-microscopic images of cross- and longitudinal sections of a copper-coated C fibre embedded into C-fibre-reinforced plastic

4 Summary and conclusion

The result of the strain-induced electrical resistivity change of single HTA 5241 C fibres is promising and offers an opportunity for strain-microsensor applications. The advantages in comparison with standard strain gauges or strain-sensitive metallic wires can be seen in the higher elasticity of the fibres and the smaller diameter.

The higher elasticity ensures a longer sensor life-time because the sensor withstands the same strain like the composite material in which it is embedded. Due to the small diameter of the C fibre sensors, they can be embedded into CFRP without producing artefacts in the material composition and the sensor signal. Further investigations are necessary to develop truly elastic layers. These layers have to be conductive in accordance with the necessary signal transfer. Another type of layers needs to be isolating in order to guarantee the electric decoupling between sensor and composite structure. The ongoing research must also find practical solutions for the contacting question.

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