Screen-Printed Sensor Inlays for Monitoring Bondlines in CFRP-Components

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ABSTRACT

Adhesive bonding is a promising approach for joining lightweight composite components. However, the reliability remains a major challenge, because failures due to fatigue are difficult. In this study, we report on the integration of a screen-printed sensor on polyetherimide substrate into the adhesive layer during CFRP fabrication, enabling in-situ monitoring of potential crack propagation due to internal strain measurement under service loading. The sensor concept is based on the comparison of strain measurements in two different sensor rows to detect deviations in the sensor signal that indicate damage. This work marks the first successful fabrication by screen-printing of a fully polyetherimide-based sensor inlay that exhibits excellent adhesion to the epoxy matrix in CFRP. We used carbon-based inks that withstand the harsh conditions during the co-curing during the CFRP-prepreg-autoclave process. After the integration process, the sensors remained fully functional and achieved a gauge factor of up to 49.

INTRODUCTION

Adhesive bonding is ideal for joining lightweight components made of composite materials due to the two-dimensional force transmission. However, the reliability of this structural bonding is an important concern, and fatigue and failure are difficult to predict. In this context, the internal strain is relevant and must be recorded, which is therefore aim to develop a sensor inlay that can be placed into the adhesive layer during

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carbon fiber-reinforced plastic (CFRP)-integration to detect and measure potential crack propagation during operational load.

In previous work, we deposited micro-strain sensors to crack-resistant PVDF films known as disbond arrest features (DAFs) [1, 2], but their thin metallic structures float due to the melting of PVDF during CFRP integration and appear destroyed after cooling. With the change to a PEI carrier film, which has a significantly higher melting point, and using PVDF for sensor encapsulation and as DAF, the crack detection capability of the approach could be demonstrated. In dynamic fatigue tests, detection of cracks occurring within the first 50,000 cycles and recognition of the moment when the crack reaches the DAF could be demonstrated. However, the inlay interfaces often caused damage to the fabricated composite samples [3, 4] and the fabrication process was difficult to scale.

In this work, we aimed to improve the sensor inlay integration and crack detection by fully encapsulating the inlay with PEI, known for its strong adhesion to CFRP epoxy [5, 6] and minimal impact on tensile strength [7]. In addition, using the cost-effective screen-printing also enables faster, scalable strain-sensor production compared to lithographic fabrication. Stretchable and highly sensitive inks will benefit for dynamic load conditions. Further research on the electromechanical properties of these inks under harsh conditions will guide future developments.

SENSOR INLAY CONCEPT

The sensor inlay design consists of four sensor bridges, each arranged in pairs in two rows. Disbond arrest features (DAFs) are also integrated into the area of the sensor rows, which is intended to stop a potential crack. The sensor inlay and the DAFs are integrated into the CFRP component so that a potential crack front through the bondline first reaches the first row of sensors. The sensor rows have a distance of 10 mm and are each 10 mm wide; the functionality for these dimensions has already been shown previously [1]. Each sensor row in the screen-printed sensor inlay consists of two Wheatstone quarter bridges (Fig. 1). The stress profile in the bondline due to a crack is 10 mm behind the crack just as large as in the healthy state. In a healthy state, both rows of sensors show the same healthy signal, which is only load-dependent. When the crack front reaches the first row of sensors, the sensor signal increases here, whereby the sensors in the second row show no signal change. The difference in the sensor signal can thus directly indicate a crack initiation [8]. In addition, the crack can cause local stress peaks in the first row of sensors, which can lead to damage. In this case, the sensors in the second row are still functional and can thus detect an unexpected crack propagation.

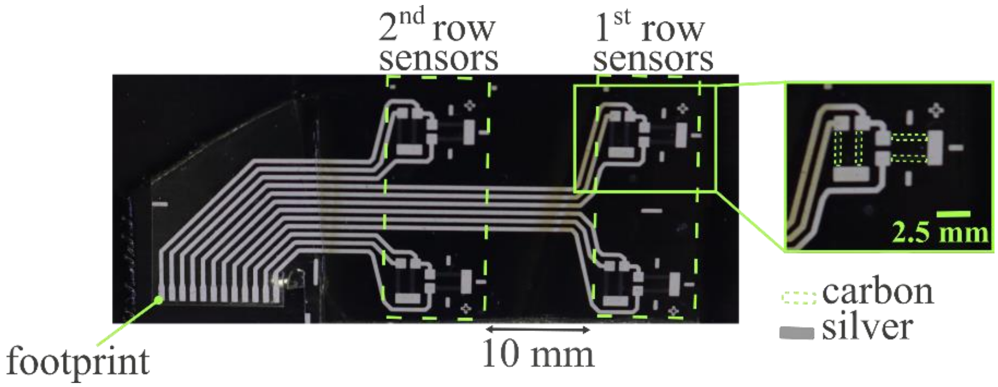

Figure 1. Photograph of screen-printed sensor inlays integrated on CFRP consisting of two sensor rows. The zoom on the right shows the Wheatstone quarter sensor bridge with a variable longitudinal and a transversal sensor. Both rows of the sensor inlay consists of two Wheatstone quarter bridges (1^{st} sensor row: 1L and 1R, 2^{nd} sensor row: 2L and 2R)

MATERIAL AND METHODS

A 125 µm PEI film (ULTEM 1000B, Vink König Deutschland GmbH, Wuppertal, Germany) was utilized as the substrate for the sensor inlay. To minimize shrinkage during curing, the PEI films were pre-treated at 130 °C for 90 minutes. Sensor elements and conductive paths were coated using screen printing. First, silver ink (DM-SIP-2006, Dycotec, Calne, UK) was printed in the desired pattern for conductive paths and cured at 120 °C for 5 minutes. Then, carbon ink (Saral StretchCarbon 100, Saralon GmbH, Chemnitz, Germany) was printed to create the high-resistance resistors and dried at 120 °C for 5 minutes. A second 25 µm PEI Ultem 1000 film was then bonded on top of the sensor layers by diffusion bonding. The sensor inlays were subsequently integrated into the composite components via co-curing during the prepreg-autoclave process, as described by [2]. After integration, 25 mm × 200 mm samples were cut by saw for testing. Figure 2 illustrates the whole fabrication and the saw-cutted sample design.

Tensile testing was performed to evaluate the functionality of the integrated sensor inlay. The sensor's footprint was connected to a ZIF connector, and piezoresistive signals were recorded with a multi-channel strain gauge amplifier (QuantumX MX1616B, HBM, Darmstadt, Germany). A force-controlled machine (Amsler HC 25, ZwickRoell, Ulm, Germany) with a 25 kN load cell was utilized, in which the CFRP samples with a measuring length of 160 mm were clamped. Samples were first loaded to 3.033 kN (ca. 1196 $\mu m \cdot m^{-1}$ strain) in 10 s, held for 20 s, then unloaded to 0 N in 10 s. After resetting the sensor signal to zero, this cycle repeated ten times.

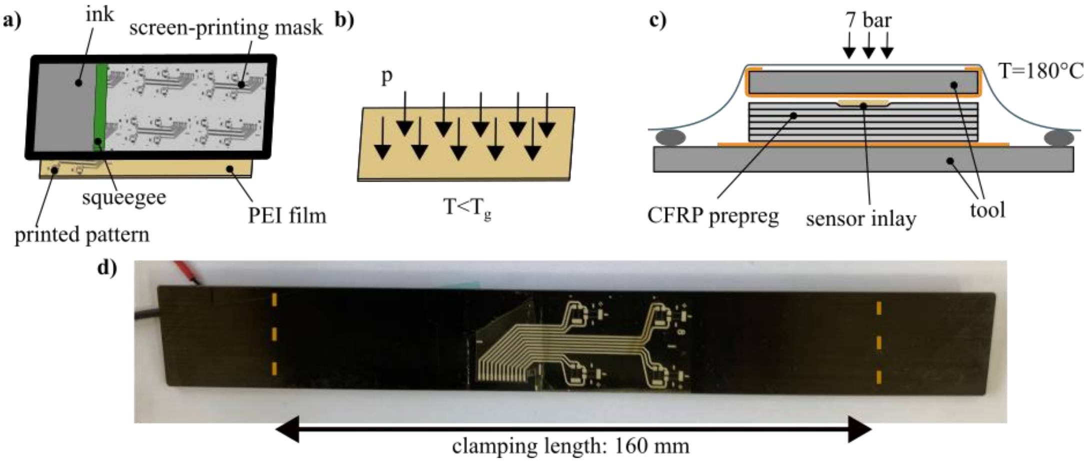

Figure 2. Schematic illustration of a) sensor inlay fabrication by screen-printing, b) encapsulation of functionalized PEI film with second PEI film on top using diffusion bonding, and c) set-up for co-curing in prepreg autoclave process. d) Photograph of the saw cutted CFRP sample with integrated screen-printed sensor inlay.

These results were also used to investigate the sensor sensitivity. The sensor signal was defined as

$$S = \frac{V_D}{V_S} \tag{1}$$

, where V_D is the signal of the Wheatstone bridge and V_S is the supply voltage. The gauge factor *GF* representing the piezoresistive sensitivity was defined as

$$GF = \frac{\frac{\Delta R}{R_0}}{\varepsilon} \tag{2}$$

, where ΔR is the change of resistance, R_0 the initial resistance, and $\varepsilon = \frac{\Delta l}{l_0}$ the longitudinal strain calculated based on crosshead displacement Δl. *GF* was calculated based on *S* as

$$GF = \frac{4 \cdot S}{\varepsilon \cdot (1 + \upsilon)} \tag{3}$$

, where υ is the Poisson ratio (assumed as 0.36 for all setups).

RESULTS AND DISCUSSION

By evaluating the sensor signal during non-destructive static tensile testing, the sensor properties were determined. Figures 3a and 3b present the sensor signal and a representative detailed view of the increasing sensor signal, respectively. According to the measured longitudinal strain, the samples reached a maximum deflection of 0.191

mm, corresponding to a peak strain of 1,196 µm·m⁻¹. With increasing longitudinal strain, the sensor signal rises monotonically with a non-linear relationship between sensor signal and longitudinal strain. For the average sensor signal 1L, the sensor signal can be distinguished into two linear regions (Figure 4a). Figure 4b displays the corresponding gauge factor for all four sensing bridges. In the first region, the gauge factor averaged about 22. In the second region, it reached around 35 (1L, 2L, and 2R), and for 1R, even 49. Compared to thin film sensors made of metal, these gauge factors are for both regions much higher than 2.

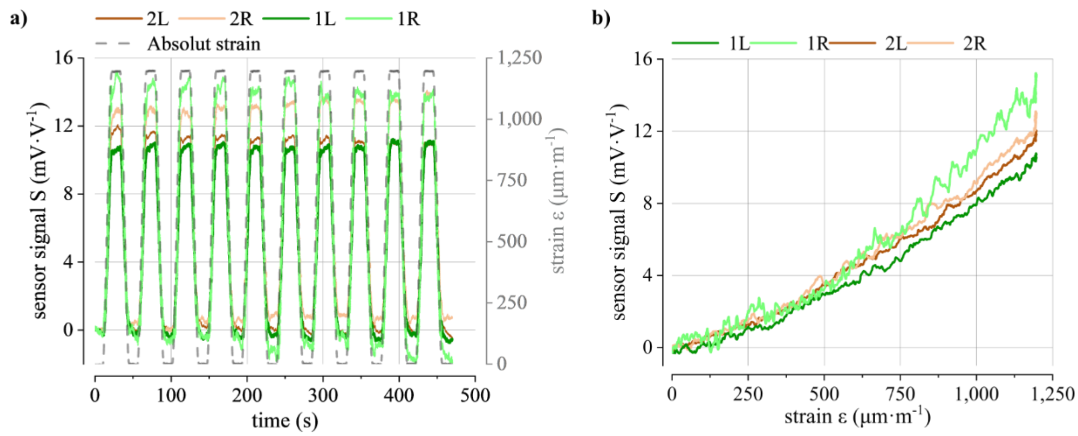

Figure 3. Screen-printed sensor inlay calibration: a) sensor signal for all sensor bridges and applied strain over time. The specimen was loaded using a ramp signal up to a maximum strain of 1,196 µm·m^{-1} and subsequently unloaded. b) representative section of the sensor signal as a function of longitudinal strain for one loading cycle.

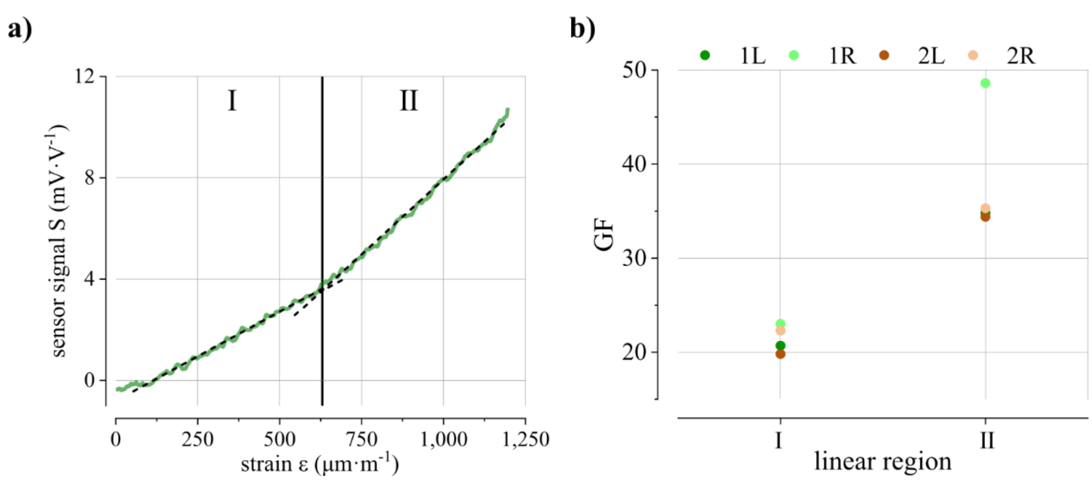

Figure 4. a) Mean sensor signal 1L for loading (blue line) and linear fitted curves (dashed black lines) with correlation R2=0.994 and R2=0.996 representing two linear regions. b) Gauge factor versus linear region for all four sensing bridges.

Carbon ink consists of an insulating polymer matrix containing randomly distributed carbon particles of different sizes. The resulting conductive network is a combination of several contributions, including filler resistance, contact resistance, and tunnel resistance. Two main models describe the piezoresistive behavior. In the first model, percolation theory is based on the volume fraction of the carbon particles. That means that piezoresistivity is dependent on aspect ratio and concentration of the carbon particles [9]. The second model attributes the piezoresistivity to the reorientation of the particles and the restructuring of the network during mechanical deformation. In a recent study on stretchable conductive elastomers with carbon black filler, Ritchie et al concluded that the restructuring of the particle network has a stronger influence on piezoresistivity than volumetric changes [10].

Several studies have indicated a change in piezoresistive behavior beyond a critical strain. Using the two theories described above, researchers have explained the nonlinear piezoresistive behavior of carbon-filled polymer composites by identifying two, three or even five linear regions [11, 12]. However, according to the findings in [10], restructuring within the particle network appears to be an important factor in piezoresistivity, indicating the need for further investigation of this behavior.

Repeating the loading for ten cycles made it possible to evaluate the stability and repeatability of the sensor signal. Figure 5 shows the loading and unloading signals for the representative averaged sensor signal 1L with standard deviation for ten cycles. The overall behavior remained consistent, yielding a repeatability error of 3.9 ± 1.4% over ten cycles and a hysteresis of 12.3 ± 0.99%.

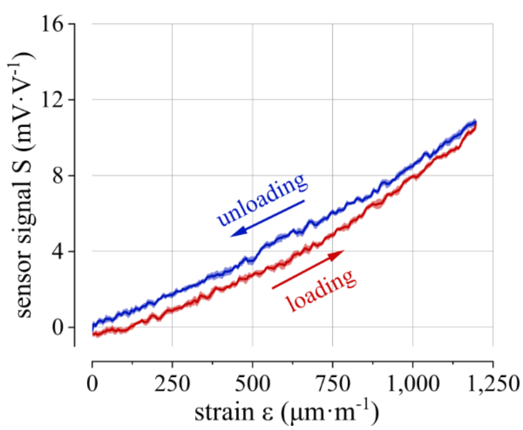

Figure 5. Averaged sensor signal 1L and standard deviation under loading and unloading of all ten cycles.

CONCLUSION

In the present study, screen-printing ink was used to fabricate a PEI sensor inlay that can be integrated in the adhesive bondline during the co-curing in the prepreg-autoclave process. We chose highly stretchable silver and carbon composites as screen-printing inks**.** The electromechanical and piezoresistive behavior of the sensors is non-linear, but can be linearized in separate regimes. Compared to conventional metallic strain gauges, the screen-printed stretchable carbon sensors are significantly more sensitive and achieve a max. gauge factor of 49 on PEI integrated into CFRP. We were able to show that our sensor inlays withstand the harsh conditions during co-curing in the prepreg-autoclave process and do not lose their function. The results of destructive static tensile tests show a highly reproducible sensor behavior. With these results, we are confident that monitoring of crack initiation and progression by our sensor inlays can also be demonstrated in dynamic fatigue tests, which will prove the broad applicability of this SHM approach. For future applications, the fabrication of our sensor inlays is now significantly faster with fewer steps and therefore more cost-efficient, compared to our previous work with lithographic microfabrication. Screen-printing can now also be used for production scale-up and significantly larger sensor networks.

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