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Material integrated textile sensors in lightweight structures for applications in civil engineering

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ABSTRACT:

The integration of electronic units, sensors and actuators into complex function-oriented systems is one key point in development of intelligent lightweight composites and lightweight structures. A wide range of materials are available for that purpose and can be used to create active structures with selective properties. Often, these complex systems are manually integrated into smart structures with prefabricated and individually designed layer materials. But, automated production is difficult. Therefore, main aim of Department of Lightweight Structures and Polymer Technology (SLK) in cooperation with Competence Centre for Lightweight Structures (SLB) is developing application-oriented technical solutions for series production.

1 POTENTIAL OF RESEARCH

Embroidering, micro system technology and polymers combined in a closed process chain is quite unusual so far. However the research project "HighSTICK" and its research results showed that there are novel and future orientated fields of applications by embroidery technology. This technology is actually well known in industrial applications like Tailored Fiber Placement (TFP) for selective reinforcement of high duty plastic systems. In both ways, the TFP and embroidery method, fibers or wires can be places in individual patterns on flexible base materials. Furthermore, this technique is known for producing micro system structures in the field of flexible materials. The Institute for Special Textiles and Flexible Materials Greiz (TITV Greiz) had a leading contribution on that development in the last couple of years. In contrast, combination of embroidering, micro systems and polymers to a closed production chain is virgin territory. Motivation for that leads off bionics. And claim on engineering sciences is always associated with efficient design of its products and production processes. Due to this a complete analysis of key factors like energy efficiency, production method, material minimizing, resource efficiency, long-life product cycles, low energy consumption, low costs, multi functionality and the ability of self-repair is of essential meaning. In these points nature developed powerful solutions which can be used as structural examples that are far ahead from human engineering skills. There is no inefficient isotropic material applied at biological structure. Instead its design is optimized regarding load direction and amount. At the moment fiber reinforces materials are the best way to copy the structural ideal model from nature. Multifunctional structures with high functional density and customized properties cannot be made by other materials. The aim is that structures can respond on environmental changes in different fields of application and adapt the structural properties. That means high function integration instead of function separation, multi-functionality instead of mono-functionality, integrated optimization, minimal use of energy, use of existing external energies as well as fine tuning compared to environment. In regard to function integration embroider technology can make a contribution to manufacturing fiber reinforced products with selective semi-finished textile materials. In perfect way the embroidery process allows free positioning in x- and y-direction on the embroidery base. With full use of all possibilities a complex structure can be created which comes close to structures of a printed circuit board. Which future projects could lead of that? The first step to increase the functional density of fiber reinforces polymers is the existence of sensor properties or complex functional structures in the sense of structure integration. For embroidered structures the following sensor functions have been identified: signal generation due to material deformation, humidity sensor, temperature sensor, fill level sensor and touch sensor. Embroidered heating structures, radio antenna and conducting paths are known as functional structures.

2 EMBROIDERED SENSOR STRUCTURES

Thin metallic wires or conductive coated or rather conductive yarn are used as sensor materials. Embroider techniques are used to attach the sensor material on a non-woven. Figure 1 shows a larger scale image of that. The wire shown in this picture is positioned by Tailored Fiber Placement technologies and fixed with clearly visible purple yarn on a non-woven polymer. In principle the shape and dimension can be designed individually. At the moment the achievable resolution is about 0.8 mm.

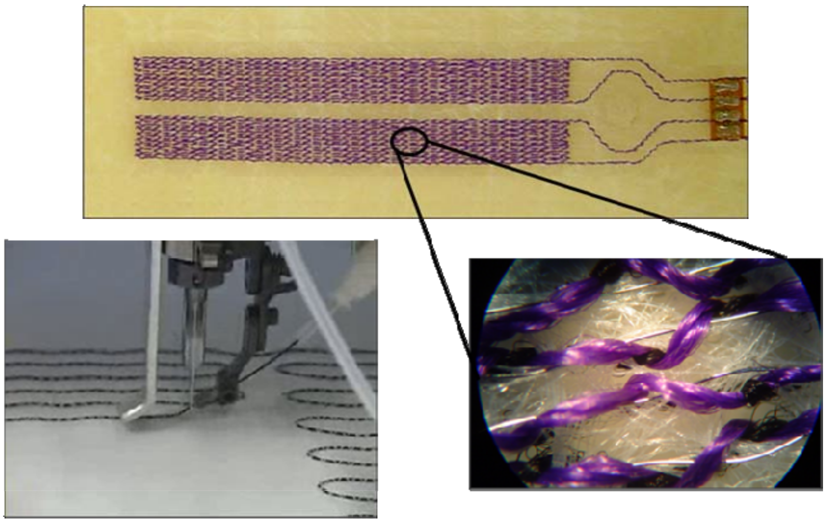


Figure 1: Embroidered sensor structures

The sensor could operate on capacitive, inductive or resistive working principles. The chosen wire material depends on the purpose of the specific sensor or sensor array. For strain sensors (analogous to strain gauges) resistive wires of constantan are used. Inductive and capacitive sensors are made of copper wire. Conductive yarn or yarn coated with conductive materials can be processed as well. The typical diameter is from 40 µm up to 100 µm. Necessary diameters need to be chosen respective to sensor dimension and the required resistance. The usual use of chemicals to achieve required conductive geometry is not applicable. Sensor wires are soldered to contact pads after embroidering. Further processes on other sensors depend on desired application. Signals can be transmitted wireless from inside of the part by integrating radio antennas and radio electronics.

3 APPLICATIONS OF EMBROIDERED SENSOR STRUCTURES

3.1 Application as strain sensor

The total resistance is a very important parameter for strain sensors. Its value is key factor for power consumption by sensor system. Besides, typical resistances of 120Ω, 350Ω and 1kΩ per sensor can be designed for any value between and around that. Tolerance for series production is about ±10% at the moment. For small scale and laboratory application a tolerance of ±3% is achievable.

The demonstrated strain sensor has less priority in exact measurement of mechanical strains inside a component like common strain gauges. It is rather used to functionalize fiber reinforced structure components. For example it is possible to adapt a part with a sensor that gives information about current status (health monitoring). Hence the sensor is embedded it is protected against environmental influence like humidity. By choosing an appropriate geometry and adjusting resistance the sensor can be freely customized and fitted to almost any component.

A common bridge connection is used to analyze the sensor signal in the same way as for typical strain gauges. If a standard value is chosen for resistance a usual industrial analysis unit can be applied.

To proof the functionality of the embroidered sensor the output signal is compared with a regular strain gauge. Both sensor systems are glued on a cantilever structure to perform various tests (see figure 2). Both sensors have a resistance of 120Ω.

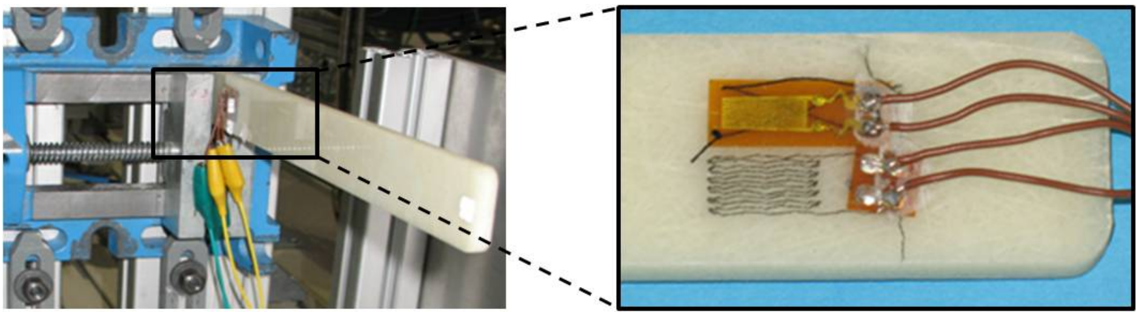
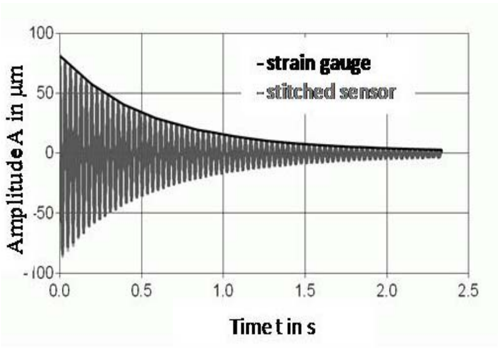


Figure 2: Beam arrangement to compare embroidered sensor with regular strain gauge

For the first test the cantilever beam was deflected to 5mm at the free end of the structure. When the beam is released it comes to a free damped oscillation. The amplitude of both sensor outputs is measured during the whole time of the free vibration decay test. The result was a very good correlation between both sensors (see figure 3).

In another test a vibration was induced by an impulse hammer at the fixed side of the cantilever beam. The impact causes vibrations in the whole frequency spectrum up to about 250Hz. The signal amplitude can be determined for each single frequency via Fast Fourier Transformation (FFT). The following figure shows the amplitude according to the frequency.



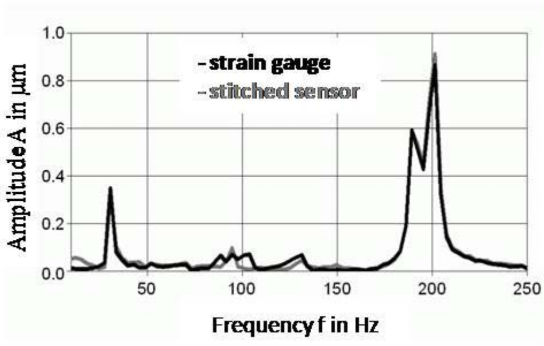


Figure 3: Diagram of free vibration decay test Figure 4: Signal of embroidered sensor and strain gauge

The test result shows sufficient matches between both sensors. The best correlation was reached at the natural frequencies of the cantilever beam.

The gauge factor of that sensor was determined as well. Therefore the sensor was glued on another beam. That beam was deflected in a four-point bending experiments. The test was carried out according to the VDI/VDE GESA 2635 norm (see Figure 5).

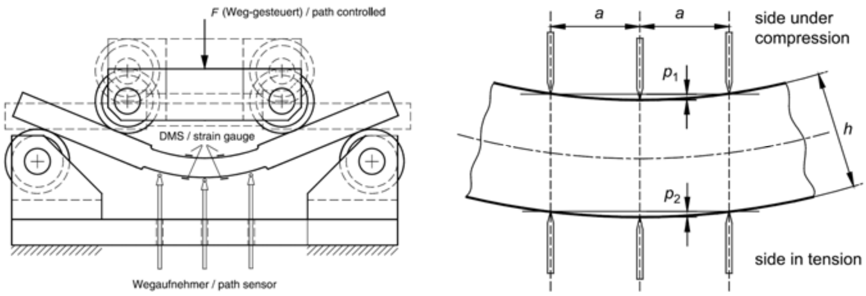


Figure 5: Comparison of embroidered sensor signal with strain gauge signal

The gauge factor is the proportion of the elongation of the sensor to its change in resistance. Due to the four-point bending experiment the deformation at the sensor area is clearly defined. The gauge factor can be calculated as followed:

$$k = \frac{\left|\overline{\Delta R/R_{0}}_{\text{pos}}\right| + \left|\overline{\Delta R/R_{0}}_{\text{neg}}\right|}{\left|\bar{\varepsilon}_{\text{M}_{\text{pos}}}\right| + \left|\bar{\varepsilon}_{\text{M}_{\text{neg}}}\right|}$$

The experiment results are shown in figure 6. Both sensors provide a nearly constant gauge factor over a width elongation range.

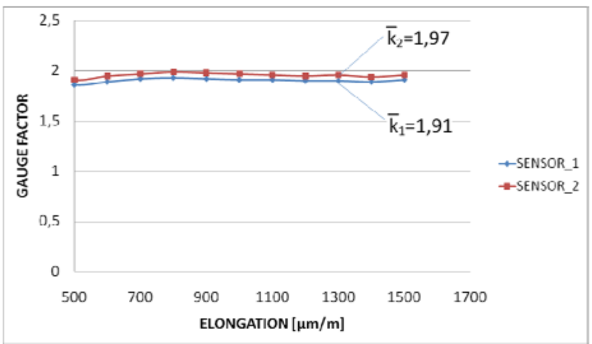


Figure 6: Gauge factor measurement

3.2 Application as fill level sensor

Capacitive sensors are applied to measure fill levels in tanks. Working principles and measuring methods of that kind of sensors are well known. One possible method is detecting changes in the electric field. Hence, the medium to be measured must be at least weakly conductive. With that method limits can be detected or fill levels can be measured continuously. Two electrodes are required and needed to be placed as close as possible to the liquid. For thick walled containers this can be a real challenge. To get a stronger signal it is better to place it as close to the medium (liquid) as possible. Using those sensors developed by the Competence Centre for Lightweight Structures, it is possible to position them anywhere within the wall thickness. The total thickness of the wall is nearly unimportant (compare Figure 4). Due to the sensors thickness of about 200µm they are very suitable for thin walls as well. The non-woven with sensor geometry embroidered is embedded in thermosetting resin. Therefore the sensor becomes part of the support structure of the polymer matrix. So it is not creating a separate layer which is leading to structural weakness. The same applies to embedding into thermoplastic materials.

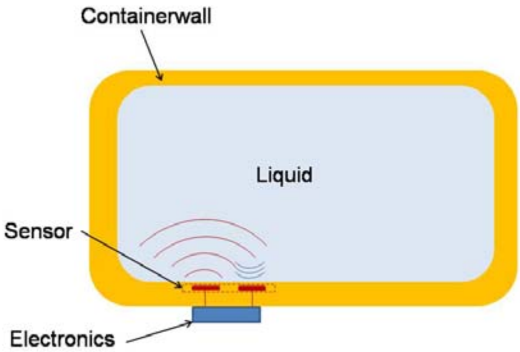


Figure 3: Functional principle of a capacitive fill level measurement system

Other authors of different publications name some possibilities to integrate sensors into container walls, but this has never been realized in a real application. Apparently suitable production technologies or integration methods and proper sensors are missing.

Because of the small installation height the embroidered sensor is quasi-two-dimensional shaped. Therefore they can be integrated into tank wall or applied outside. Due to embroider technology shape and size of these sensors can be designed freely. Hence small and larger series can be produced economically. Because of embedding the sensor inside of the polymer matrix the medium (liquid) cannot touch the sensible wire construction. At the same time the sensor is protected against mechanical damage, corrosion and dirt during the whole product life cycle. Additionally the sensor cannot be damaged while cleaning the container. The wall itself is the sensor case. The tank remains form-fitted and still has the same structural stability as without sensor. The sensor can be fitted to arced or buckled surfaces. The used thermosetting or thermo plastics must not be conductive. Improved productions methods for structure integration into polymers are a real innovation. Novel sensitized tanks with new functions can be created. Additional mounting and adjustment processes are no longer necessary.

For a concrete sensor geometry is the achievable capacity about 100 pF (see Figure 5). For demonstration purposes the sensor is taped on the outside of a glass cup. The distance of the sensor structure to the medium is about 1mm.

Figure 5: Possible sensor geometry with a capacity of 100 pF

For water as liquid medium the change in capacity of the wire structure could be about 30% to 50%. The liquid level can be measured analogue and gapless. An electronic circuit converts the detected capacity into a voltage range of 0V to 1V. If the cup is empty the output signal is 1V. When the cup gets filled up with a liquid the output voltage drops depending on the medium and the fill level. The following figure shows fill level measurements of different liquids.

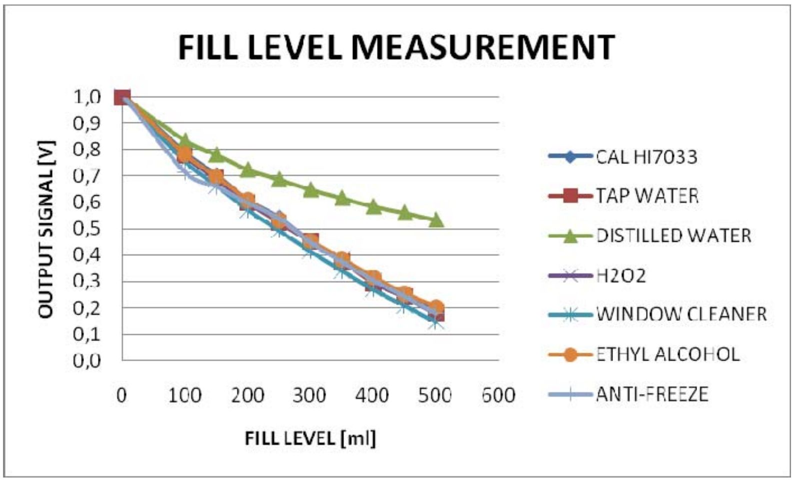


Figure 6: Fill level measurements of different liquids

3.3 *Application as humidity sensor*

Capacitive and resistive measurement setups are known techniques to measure humidity inside materials. For the first time economic measurements of humidity directly inside a material are possible using the embroidered and structure integrated sensor system developed by Competence Centre for Lightweight Structures.

Through the embedding of embroidered sensor systems in mineral building materials (e.g. masonry, concrete, plaster, etc.) as lost sensors permanent measurements can be taken in defined periods of time. That cannot be realized with any existing measurement technique. Stable Measurements can be taken any time, even after many years. In case of renovation works leak detection or wet areas can be localized easily. Therefore actions of quality control and quality assurance can be significantly improved.

Based on own research activities it can be shown that capacitive measurement methods give better result in mineral building materials. Thereby the measurement principle is similar to DNS method in building industry with the advantage of performing measurements directly inside the structure. Comparisons between embroidered structure integrated humidity sensors and general accepted laboratory methods according to the Darr-method show sufficient matches.

In figure 7 the relative humidity was determined by the use of gravimetric analysis. The weight of a sample component made of concrete is measured when it is wet and under absolutely dries condition. To make it dry the sample is put in an oven at 120°C. The difference between both measurements divided by oven-dry weight is the relative humidity according to the Darr-method. Additionally 3 capacitive sensors are placed inside the sample component. Figure 7 also shows the change in capacity while the structure is drying-out. The result is a clearly correlation between the relative humidity and the sensor signal.

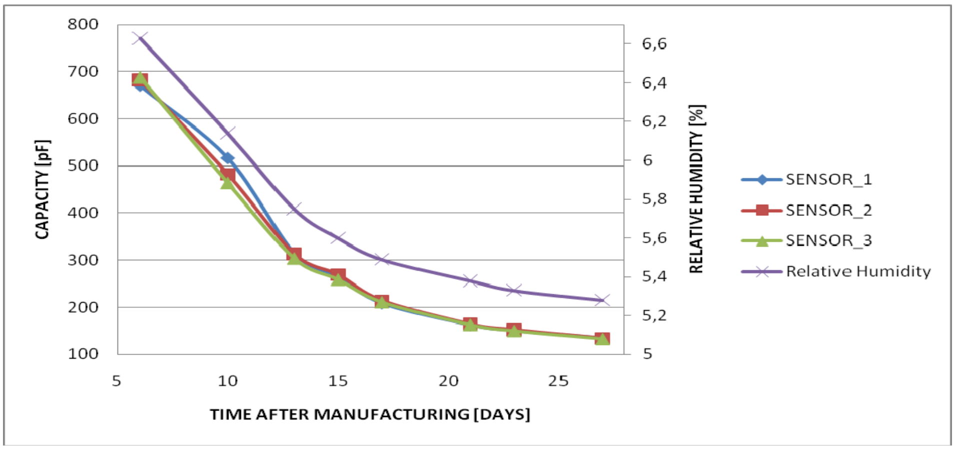


Figure 7: Correlation between sensor signal and relative humidity

4 CONCLUSION

Embroidered sensor systems have huge potential of innovation. The high degree of design freedom with conductive wires allows individual solutions where standard sensors cannot be applied. Size, shape and output signal of sensors can be adjusted as desired. If sensor geometry is placed in pattern, a high flexible functional sensor system can be created. Depending on sensor applications and required properties different conductive materials and diameters can be used. Due to their small thickness of about 200µm and flexible base material embroidered sensors can be embedded into fiber reinforced plastics. This sensor becomes just another layer and does not affect the structures stability at all. The embedding protects the sensor against environmental influence of any kind because the component is casing the sensor at the same time. This technology can be applied to thermo or thermosetting polymers and others like mineral building materials. Components can be functionalized with positive affects to the value chain. Additional mounting and adjusting steps of those sensors can be omitted. The sensors can be applied in different ways. They can detect intern status of structures like stress or health monitoring or they can measure external properties like temperature or fill levels. Embroidery is a very customizable technology which allows a wide range from small to large scale production.

All these facts show the potential of this technology. Though, more research needs to be done. Not all side effects are understood yet. There are no design rules or standards for embroidered sensors. Any sensor needs to be designed individually. There is no out-of-box solution for standard applications yet. For industrial applications reliability and production methods needs to be improved as well.

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