Strain sensing of textile structures with polymer-based bicomponent filaments

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Abstract

Strain monitoring can be critical for structures such as light weight composites or civil structures. Many of these application already use textiles or fibres, meaning that sensor fibres are predestined for incorporation and monitoring. Polymer-based sensor filaments allow for a wide range of tailorability for the individual applications. In this work, particle based nanocomposite filaments are melt spun. Afterward, they are characterised regarding the morphology and static resistivities. Lastly, selected filaments are tested regarding the dynamic resistivity to evaluate the suitability for use as a strain sensor using the example of carbon fibre composite structures. It is shown in this work that the sensor filament can be produced by the melt spinning process. Further challenges which are not yet solved included the identification of outlier filaments without destructive testing, as well as the data analysis for the generation of a calibration curve. In further work, other application cases will be tested as well as additional, elastic filaments.

Introduction

Smart textiles and wearables are no new topics in the field of textile research. Nevertheless, they have yet to reach the market breakthrough expected. Instead, the drastic increase in the market share is pushed into the future with each new study. Despite this breakthrough delay, there is no shortage of work in the academic field.

Much of the work is currently focusing on employing metal coated yarns for applications in which electrical signals are detected and transmitted. Although the electrical conductivity of these materials is in the range of typical metals, they are often negatively influenced from external factors such as moisture and friction. One approach to combat the wear is to employ a material in which the conductive component is integrated during production rather than subsequently applied as a coating. This can be done through the melt compounding of conductive particles into thermoplastic polymers, which are then extruded to filaments. These materials are inherently conductive but, when spun alone, are still subject to the influence of external moisture.

In order to solve both problems of wear and influence of moisture, bicomponent thermoplastic filaments have been developed at ITA. Additionally, these filaments open up opportunities for new filament sensors to be integrated not only in clothing but also lightweight composites and civil structures. The production, characterisation and outlook of these novel filaments is described below.

Production

Melt spinning is a method for the continuous filament production. Specifically, monofilament melt spinning is used for the manufacturing of products such as fishing line, tennis strings and 3D-printer filament. With the addition of a second extruder bicomponent filaments can also be produced. A schematic visualisation of the employed bicomponent monofilament machine is shown in Figure 1.

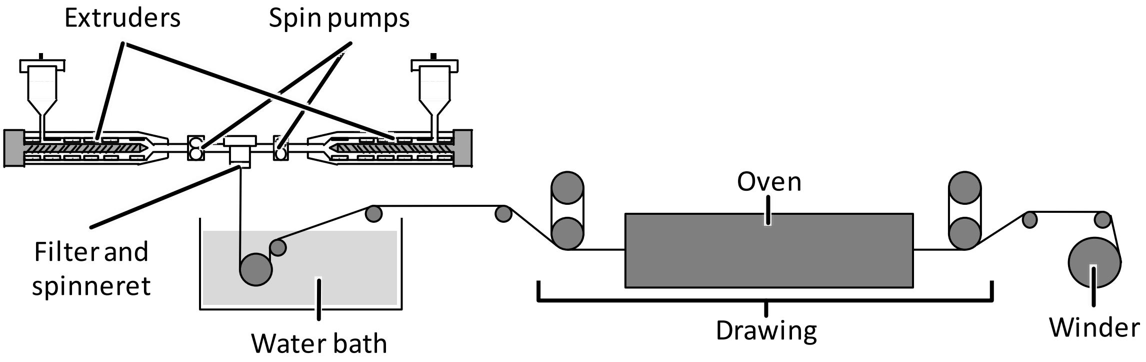

Figure 1: Melt spinning machine for bicomponent monofilament

In order to generate an inherently conductive compound, conductive nanoparticles are mixed with a carrier thermoplastic material. In this work, a commercially available compound consisting of 4 wt.% carbon nanotubes (CNTs) and 96 wt.% thermoplastic polyurethane (TPU) from the company NanoCyl SA, Sambreville, Belgium is used. This compound is the core component of the filament. Two different sheath components are used: Polypropylene (PP) Moplen HP561R, LyondellBasel Industries Holding B.V., Rotterdam, The Netherlands and TPU 1185 from BASF Polyurethane, Lemsförde, Germany. The resulting filaments will be further referred to as PP/TPU and TPU/TPU. The production parameters for the filaments are shown in Table 1.

Table 1: Production parameters for the monofilaments

		Pump speed [RPM]			
Filament	**Extrusion temperature [°C]**	**Core**	**Sheath**	**Spinneret diameter [mm]**	**Winding speed [m/min]**
PP/TPU	250	5	20	1,1	29
TPU/TPU	205				30

Results and discussion

The cross-sections of the filaments are analysed using light microscopy. The samples are first embedded in epoxy and polished. The images of the filaments are shown in Figure 2. The variance of the final areas and diameters stem from the difference in the material density in the molten and solid state. In both filaments a clear distinction between the core and sheath components is visible.

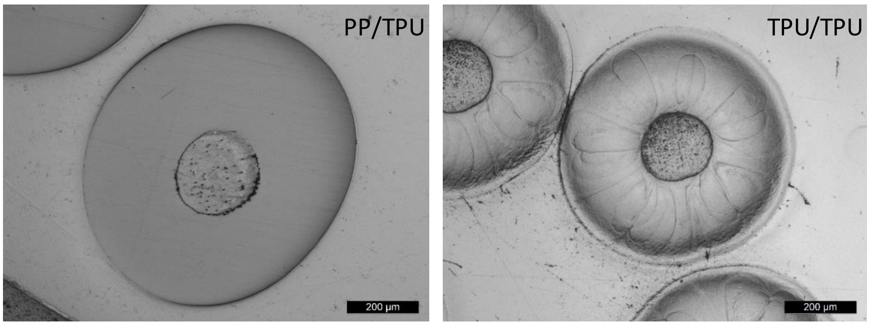

Figure 2: Cross-sectional microscope images of bicomponent monofilaments

Electrical analysis to determine the static and dynamic electrical resistance is done by cutting the filament cleanly to expose the core and then dipping the filament in silver paint. An electrical path from the core to the surface of the filament is generated and the filament can be contacted with standard clamps. This method is schematically shown in Figure 3. Unfortunately, due to the softness of the TPU in the sheath, this method is not suitable for the electrical contacting of the TPU/TPU filament. Therefore, only the results of the PP/TPU filament are presented.

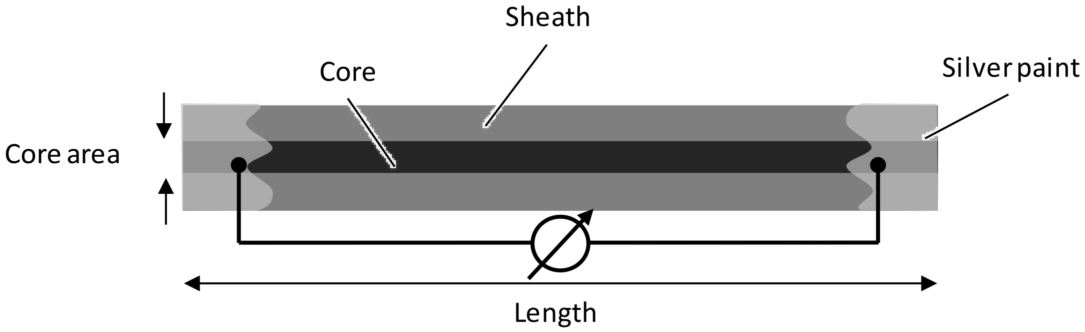

Figure 3: Contacting method for internally conductive bicomponent monofilaments

For the first quantitative tests, electrical resistance is measured simultaneously while applying a tensile strain. The starting length of the filament to be deformed is 5 cm and a constant speed of 1 mm/min is applied. This roughly corresponds to a strain rate of 2 %/min. This slow speed is derived from the strain rates for testing of geoplastics. The total length of the sensor filament, including the length clamped in the tensile machine and length needed to attach the multimeter, is 20 cm. Five filament samples are tested in this set-up. The test set-up is shown schematically in Figure 4.

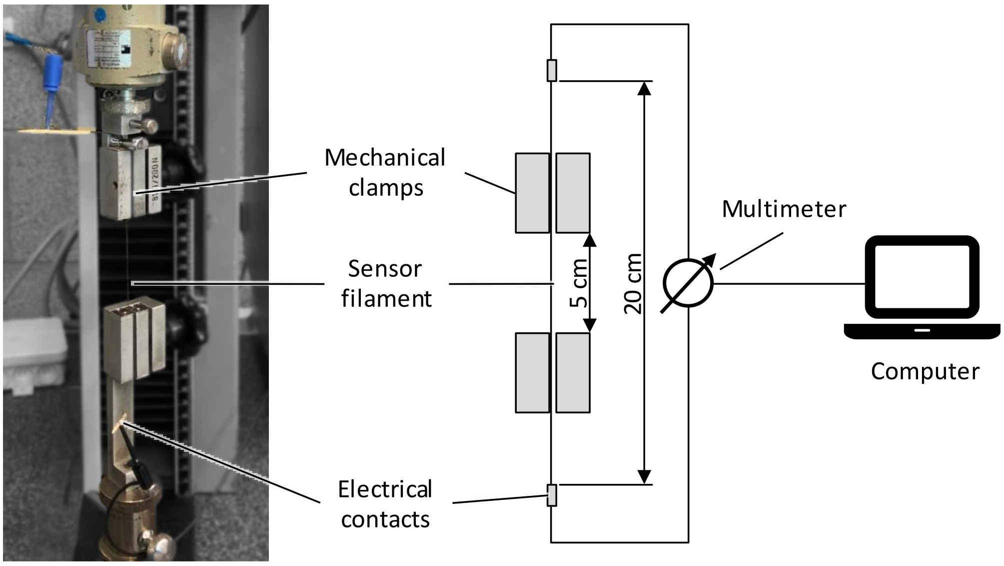

Figure 4: Schematic representation of the electro-mechanical analysis

In conventional strain gauge technology, the electrical response of the sensor is given as the normalised change of the resistance using the equation below. Here R_ε is the resistance at strain ε and R_0 is the resistance at strain 0 %.

$$\Delta R/R\ [-] = \frac{R_\varepsilon\ [\Omega] - R_0\ [\Omega]}{R_0\ [\Omega]} \qquad (1)$$

This same convention is initially used for the analysis of the sensor filaments. The resulting curves for the filament PP/TPU is shown in Figure 5, left. It can be seen that, although the general trend of the curves is similar, an exact calibration of the sensors is not yet possible. One assumption for the varying trends results from the variance in the R_0 of the filaments, causing a difference in the scaling of the curves as shown is Eq. 1. The initial values R_0 can be seen in Figure 6.

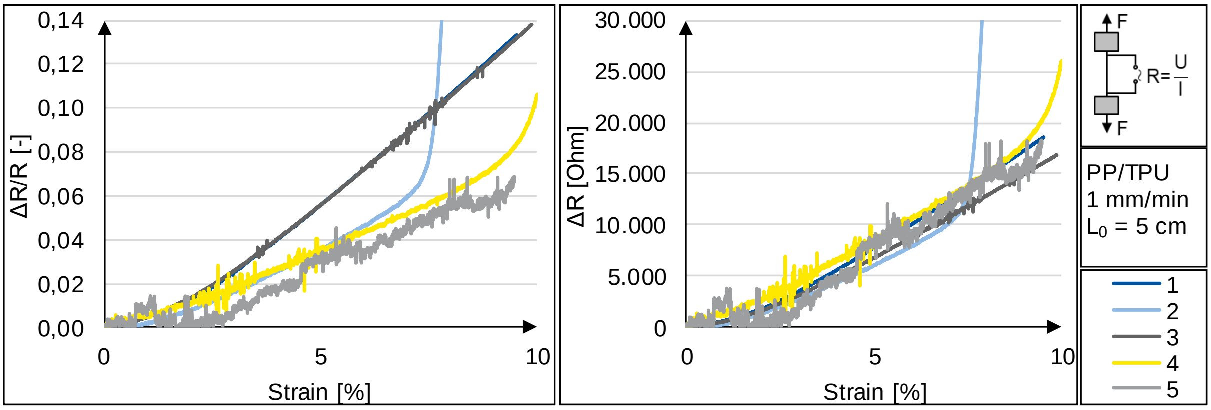

Figure 5: Response for the sensor filament PP/TPU (ΔR/R [-] left and ΔR [Ω] right)

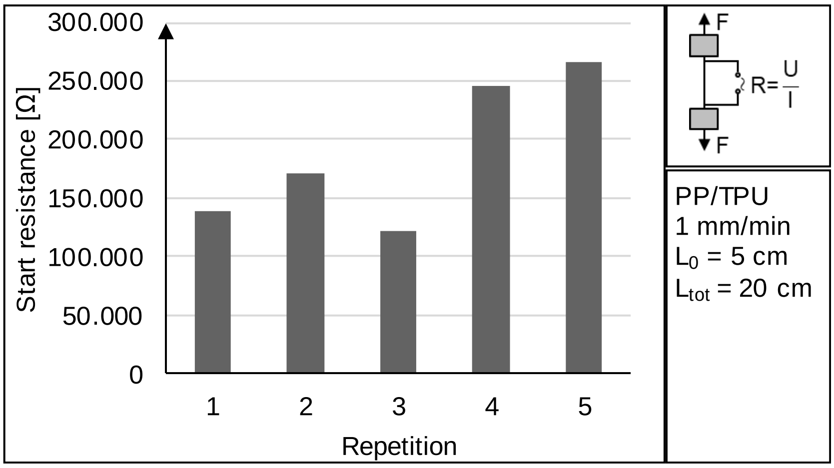

Figure 6: R_0 for the five tested sensor filament samples

The sensor response is then calculated in regards only to the change in resistance, as opposed to the normalised change. This alternate equation can be seen below and the resulting diagram can be seen in Figure 5, right.

$$\Delta R\ [\Omega] = R\ [\Omega] - R_0\ [\Omega] \tag{2}$$

It can be seen that the response of the five tested filaments is in much more agreement when only the change in the resistance is considered. This result demonstrates the fact that the analysis of the novel sensor filaments may not be taken completely from conventional, current solutions and may have to be rethought entirely. Additionally, there seems to be a correlation between the noise of the measurements and the high R_0, for example for repetitions 4 and 5. When these filaments are removed from the visual representation, a calibration of the sensor filament can be done with high precision until 7 %, which is generally larger than expected strains in structural applications (Figure 7).

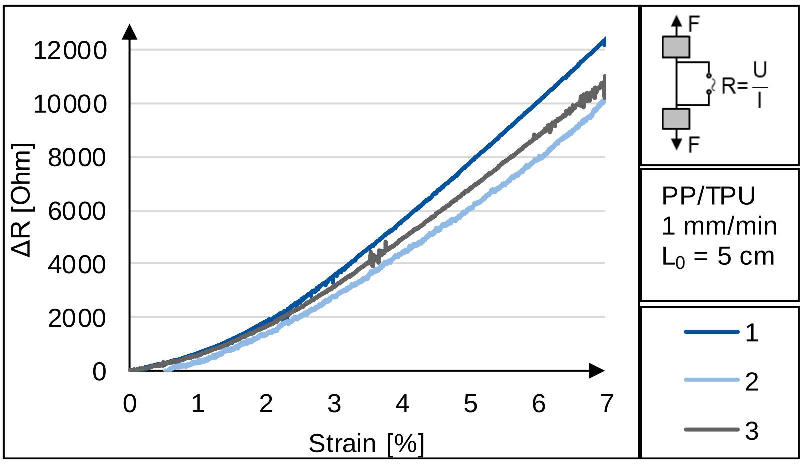

Figure 7: *ΔR [Ω] response for the sensor filament PP/TPU without the outliers 4 and 5*

Conclusion and Outlook

The results presented here show the extreme potential of polymer-based sensor filaments. Through the production parameters, the filaments can be tailored to match specific requirements of a variety of applications. These sensor filaments can revolutionise structural health monitoring in civil structures, lightweight components and many, yet to be discovered, applications. In order to realise this technological breakthrough, work still needs to be done in various aspects:

- Identification of more technical applications, for which the sensor filaments can be relevant
- Mechanical and electrical contacting of the filaments in a more robust manner, as well as contacting of the softer TPU/TPU filaments
- Variation of testing parameters in order to investigate the sensor response under different loading cases (cyclic, relaxation, creep, different strain rates, combination of loading)
- Testing of the sensor response after integration in to the substrate material
- Data analysis to understand the proper data visualisation for the novel material
- Improvements of the electrical circuit while testing to include four-point electrical measurements as well as the incorporation of a Wheatstone bridge

Acknowledgment

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