XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22–27, 2003, Dubrovnik, Croatia

INTEGRATED WIRES FOR STRAIN MEASUREMENT IN COMPOSITES CONSISTING OF CARBON-THERMOPLASTIC MATERIALS

Stefan Folprecht, Günther Pfeifer, Jürgen Landgraf

Dresden University of Technology, Department of Electrical Engineering and Information Technology
Dresden, Germany

Abstract – It is possible to integrate strain measurement elements below the surface in fast rotating composite parts consisting of carbon reinforced Polyetheretherketone (CF-PEEK).

Such measurement elements are made of resistance wires insulated by a netting of glass fibres. This way it is possible to monitor large portions of a composite part up to the limit of loading.

In this article measurement results are published which were obtained by means of resistant wires embedded below the surface of the composite material. The wires are made from the resisting material ISAOHM.

Keywords: stress measurement, structure integrated, carbon thermoplastic composite.

1. BASIC INFORMATION

Complex material requirements for high-performance rotors increasingly demand the use of hybrid material structures with properties tailored to the direction of loading as monolithic materials are frequently unable to provide optimum conditions for the high performance application.

A high potential for innovation in this respect is to be expected from the use of advanced textile reinforcements in the development of load-adapted lightweight structures. The optimum utilization of special 3D textile performs with variable reinforcement arrangement, could make a significant contribution to the development of highly innovative composite parts. This will be of great interest not only from a scientific or technological, but also from an economic point of view.

Essential features of variable-axial 3D textile reinforcements are layers of orientated yarns, which can be arranged to match the directions of loading while the perform is made to near-net shape. Using an additional system which allows online monitoring of the effective forces in the reinforcing fibre permits more effective exploitation of the characteristic potential in the composite component.

In the following information regarding embedded wires for strain measurement especially for the use in carbon fiber reinforced Polyetheretherketone (CF-PEEK) will be provided.

Mandatory for the use of these measurement wires is the incorporation of a wire insulation that can withstand severe enviromential conditions during fabrication (such as high temperature and pressure).

2. EMPLACEMENT OF WIRES FOR STRESS MEASUREMENT WITHIN THE CARBON REINFORCED THERMOPLASTIC MATERIAL CF-PEEK

To monitor high performance rotors the classical surface stress measurement technology cannot be applied either because of very high centrifugal forces or because the surface itself is exposed to an aggressive chemical or construct biological medium respectively. In such case it is reasonable to enclose the measurement elements below the surface of the composite.

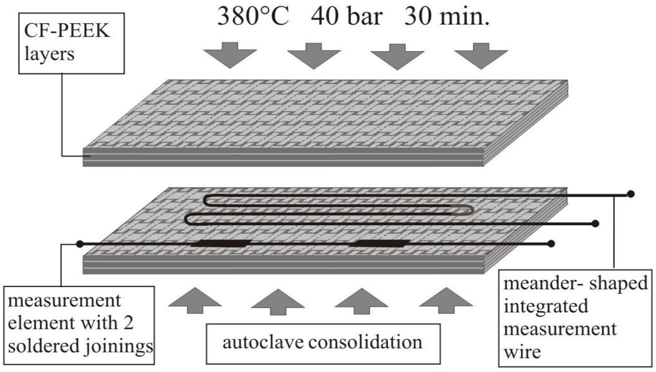

Fig. 1. Manufacture of a component with embedded measurement elements

One of the most important requirements is not to decrease the strength properties of the composite material too much ducto the integrated measurement fibre. It is necessary to have 8 layers of CF-PEEK at least. The wire insulation has also to transfer the forces from the material to the wire.

Further problems are the electrical insulation of the measurement wire and connecting wires. The electrical insulation is require to withstand a fabrication temperature of 400 °C for half an hour at a pressure of about 40 bar.

2.1 Stress measurement with embedded wires

For measurement applications which aim at the average value of stresses, large variable areas with measurement elements are required. In conclusion of several trials it seems that fine wires are the most effective solution.

Employing one of the reinforcing carbon filament yarns as a measurement element would be the best solution from the technological point of view. Because of the necessity of an electrical insulation against the other carbon fibres this approach is no longer advantageous.

To avoid a significant loss of vicinity in the component the wire itself should be as thin as possible. Moreover, the electrical insulation has to be strong and closed in such a way that there is a sufficient contact between the reinforcing fibre and the measurement wire.

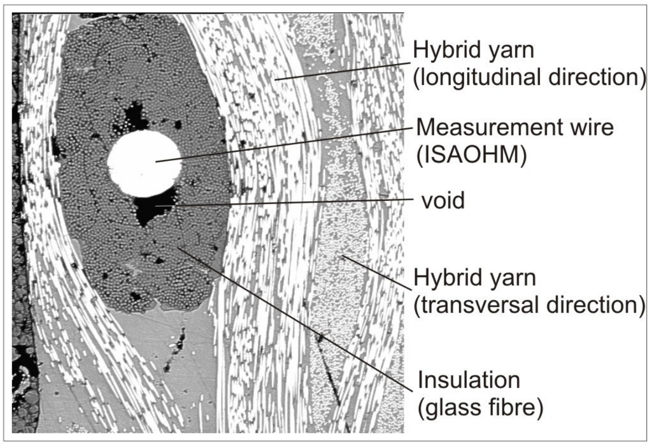

Fig. 2. Micrograph of an embedded measurement wire

A very suitable solution for these conditions is the use of wires insulated with a netting of glass fibres. The netting needs to be additionally impregnated with silicone resin. The least diameter of measurement wire which is possible to be insulated according to information from the manufactorer is 0.2 mm. The favored material for resistive wire is ISAOHM (NiCr20AlSi). This material has the greatest specific resistance (1.32 $\Omega mm^2/m$).

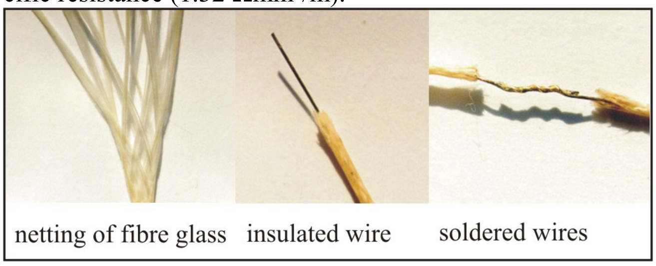

Fig. 3. Insulation and joining of the wires before integration

For some applications measurement elements with a small active size are demand. In such case there is the possibility to connect the measurement wire (ISAOHM) with a connecting wire (Cu) inside the material. The exclusive way is to hard soldering both wires with the soldering metal AP35XL. After soldering the bond has to be insulated with a hose of glass fibre. Unfortunetely the bond has the behavior of a thermo couple of 0.001 mV/K. This effect has to be considered when working with changing temperatures. The small wire-based stress measurement elements here described, have a resistance of about 10 Ω. Every measurement element is connected with two joinings. Having a bridge voltage of 1 V, a step in enviroment temperatue of 100 K causes a virtually stress of 1 ‰. This value was verified by experimental testing (measurement result: 1.003 ‰/100K). Because of this comprehensive behavior this failure don't lead to a real problem. The use of additional temperature sensor allows to predict and correct this deviation.

2.2 Specimen

For the analysis of measurement attributes the insulated measurement wires are embedded inside strip-shaped specimens. These strips are manufactured from 8 layers of woven CF-PEEK fabric with the measurement wire arranged in the symmetry plane (between 4^{th} and 5^{th} layer).

Two kinds of specimen are manufactured (Fig. 1). One with a long meander-shaped wire without any joinings. This kind of specimen is suitable for large measurement areas where the influence of the connecting area can be neglected. Such long measurement wire has a high resistance. The measurement bridge to manage-with low currents. Furthermore such measurement element does not behave as a thermo couple which benefits the use in applications with changing temperatures. For the use of wires in applications with small active areas the problem arises, that the failure, caused by the connecting area has about the same value like the stress effect. That is why it is necessary to solder connecting wires with a low resistance. Especially for investigation of the measurement behavior this kind of measurement element is prefered. For laboratory testings doesn't exist any difficulties in view of high measurement-bridge current and the temerature control of the specimen .

2.3 Measurement conditions

The measuring system operates with a materials testing machine and a data acquisition system (Hottinger Baldwin) for the stress signals. Both machines are connected with a PC which provides the measurement program and the data analysis. For investigation of the measurement behavior at higher enviroment temperatures the material testing machine was equipped with a small temperature chamber.

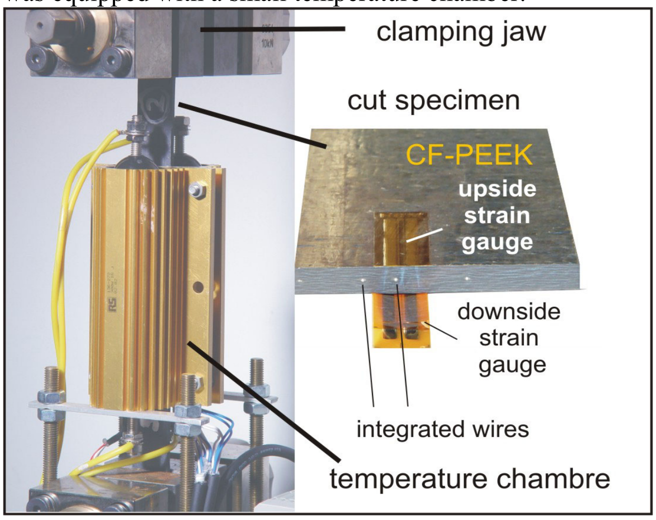

Fig. 4. Specimen in material testing machine with additional temperature chamber

This temperature chambre is sufficient to heat a 100 mm long section of a strip-shaped specimen to a maximum temperature of 200 °C. When using an active area of 60 mm with a maximal temperature of 150 °C, the failure in nominal temperature value is less than 1 %.

The specimens were tested with stair-shaped cyclic load as well as a permanent load (10 min.). The failures were collected in view of reduced linearity, hysteresis, displacement from the point of zero and the creeping behavior in the stressed condition. The behavior was also investigated with different enviromental temperatures.

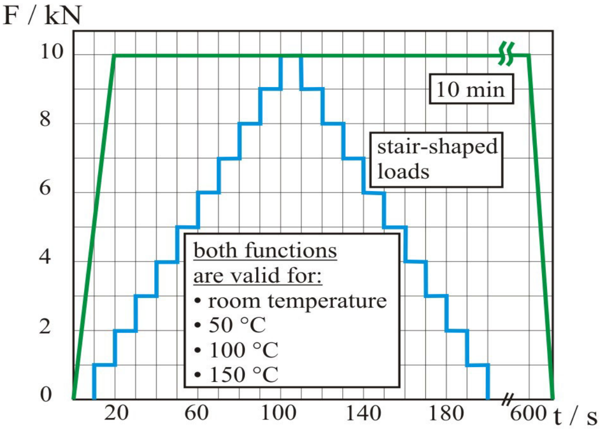

Fig. 5. Procedure of loading for investigation of the behavior in measurement precision

Because of their well known attributes, commercial strain gauges were used at the surface of the specimen where the wire is located inside – one on the upside and one on the downside. The average value of both strain gauge signals is to be taken as a comparision signal for evaluation of measurement wire inside. All stated failures refer to this comparision signal.

2.4 Measurement ranges

Online monitoring with stress measurement sensors aims at predicting possible crash situations in the material. That is why the measurement sensors are required to work properly up to the limit of fibre failure. It has been found that CF-PEEK composites have very brittle behavior. At a strain of about 0.7 % the material fails spontaneously. In order to analyze reliability of the measurement, the wire sensors were tested during first investigations below the ultimate load (30 % of ultimate load). This kind of investigation doesnot lead to permanent material changes. The trials can be repeated as often as necessary. With a small load it is also possible, to investigate how the measurement element corresponds with the material during first loading. After finishing the investigations at room temperature are, the specimen were tested at elevated temperatures. After these test series the specimens were loaded up to the failure limit. Furthermore, the influence of the embedded measurement elements on the material strength was determined.

2.5 Behavior of failures at small load

Investigations were carried out in order to investigate measurement errors and creep at small force. The tests were carried out at room temperature (see section 2.3) with a stress factor of less than 0.25 %.

During first loading a small material elongation is observed. So it is not possible, to get exact informations about the behavior of the measurement elements from these tests. It has been found that after 2 loading cycles the results become reproducible. For very precious results it is advisable to analyze the results after more than 10 cycles of loading.

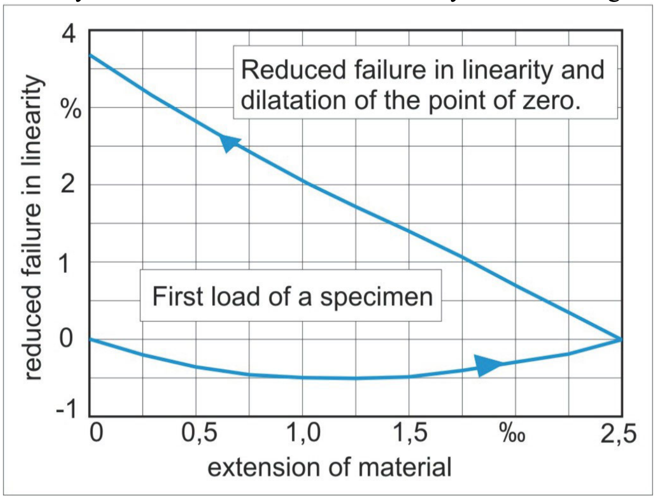

Fig. 6. Behavior of an integrated wire during first loading.

The dilatation of the point of zero after 12 cycles was less than 0.15 %. The failure in hysteresis was 0.6 % at the most.

If one takes a look at the failures in linearity from the wire-based measurement element against the reference strain gauges there is only a small difference. The difference between the 2 reference strain gauges has emerged in the same partition of failure. This result showes that the failures of the measurement elements are similar to the limit of measurement precision.

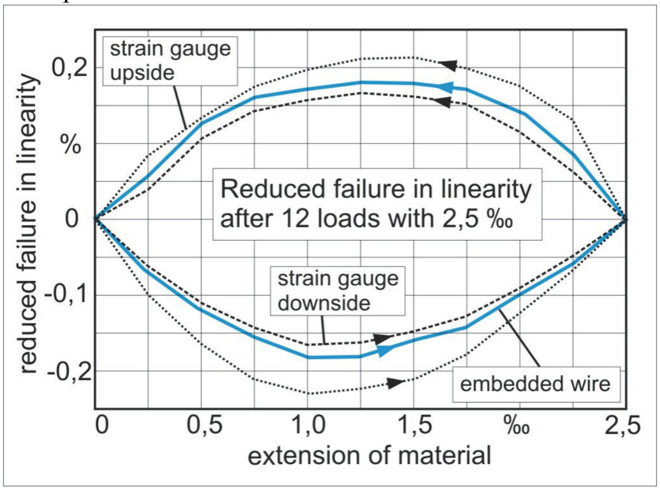

Fig. 7. Reduced failure in linearity after 12 loading cycles with small force. The specimen has accomplished the operating state.

The elongation of the material after 10 minutes is 0.7 % with an exposed stress of 2.5 ‰ (indicated by the reference strain gauges; the material was tested before with 12 cyclical stair-shaped loading cycles). At the same time an expansion of only 0.4 % is indicated by the embedded wires. The reason for the difference between the two measurement results is due to the creeping behavior of the measurement wire against the insulation and the material.

2.6 Testing up to ultimate load

When preparing tests for the investigation of the measurement behavior near to the point of ultimate loading of the material some specimens were made with a larger cross section. The cross section of these specimens was 20 times of that of the effective cross section of the installed measurement wire (similar to the specimen in Fig. 4). In this way it was possible to avoid a significant loss of material strength because of the measurement element. The mechanical influence of the wires onto the material behavior can be neglected.

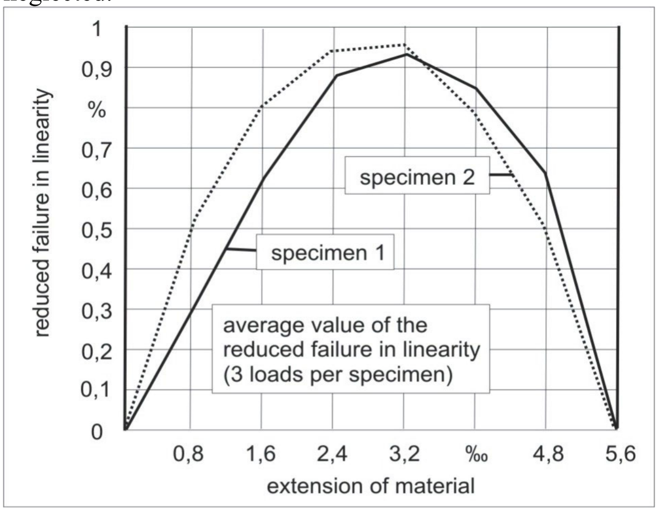

Fig. 8. Failure for two specimens loaded near the ultimate load.

Two specimen have been tested with a 100 kN material testing machine. Unfortunately the used 100 kN material testing machine is not capable of stair shaped loading of specimens. Furthermore the reset of the load is not controllable. That is the reason why we have tested the specimen only with a simple increase in loading. The measurement failures with an exposed stress of 5.6 ‰ were less than 1 % in all cases. After that the material was tested up to failure. The specimen failed with an actual stress of 6.2 ‰. All measurement wires were still functioning at the moment of failure.

2.7 Investigations with different enviromential temperatures

Because of the use of the PEEK matrix material the components are qualified for applications at elevated enviromential temperatures. On this account the specimen were tested at different temperatures. The tests have been carried out with small loads (2.5 ‰ maximum). It turned out that the failure in linearity increases significantly, when the temperature exceeds the value of about 100 °C. The reason for this is a change of properties in the material. Both strain gauges at the surface yield comparable results. For a better clarity only the results for the integrated wires while at increasing forces are shown in fig. 9. As can be seen from figure 9 the failure does not exceed 1 % if the temperature is below 100 °C.

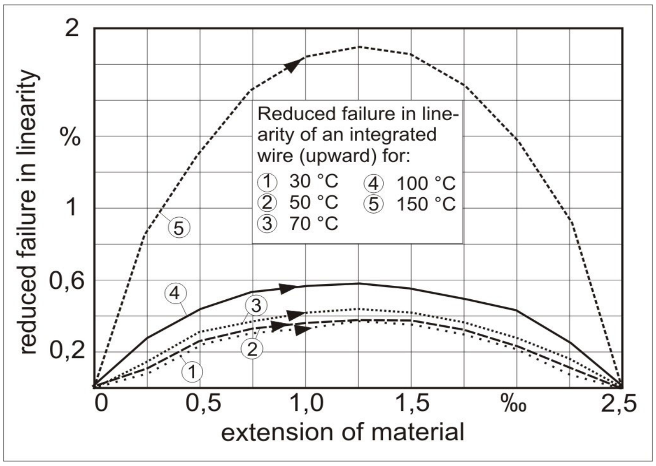

Fig. 9. Behavior of a specimen at different enviromential temperatures. Because of clarity only the upward loads are shown.

3. CONCLUSIONS

It is possible to incorporate wire-based stress measurement elements in CF-PEEK composites. These measurement elements allow for the monitoring of stress loads and thus for a crash prediction. The integrated wires were also investigated at elevated temperatures. The highest test temperature was 150 °C. During all investigations (excluding first loading of a specimen) the detected failures in measurement precision were less than 1 %. Because of the well known behavior of strain gauges which is by far better than the combined result with the CF-PEEK material it can be concluded, that the CF-PEEK material itselve causes the most important part of the detected failure.

The wire-based measurement elements, as described in this article, were especially developed for the material combination of CF-PEEK. That is why it cannot be assessed, how the wires would work with other materials. Because of the very similar results gained from the use of strain gauges at the surface respectively it can be concluded, that the wires inside have a comparable measurement accuracy.

REFERENCES

[1] Hufenbach, W.; Offermann, P.; Pfeifer, G.; Rödel, H.: Zwischenbericht der DFG-Forschergruppe „Textile Verstärkungen für Hochleistungsrotoren in komplexen Anwendungen - Beanspruchungsgerechte und versagens-tolerante Hybridstrukturen“. Dresden, November 1999. In German.

[2] Landgraf, J.; Pfeifer, G.: Werkstoffintegrierte Rissdetektion und Dehnungsmesstechnik in Strukturen aus kohlenstofffaserverstärkten Hochtemperatur-Thermoplasten. Ludwigsburg, Sensoren und Messsysteme 2000. In German.

[3] Folprecht, S.; Pfeifer, G.; Landgraf, J.: Integrierte Dehnungsmesstechnik zur Applikation in hochschmelzenden Kohlefaser-Thermoplast-Verbundwerkstoffen. Ludwigsburg, Sensoren und Messsysteme 2002. In German.

Authors: Folprecht Stefan, Pfeifer Günther, Landgraf Jürgen: Department of Electrical Engineering and Information Technology Dresden, Germany. Mommsenstrasse 13, 01062 Dresden, Germany email: stefan.folprecht@ias.et.tu-dresden.de