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HEALTH MONITORING OF HIGH-PERFORMANCE POLYMER COMPOSITES WITH MULTIFUNCTIONAL FIBERS

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ABSTRACT

In this paper multifunctional composite materials are presented through two examples in which sensing properties were added to the structural materials. In one method we used the light transmission property of glass fiber which would change under tension or when the fiber is broken. The other method is based on the electric conductivity of carbon fiber, which changes according to the load. Hand-laminated specimens were made for the tensile test, in which the special sensing fibers were built in. During load either transmitted light power or electrical voltage signals from the fibers were monitored continuously and were compared to the deformation value indicated by crosshead travel. In order to detect the failure of the test pieces, we looked for a sudden change in the signal, which is an indicator of a broken sensing fiber.

1 INTRODUCTION

Fiber-reinforced polymer composites are one of the most commonly used structural materials for high-performance engineering applications. Glass fibers are still by far the most commonly used reinforcing materials, used in almost 95% of the total volume of composites [1]. The volume of glass fiber reinforced polymer composites manufactured has grown every year since 2010, and it is more than one million tons just in Europe. One third of total production is consumed by transport, and another third is consumed by the construction sector. The rest of glass fiber reinforced plastic (GFRP) is used by other industries, such as the electric/electronics sector and the sport and leisure segment. Thanks to new research and development, large-scale manufacturing processes of composites are a hot topic. In the automotive industry more and more metal components can be replaced with composite elements with the use of different manufacturing techniques (such as sheet molding compound – SMC, bulk molding compound – BMC, resin transfer molding – RTM, or even thermoplastic resin transfer molding – T-RTM), and the overall percentage of the GRP market is likely to grow further. Unsaturated polyester resins are the most commonly used matrix material, but glass-reinforced thermoplastics are the fastest growing segment of this market. The automotive industry is the main driving force, because the thermoplastic matrix can be combined well with other materials and can be processed by the already well-known injection molding technology [1].

The second most used reinforcing material is carbon fiber. In 2015 the global requirement for carbon fiber was approximately 58000 tons and it grows every year by about 9-12% [1]. In accordance with the production of carbon fiber, the carbon fiber reinforced polymer composites (CFRP) market grows as well. The estimated growth of this segment is 10% to 13% per year, and the driving force of that rising usage is the aerospace and automotive industries. With the application of carbon fiber reinforced composites lightweight constructions can be made, and this is the key to the efficient use of fuel. In 2015 aerospace and defense applications used 30% and the automotive industry used 22% of total manufactured CFRP. In the Boeing 787, composite structures account for around 50% of the airplane, used mostly in fuselage and wing sections. CFRP are preferred by car manufacturers to produce lightweight electric cars, such as the BMW i3 and i8 (in 2015 about 24000 i3s and 5500 i8s were sold).

With the research and development of manufacturing techniques, the predicted demand of the automotive industry for CFRP will grow by almost 300% to 2022 [1].

As a result of expanding usage, more and more information has become available concerning the behavior of the material. This knowledge combined with various modeling software packages allows the construction of more sophisticated structures. However, in a composite structure critical deformation may occur due to an unexpected load or impact and this can damage the material irreversibly. To facilitate the successful spread of composites into safety-critical applications, such as in the civil aircraft, automobile and construction industries, a simple, non-destructive structural analysis method is needed. Most of the currently used evaluation methods need relatively complicated equipment which is independent of the tested part or product. The efficiency of these processes is varied, furthermore they can usually not be used during operation (*in-situ*).

On the other hand, there are different types of evaluation methods where the sensor is built into the composite part during production. With these methods, the signal of the sensor must be measured by an external unit. The response of the sensor depends on the magnitude of environmental impacts such as temperature change or deformation. Because of the built-in sensors, these monitoring devices could be used continuously during operation as the structure does not need to be accessed, removed or disassembled while being tested. However, these sensing methods have their drawback: the integration of the sensor modifies the internal structure and continuity of the composite material. To overcome this disadvantage, the fiber reinforcement can be utilized as detector. So-called multifunctional materials or multifunctional composites, which can react to any change in their environment or modification of the structure, could be used to indicate fracture.

In recent years more and more papers have been published which introduce polyvalent materials and structures to increase system-level efficiency. Multifunctional Material Systems (MFMS) can merge more than one functions in the material itself, for example, if a part of a material can act as a sensor, it may eliminate the need for other built-in sensing systems. This involves fewer parts, saving weight and volume, increasing efficiency and reducing the time needed for assembly. All these mean a reduction in costs. Multifunctional composites are structural materials, and have an extra function [2]. This additional function can be fulfilled through the reinforcing materials. Different signals are transmitted in the reinforcing fibers, then the change in the signal is measured in a sensing system, where structural health can be monitored. In glass fiber reinforced composites the individual fibers can act similarly to an optical cable used in communication, hence it is capable of transmitting light [3, 4]. Change in light intensity can indicate a change in structural integrity. In the case of carbon fiber reinforcement, electrical resistance can be the basis for self-sensing, as it varies due to deformation, temperature change and fracture [5]. Therefore, measuring the electrical resistance of an isolated carbon fiber bundle placed in the structure means continuous data collection about structural health. Both processes make complicated external detector and signal processing units unnecessary, and the mechanical properties are not modified significantly. The use of reinforcing materials as sensors gives the opportunity of lifetime monitoring. If the fibers are themselves the sensors, they are able to monitor the state of the part during manufacturing, assembling, operation and in the case of damage. The manufacturing process can be monitored *in-situ*, and with the evaluating of the collected data, process parameters can be easily adjusted to the optimum depending on the measured values. With a method like that, the sensor, or more precisely, the part itself can control / regulate the manufacturing parameters, which can help to realize the principles of industry 4.0 in the composite manufacturing sector. By collecting and evaluating the measured values, not just the health of the part can be monitored, but its lifetime can be predicted, too.

In this paper two examples of continuous structural health monitoring processes applicable for polymer composite structures are presented. The integrity of the composite structure in the case of glass fiber reinforcement is examined by light intensity measurement and in case of carbon fiber reinforcement it is achieved by electrical resistance measurement. As part of the research, various types of specimens were loaded and fractured while the signals from the built-in sensors were monitored. As a result, *in-situ* data collection is accomplished with more reliable materials while mechanical properties of the material are not modified, consequently this measuring system can contribute to the further development of intelligent structures.

2 EXPERIMENTAL

In our research we aimed to create reinforced polymer composites which are able to sense their structural health. We used two approaches: one would utilize the light transmitting effect of reinforcing glass fiber, the other uses the electrical properties of carbon fiber.

2.1 Multifuncitonal glass fiber

The continuous reinforcing glass fibers in polymer composites can be prepared to transmit light in a proper matrix material which has a lower refractive index than the reinforcing glass has. Light entering the fiber reaches the fiber-matrix boundary at an angle higher than the critical angle and is reflected because of total reflection. The reinforcing glass fiber is able to transmit light while it is undamaged. When it is broken, the light will leave the fiber, and the emitted intensity of the bundle will be reduced. Measuring the intensity of the emitted light, one can monitor the soundness of the fibers and the health of the structure [4, 6].

Many researchers investigated the possibility of using glass fibers as optical sensors in composite structures. The optical power transmitted by the glass fiber can be measured and it can indicate damaged fibers. Hayes *et al.* [6] used commercially available Quartzel fibers in resin with a low refractive index. The Quartzel fiber can transmit light better than E-glass fibers, which are used as reinforcing material in composites, but the cost of these fibers are also higher. The light transmission characteristics of unsized E-glass reinforcing fibers were examined as well by several authors [4, 7-10] in various resin systems used in the optic sector. The disadvantage of these fibers are that their light transmission capability is far worse than that of the optic fibers used in telecommunications. The diameter of optic fibers is approximately ten times the diameter of reinforcing glass fibers. With special preparation, the diameter of commercially available optic fibers can be reduced to roughly that of reinforcing glass fibers. Malik *et al.* [3, 9] investigated the behavior of these custom-made small-diameter optic fibers during tensile test. In all the publications mentioned there was a clear correlation/relationship between the power of the transmitted light, and the load/damage caused by external circumstances.

In the papers published so far it has been proved that the measuring of emitted light power can be used to monitor the health of the fibers, and so the health of the composite structure. The authors investigated fibers without sizing in special resin systems. The sizing of the reinforcing glass fibers provides protection against further mechanical processing steps and holds the fibers together. Besides this, the main function of the sizing is to provide a good connection between the fiber and the resin. A good adhesion connection between the reinforcing material and the matrix material is essential in composites structures, because this greatly affects the mechanical properties of the composite.

The aim of our research was to examine the light transmission characteristics of E-glass fibers without removing the sizing, and to investigate the opportunity to use it in a common resin as a sensor to measure deformation.

For the measurement of the light transmitting ability of the reinforcing glass fibers, it is necessary to find the proper thermoset resin with a refractive index less than the refractive index of the reinforcing glass fiber (in our study reinforcement is a continuous boron-free E-CR glass bundle – Advantex T30 R25H-1200 TEX, Owen's Corning, Belgium). We investigated the refractive index of some commercially available transparent resins. Datasheets rarely include the refractive index of resins, therefore it was measured with an Abbe refractometer (A.Krüss Optronic, AR4, Germany). Eight different resin systems were examined, and for further experiments we chose MR3012 epoxy resin (ipox chemicals, Germany) and MH3122 hardener (ipox chemicals, Germany) at a weight ratio of 100:40. Its refractive index was more than 2% less than the refractive index of the reinforcing glass fibers. The mechanical properties of this resin system can be varied in a wide range with the mixing ratio.

To investigate the light transmission characteristic of the bundle, we used a green Nd:YAG laser (532 nm wave length, Suwtech, dpgc-2250) light source. The emitted light was examined with a high sensitivity optical power sensor (Coherent, OP-2VIS, USA).

The intensity of the transmitted light of the fiber bundle was measured at room temperature and at different distances from the light source (Fig. 1).

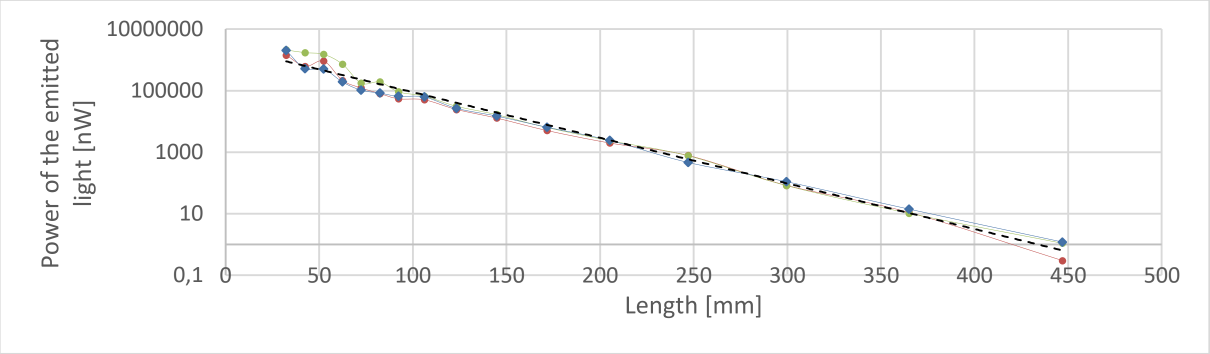

Figure 1: Light transmission graph of the fiber bundle in MR3012:MH3122 100:40 resin at different lengths

Specimens were made to investigate the transmitted light during a tensile test (Fig. 2). The predicted place of fracture wasn't at the gripping area. Both ends of the fiber bundle were polished. During loading a light source and a camera was connected to monitor the transmission of light continuously. We used a high-speed camera with a universal zoom lens (Keyence, VW-600M + VH-Z100UR, Japan) for monitoring, and the light of the camera as a light source. The tensile tester was Zwick, BZ020/TN2S from Germany.

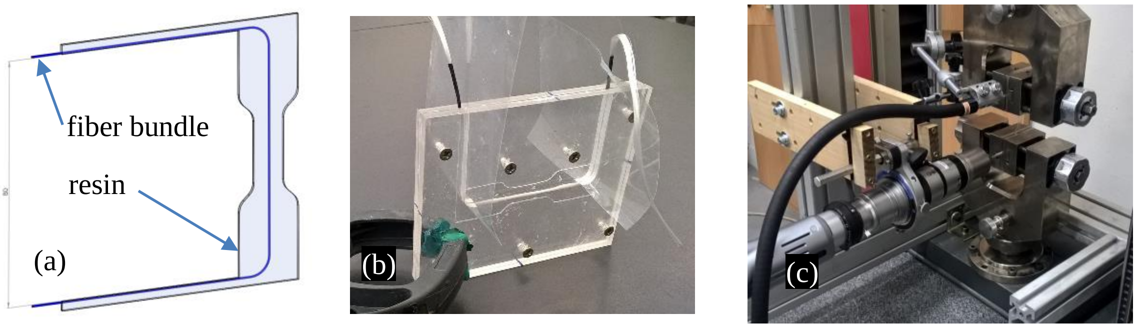

Figure 2: The geometry of the specimen (a), the mold (b) and the measurement layout (c)

During the tensile test, the end of the elemental fibers are well visible, and the intensity of light emitted from elemental fibers decrease with deformation. When the fibers broke, they couldn't act as light guides any more (Fig. 3).

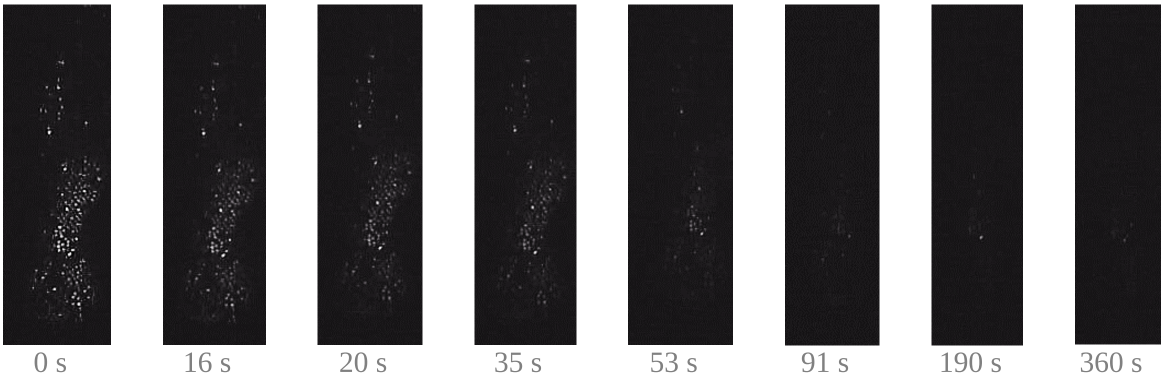

Figure 3: Monitoring emitted light during a tensile test

We demonstrated that the reinforcing E-glass fibers in the MR3012 and MH3122 epoxy resin system are able to transmit light, without the sizing removed. By in-situ monitoring of the power of transmitted light, we can get information about the integrity of the bundle, and thus the structural integrity of the composite structures. This method can be used to evaluate damage, and with the monitoring of different bundles, it can be used as structural health monitoring system.

2.2 Multifunctional carbon fiber

The special bond in the carbon structures, which has a delocalized electron below or above the carbon ring makes electric conductivity possible in the material, therefore spatial arrangements like fibers or nanostructures are capable of conducting electric current [11]. This particular property makes it possible to give carbon fiber other functions besides being a structural loadable element. As know, the temperature of a conducting element increases when a current flows through it. This is called Joule heating and it is proportional to resistance, time and the square of the current. Hayes *et al.* [12] utilized this property of carbon fiber to cure an epoxy-carbon prepreg by direct electrical heating. They stated that this electric power produced a degree of cure similar to what could be achieved by autoclave or oven curing. Kawagoe *et al.* [13] investigated a new welding method based on the Joule heating of carbon fiber. In their work, resistance heated welding was achieved with a heater element, a carbon fiber stripe which later worked as reinforcement. When electric current flowed through it, the carbon fiber heated the thermoplastic matrix around it, and with pressure applied, welding was completed. Greenhalgh *et al.* [14] developed a capacitor-like structural element in which they could store energy. It is based on the electrical conductive property of carbon fiber and on the insulator property of glass fiber. With the layer order of carbon-glass-carbon reinforcement the carbon layers with high specific surface area served as electrodes and the glass fibers were the insulator.

Because of the multiphase and layered property of composites, a part could suffer failure in many different ways: matrix cracking, fiber fracture and layer delamination even in the case of a low-velocity impact [15]. The electrical conductivity of carbon fibers makes it possible to use them as sensor: the resistance of the bundle varies under load as it stretches or breaks. Chung [5] investigated this phenomenon under different types of load, failure methods and fiber arrangements and proved that carbon fiber could be used as a structural health monitoring sensor, therefore self-sensing materials can be created with carbon fibers. An additional functionality of reinforced polymer composites could be self-healing, where in the case of a failure, the material itself would sense cracks and try to reclose them, achieving nearly original mechanical properties [16].

In our experiment, structural health monitoring was achieved by monitoring the resistance of a carbon fiber bundle. The bundle (Zoltek PX35) was laminated into an insulating composite of woven glass fiber reinforced epoxy (ipox ER 3016 mixed with MH 3124 in a ratio of 100:40). A plate was hand laminated, the voids and unnecessary resin was pressed out by pressure plates at 300000 Pa for 15 hours, and the plates were cured at 80°C for 7 hours in an oven. The bundles were placed over the top layer and were kept stretched by screwing to the mold. 300x25 mm specimens were cut from the plate parallel to the carbon fiber bundles. We made the electric connection with the data collector unit by grinding back the matrix by sandpaper and gluing wires to the carbon fibers with Loctite 3888 silver-filled two-component epoxy glue. Then a tensile test was performed on the specimen in a Zwick Z250 universal testing machine, while the resistance of the carbon fiber bundle was monitored with an Agilent 34970A data collector unit (Fig. 4).

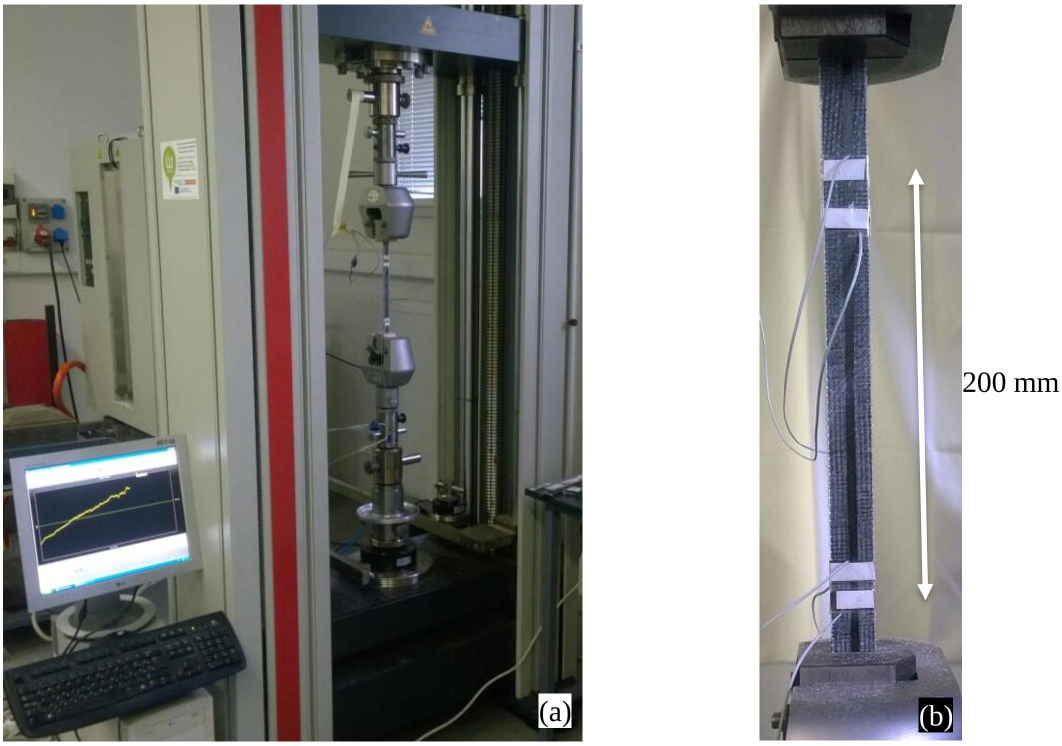

Figure 4: Measurement layout (a) and a close-up of the specimen (b)

Resistance was measured by the four-wire method, which does not measure the resistance of the unit or the wires. It is also more sensitive to small changes in resistance than the two-wire method. Constant current was connected through the outer two wires and the voltage drop was measured between the two middle wires. The resistance and elongation data from a typical measurement as a function of time are shown in Fig. 5.

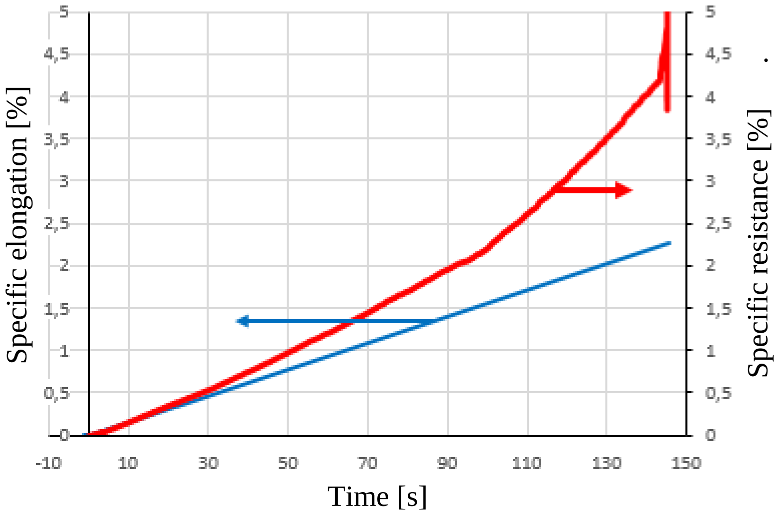

Figure 5: Measured data of specific strain and specific resistance

At the beginning of the test, specific resistance was proportional to deformation, here the change in resistance follows Ohm’s law. After a point, which varies from specimen to specimen, the change in resistance increases. This effect could be the result of the fracture of a single filament: the carbon fiber bundle impregnated with epoxy is similar to a parallel connection, where the breaking of one line leads to a change in resistance. At the failure of the specimen the electric circuit opens, therefore the measured resistance will be infinity.

3 CONCLUSIONS

In this paper we presented multifunctional composites, where fibers can be given a health-sensing function besides load bearing. Since glass fiber can transmit light, it can be used as a damage sensor, as the amount of transmitted light drops when the fiber breaks. We found a way to use commercial fibers, which do not need any special treatment e.g. removing the sizing, which reduces cost. In the case of carbon fiber, resistance also changes under load. In this article we pointed out that the change in specific resistance is not linear due to the fibers breaking one after another. Both methods presented make it possible to immediately detect failure during operation, which means they are multifunctional materials.

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