Multi-layered sensor yarns for in situ monitoring of textile reinforced composites

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Abstract. In this contribution, the characteristic of yarns that have intrinsically conductivity as well as such with coaxial conductive coatings acting as in situ strain sensors are described. The objective of the based research projects is the real-time in situ sensing of both global stresses acting on fibre reinforced plastic (FRP) components and the detection of resulted local microscopic damages due to creep, delamination and micro-cracks in the fibre-matrix interphase of glass fibre (GFRP) and carbon fibre (CFRP) composites. Sensor materials similar to the particular FRP and its mechanical behaviour have been chosen. In the first approach, GF- and aramid-based sensor yarns have been developed with multiple tailored silver layer coating system capable to distinguish multiple scaled damage mechanism due to these effects globally and locally. The second approach bases on the piezoresistive effect of CF rovings for their usage as in situ strain sensors. In the next step, suitable fibre and polymer film-based cleading have been tested and evaluated, granting sufficient electrical isolation to avoid short-circuits between the conductive sensor layers itself or between the sensor and intrinsically conductive CFRP respectively. Initially, the sensor performance of global strain measurement, means the accumulated strain along the integration length of the sensor yarn, has been evaluated during tensile stressing of FRP with integrated suchlike functionalised sensor yarns.

1. Introduction

Fibre reinforced plastics (FRPs), especially those with thermoplastic matrices, have sparked the interest of mass markets, e.g. in the automobile or in the sports sector. Due to its adjustable material behaviour and its outstanding processing properties – like high fracture toughness against impact damages, hot workability, reforming and therefore short processing time, weldability and easy recycling – in comparison to thermoset composites or conventional metal constructions, FRPs are attracting growing interest and therefore demands from both the scientific community and the industry. With the increased application of FRPs in diverse fields, the monitoring of structural damage and serious material degradation that occur due to loading during in-service operation is getting more importance.

However, for the purpose of structural health monitoring (SHM), the development and structural integration of suitable sensor components for FRPs is still a challenge for materials science. Although, the embedding or attachment of the non-destructive evaluation systems, like strain gages or acoustic emission transducers, into/onto FRPs is possible, they are usually expensive and their application potential as an integral part of the textile reinforcement structure is limited due to higher temperatures
and higher pressures for the consolidation compared to those in case of thermoset composites. For the purpose of both, the operational load monitoring and the SHM of FRP components, the literatures reports two approaches using the principle of electrical resistance measurements. The first approach includes the use of CNTs distributed throughout the bulk matrix for sensing mechanical strains [1]-[6]. The second approach involves the insertion of either inherently conductive fibres, e.g. CF [7]-[9] or GF coated with CNTs [10].

Since the breaking strain of GF reinforced composites can vary in the range of 2.5 – 5 %, reproducible sensor signals for SHM with CNT based methods cannot be guaranteed for these composites because of their limited strain of 0.5 % due to the percolation threshold. Because of its low breaking strain in a range of 0.8 – 1.5 % and higher stiffness compared to GF, CF strain sensors provides a high temperature stability suitable for thermoplastic applications, but reproducible sensor behaviour (i.e. gage factor k, hysteresis) are limited to maximum of 1 % elongation of the bulk GF reinforced composites [8]. Therefore, the need for a textile-based sensor able to detect local micro cracks (in the interphase region between matrix und fibre) and simultaneously able to monitor global loading condition even at higher straining region up to 5 % of the GFRPs is very high.

2. Materials and methods

2.1. GF sensor yarns with silver layer coatings for GFRP

The first approach, GF rovings with yarn count of 300 tex, 900 tex and 1,200 tex were used as base for the continuous wet-chemical deposition of metallic sliver. Therefore, the GF is guided with 0.385 m/min through a solution tempered to 95 °C consisting of (480 or 710) mg/l silver nitrate, 0.27 mol/l N,N,N',N'-tetrakis (2-hydroxypropyl) ethylene diamine (complexing agent) and 0.027 mol/l hexamethylenetetramine (reducing agent). The reached layer thickness was empirically determined using digital light microscopy and is in a range between 1.4 – 1.7 µm. The structural and surface analysation of the sensor yarns includes EDX, SEM (figure 1-2) and additional fibre tensiometry for the evaluation of both surface energy and tension.

![Figure 1. EDX of the bare 1,200tex GF roving (a) and coated with 5.9 % of silver (b)](image)

![Figure 2. SEM of the fibre surface of idem sensor yarn](image)

2.2. CF-based sensors for CFRPs

The second approach focuses on the usage of intrinsically conductive CF rovings Tenax HTA40 H15 with a yarn count of 67 tex. For the forming of filament-based cleading by using the DREF friction spinning technology, PES staple fibre with 60 mm length is processed to two 4.0 ktex slivers that then have been spun around the CF core to form a cleading of approx. 210 tex (cf. figure 3). This isolated CFS reach a leakage resistance of approximately 365 MΩ in standard climate DIN EN ISO139 at a lineic resistance of 440 Ω/m.
2.3. Integration of textile-based sensors in reinforcement fabrics for FRP

The integration of the above described textile-based sensors into reinforcement structures during its manufacturing process, has been realised successfully at ITM [9,11,12] using open reed weave ORW technology and multi-axial warp knitting process with warp yarn path manipulation unit for the lateral displacement of single or band of sensor yarns in user-defined angles to the warp direction of the non-crimp fabric. For a fast characterisation of the sensory behaviour under mechanical stressing of the FRP, the sensor yarns can be embroidered in straight aligned form onto any reinforcement structure, which then are processed to tensile test specimens (cf. schematic in figure 4) according to standard DIN EN ISO 527-4. After the textile-technological manufacturing process but before the FRP consolidation, the textile-based sensors have to be electrical contacted manually (figure 5) by clamping each of the sensor yarn ends between copper thin sheets with attached piece of metal thin wire for the interconnection with conventional measurement equipment, e.g. ohmmeter or amplifier. The used GFRP is made of three layers of a GF-polypropylene commingling yarn based biaxially knitted fabric with applied sensor yarn in major load direction (0°) of the central layer. For testing CFS, non-standardised tensile specimens [13] were made from unidirectional CFRP with thermoset matrix. Using a conventional tensile testing machine Zwick Z100, destructive quasi-static tensile tests are performed. The resistance measurement is simultaneously done to the tensile tests using a precision ohmmeter FLUKE 8846.

3. Results and Discussion

3.1. Silver coated GF based strain sensors for the application of GFRP

Nondependent of GF yarn count, the measured layer thickness is in a range of 1.32 – 1.69 µm. Using 710 mg/l solutions of silver nitrate, the highest lineic conductivity can be observed for 1,200 tex GF
with mass fraction of 5.9 % (m/m) of silver, reaching 60 – 80 S/m. Using 300 tex GF roving with 6.2 % (m/m) of silver, a conductivity of only 20 – 30 S/m has been measured.

The measurable resistance-strain behaviour (figure 6-7) of suchlike silver-coated GF strain sensors in FRPs is non-linear but continuous until GFRP specimen rupture at 3.0 % of strain at a maximum tensile stress of 300 MPa. Linearity of the sensor’s transmission behaviour is improved with increasing the mass fraction of silver. By using power functions for nonlinear fitting of the measured change-in-resistance curves \( \frac{\Delta R}{R} = f(\varepsilon) = a \cdot \varepsilon^b \) with the tensile-strain curves \( \varepsilon \), the specific reached sensitivity can compared indirectly with regard to the prefactor \( a \) and the exponent \( b \) of the calculated fit functions, cf. equation (1).

\[
\frac{\Delta R}{R} = f(\varepsilon) = a \cdot \varepsilon^b
\]  

As resumed in Table 1, that higher the yarn count of the silver coated GF roving that more linear is the sensor behaviour, means the prefactor \( a \) is increasing while the exponent \( b \) decreases. It is assumed, that the measured tensile-strain-resistance-behaviour is because of the multi-filamentous structure of the investigated sensor yarns. With increasing number of filaments the number of interconnected parallel resistances, means the conductive filaments, increases too. By applying tensile loads on the sensor carrying GFRP, filaments of the GF sensor are strained while continuously increasing their resistance until reaching the fibre specific tenacity.

**Table 1. Coefficients of fitted power functions for the measured change in resistance of GF sensors in tensile stressed GFRP.**

| GF sensor type | \( \Delta R/R = f(\varepsilon) = a \cdot \varepsilon^b \) | Coefficient of determination \( R^2 \) |
|---------------|-------------------------------------------------|----------------------------------|
| 480 mg/l solution of silver nitrate | 300 tex | 1.20 | 2.91 | 0.75 |
| | 900 tex | 3.23 | 1.58 | 0.50 |
| | 1200 tex | - | - | - |
| 710 mg/l solution of silver nitrate | 300 tex | 1.83 | 2.52 | 0.79 |
| | 900 tex | 2.09 | 1.89 | 0.97 |
| | 1200 tex | 2.62 | 1.39 | 0.67 |

**Figure 6.** Measured change-in-resistance curves for 300 / 900 tex Ag-coated GF sensors in GFRP using 480 mg/l solutions of AgNO₃

**Figure 7.** Measured change-in-resistance curves for 300 / 900 / 1,200 tex Ag-coated GF sensors in GFRP using 710 mg/l solutions of AgNO₃

Transferred this behaviour to the postulated model of a parallel resistance, the resulting change of the single filaments resistances under tensile stress is approx. only a split of the amount of their
accumulated change in resistance in serial interconnection. That higher the yarn count or the number of filaments respectively, that less significant is the measured change in the sensors resistance and that more linear the obtained strain-resistance curve, because of their telescopic and electrical interconnection within the roving.

3.2. Isolated CFS for the application in CFRPs

First test series of CFS with DREF-spun cleading consisting of PES staple fibre show that the thickness of the fibre cleading is insufficient. It is assumed, that short circuits between single filaments of the CFS and the electro conductive CFRP structure occur in statistically undefined intervals along the CFS integration length. Dependant on the number of CF filaments that are directly in contact with the CF fabric, the leakage resistance can varies in a range of $10^3 – 10^4 \Omega$.

With regard to the measured resistance-strain-behaviour of the CFS integrated in unidirectional CFRP during cyclical tensile tests, effects of short-circuited filaments of the CFS and the CFRP becomes visible. Figure 8b depicts the change in resistance of such a CFS schematically. There is no direct correlation between increasing strain and measured change in resistance of the CFS as it can be observed for functional CFS (figure 8a) or GF sensors in GFRP (cf. figure 5, 6) respectively. The transfer function of CFS in CFRP is fitted to a power function. The reached prefactor $a$ and the exponent $b$ are assumed in Table 2.

Table 2. Coefficients of fit (power function) for measured change in resistance of CF sensors in tensile stressed CFRP.

| CF sensor type  | $\Delta R/R = f(\varepsilon) = a \cdot \varepsilon^b$ | coefficient of determination $R^2$ |
|-----------------|-----------------------------------------------|----------------------------------|
| 210 tex PES cleading | 0.69 1.91 | 0.61 |

Figure 8. Measured change-in-resistance curves for carbon fibre sensors (CFS) with DREF-spun PES staple fibre cleading during cyclical tensile stressing of unidirectional CFRP: (a) functional CFS with sufficient isolation and (b) with insufficient fibre cleading due to assumed short circuits with the CFRP basis structure

4. Conclusions

It has been shown, that GF based strain sensors can be realised by applying metallic sliver coats with a layer thickness of $1.4 – 1.7 \mu m$ in a wet chemical redox reaction applying $N,N,N',N'$-tetrakis (2-hydroxypropyl) ethylene diamine as the complexing agent and hexamethylenetetramine as the reducing agent. Machine-made integrated in glass fibre reinforcement fabrics of therewith fibre reinforced plastic (GFRP), a good correlation between applied tensile strain an measured change in
resistance of such like of strain sensors, has been observed. It was determined that higher the yarn count of the GF sensors and that higher the content of silver nitrate in the used solution in the wet chemical coating process that more linear is the transfer behaviour of measureable change in sensor’s resistance to applied tensile strain. The best sensory behaviour is determined for 1,200 tex GF roving coated with a metallic silver layer applying 710 mg/l silver nitrate in solution. However, GF rovings with a smaller yarn count of 1,200 tex will be chosen for further investigations but with a higher silver layer thickness. Therefore, the coating process has to be optimised. Further investigations are necessary for the realisation of the multi-layer structure of the GF sensors, means a first dielectric cleading for the first screen, a second silver conductor screen with varying cross-section thus adjustable sensitivity and a sealing sizing or coupling agent cleading respectively.

First researches on carbon fibre based sensors (CFS) with dielectric fibre cleading for their usage as in situ strain sensors in intrinsic electro-conductive carbon fibre reinforced plastics (CFRP) have shown that only an insufficient isolation has been reached caused by the packaging design of the cleading, means the DREF friction spun PES staple fibre cleading in this case. Short-circuits have been detected due to filaments protruded out of the fibre-based cleading and it was assumed, that the observed nonlinear transfer behaviour of suchlike CFS is caused consequently. Further research efforts will be spent to reach homogenous and fully sealed cleading for suchlike CFS.

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References
[1] Li C, Thostenson E T, Chou T W 2008 Comp. Sci. and Technol. 68 iss 6 pp 1227–49
[2] Thostenson E T, Chou T W 2006 Advan. Mater. 18 pp 2837–41
[3] Böger L et al. 2008 Comp. Sci. and Technol. 68 iss. 7 pp 1886–94
[4] Alexopoulos N D et al. 2010 Comp. Sci. and Technol. 70 iss. 2 pp 260–71
[5] Zhao H, Zhang Y, Bradford P Det al. 2010: Nanotechnology 21 iss 30 305502
[6] Zhong X H, Li Y L, Liu Y K et al. 2010 Advan. Mater. 22 iss. 6 pp 692–6
[7] Muto N, Arai Y, Shin S G et al. 2001 Comp. Sci. and Technol. 61 pp 875–83
[8] Kunadt A, Starke E, Pfeifer G, Cherif Ch 2010 im-Technisches Messen 77 pp 13–20
[9] Haentzsche E et al. 2013 Sensors and Actuators A: Physical 203 pp 189–203
[10] Rausch J, Maeder E 2010 Comp. Sci. and Technol. 70 iss. 11 pp 1589–96
[11] Haentzsche E et al. 2016 J. of Smart Materials and Structures 25 iss. 10, 11pp
[12] Haentzsche E et al. 2014 Technical Textiles 57 iss. 5 pp. 175–6
[13] Minsch N, Haentzsche E, Nocke A, Gereke Th, Cherif Ch 2016 Proc. Aachen-Dresden-Denkendorf Int. Textile Conf. (Dresden) pp 113–5