Multifunctional application of carbon fiber reinforced polymer composites: electrical properties of the reinforcing carbon fibers – a short review

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Abstract

In most areas where weight reduction is crucial, carbon fiber reinforced composites (CFRPs) are an excellent choice. Carbon fiber, besides its structural role, can be applied for several secondary functions as well, based on its electrical properties; for example, it can be used for crosslinking, welding, as a sensor and it can also facilitate self-healing. By merging these functions, a multifunctional part or structure can be created. In this article, we review multifunctional application examples of reinforcing carbon fiber. The focus is on utilization: which additional function and what physical layout can be used with CFRP. In a summarizing table (Table 1), we classified the presented examples according to their secondary function, the material used and the physical layout. With the combination of different functions, important materials can be created for the energy and transportation industry, for autonomous vehicles and for Industry 4.0.

Keywords:

A. Carbon fiber
A. Polymer-matrix composites (PMCs)
A. Smart materials
B. Electrical properties
Multifunctional materials

1. INTRODUCTION

One of the main challenges of modern product development is weight reduction, while maximizing load bearing capability at the same time. Carbon fiber reinforced polymer composites (CFRP) have several excellent properties: good chemical resistance, outstanding mechanical properties at low density, and strength characteristics can be tailor-made for a given load. These properties, combined with decreasing material prices and manufacturing costs, have contributed to the spread of this type of composite. It is now widely used, even mass-produced. The growth of the carbon fiber market has an impact on different industries where energy efficiency can be increased (e.g. transportation industry) or large structures can be constructed (e.g. wind turbine blades) with a low-density high-strength material [1].

In addition to reducing the mass of a part made from low-density carbon fiber composite, the weight of a complex structure (e.g. the weight of a vehicle) can be further decreased. When load bearing and secondary functions are merged, multifunctional materials and parts are created. The conventional applications normally utilize the outstanding strength and stiffness of the material; however other properties, such as good electrical conductivity are not exploited. The electric properties of carbon fiber allow the production of multifunctional structural parts which are capable of de-icing [2] or protecting aircraft wings from thunder strike [3,4], or storing energy [5,6].

With the development of information technology and the intense automation of industry, a new industrial revolution, Industry 4.0 is spreading on production lines. For flexible production lines without human interaction, large data collection (big data) and the continuous sharing of data between equipment (internet of things) are essential. Carbon fiber reinforcement can be used as sensors (e.g. temperature, humidity, deformation failure) and products can be designed which are able to collect data throughout the lifetime of the product about its environment and structural state, thereby meeting the growing data and information need of Industry 4.0. Various embedded sensors can also be used for health monitoring and for data collection but with many disadvantages: an embedded sensor different from the base material of the structure represents an imperfection, its interface adhesion and mechanical properties are worse than that of the reinforcing fiber, and also, resin accumulates due to size difference. In addition to the difference in physical properties, embedding of external sensors external sensors represents an extra cost and requires complex manufacturing processes. In comparison, reinforcing carbon fibers have the advantage that they are an integral part of the composite structure, thus they do not affect the integrity of the material or manufacturing technology.

In this article, we present examples of applications in which a CFRP also performs a function other than structural load-carrying. This merging of functions allows us to review the design of more complex structures and to create new perspectives in design and material technology.

2. ELECTRIC CONDUCTIVITY IN CARBON FIBERS

The electrical properties of carbon fibers used as reinforcement in composite structures are the basis for several multifunctional applications. The significance of carbon is due to the extremely stable hexagonal plane grid and the delocalized electron cloud between the planes. The deformation and separation of the hexagonal carbon rings requires high energy, which provides the strength of the carbon fiber at macro level, while the free electrons in the electron cloud make it a good electrical conductor [7].

The electrical resistance of carbon fibers depends largely on the material used (precursors), the manufacturing conditions and the crystalline structure. The most common raw material for carbon fiber production is polyacrylonitrile (PAN), which accounts for 90% of world carbon fiber production. In addition, pitch is also an important precursor for industrial use [8]. Polymeric fibers are formed by spinning from a solution of polymerized PAN with comonomers. The stretching force acting on the fibers increases the orientation of the molecules and decreases the fiber cross-section. The precursor fibers with poor thermal conductivity are stabilized by slow heating at a low temperature (~ 300 °C) with partial oxidation, during which a so-called ladder molecule is formed. By carbonizing the stabilized fiber, high-modulus and high-strength fiber can be produced. During carbonization, the stabilized fibers are first heated to 1500 °C in an inert atmosphere (nitrogen or argon) and then treated at a higher temperature (1500-3000 °C). During this process, pollutant atoms are removed and a near-graphite structure is produced [9–11].

The microstructure and physical properties of carbon fiber are closely related; the modulus of elasticity, strength and electrical conductivity of the fibers are influenced by the imperfections in the fiber, the carbon content, and the orientation of the graphite structure. Qin *et al.* [12] found that a higher carbon content can be achieved by higher carbonization temperature, as in this case, fewer pollutant atoms are present. Larger sized ordered parts, that is, larger crystallites are better orientated towards the axis of the fiber, so they have better electrical conductivity. Edie [13], as well as Huang and Young [14] also pointed out that an increase in the carbonization temperature produces a more structured carbon grid, which affects the physical properties of the carbon fiber, such as modulus, strength and conductivity. As a result of the more structured atomic structure (heat treatment at higher temperature), both PAN-based [15,16], and pitch-based [17] carbon fibers have lower specific electrical resistance, thus they have better electrical conductivity.

For the multifunctional use of reinforcing carbon fiber, it is necessary to solve the problem of connecting it to the electrical circuit. For this purpose, either direct contact or induction can be used. In direct connection, the terminals of the power supply are physically connected to the reinforcing carbon fiber of the composite. In this case, the connection can be characterized by contact resistance. In a number of research projects utilizing the electrical properties of carbon fibers, a copper block, a sheet or foil, a nickel foil or silver-filled adhesive were used to achieve good electrical contact [2,4,18–28]. With this method, both direct current and alternating current can be connected to the carbon fiber. In the case of induction method, voltage is induced in a conductor placed in an alternating magnetic field, causing current to flow in the conductive material. Changes in the magnetic field can be caused by the relative movement of the magnetic field and the conductor (motion induction), or the magnitude of the field, i.e. the change of the flux in time (stationary induction) [29]. For composite products, the latter method is typically used; an alternating current flows through a coil placed over the composite, generating an alternating magnetic field in the coil, which induces voltage and thereby a current in the conducting parts of the composite (the carbon fiber reinforcement phase or nanoparticle-filled resin). Induced current can flow if the conductive material forms a closed loop [30–32]. The electrical current flows not only into the individual fibers, but can flow from one thread to another, either by direct contact or based on the dielectric properties of the matrix (the matrix is a capacitive reactance). In unidirectionally reinforced composites, this process depends on fiber content but is less effective than in woven or multi-directional reinforcing structures, as in the latter case fiber connections are more easily formed. Induced current can only flow if electrical connection among the fibers exists. This means additional resistance, and also, part of the energy becomes heat [33].

Some technologies (autoclave, pultrusion) can yield polymer composites with a fiber ratio up to 70%, but for good mechanical properties it is necessary to perfectly impregnate the fibers [34]. This also means that every elementary fiber is surrounded by the matrix material; fiber-fiber contact is theoretically not possible, consequently each fiber is a single conductor, and each fiber bundle can be considered as a series of parallel resistors. Assuming that all elemental carbon fibers of the specimen can be perfectly connected to the circuit, the full cross section will have an even distribution of the current. However, in practice, neither perfect impregnation nor perfect connection can be achieved, therefore there is usually a flow of current between the fibers, and the product only partially conducts current.

3. MULTIFUNCTIONAL CARBON FIBER REINFORCED POLYMER COMPOSITES

In the case of CFRP materials, the conductivity of the load-bearing carbon fiber can be used for a secondary function, and so functions can be merged. In the following subchapters, we present these secondary functions and multifunctional application examples based on the electrical properties of the composite material.

3.1. Resistive heating of carbon fiber

Due to the resistance of a conductive material, some of the electric power is converted to heat. The amount of heat generated depends on material characteristics and the intensity of the current. The phenomenon is called electric resistance heating; the resulting heat is called Joule heat. In this chapter, the examples are characterised based on how the electric current can be connected to carbon fibers (directly or by induction)[35]. Several applications of resistive heating are also described.

In their article Schulte and Baron [36] noted that in the case of carbon fiber, Joule heating should be taken into account as it may modify the mechanical properties of the structure and can influence the fiber's environment. They realized that the temperature of the carbon fibers increases significantly with a current of 1 A or greater. They considered this temperature change an error in their measurements, however, in other configurations, the released heat can be used for various application, presented below. Athanasopoulos and Kostopoulos [37] focused on the problem of describing anisotropic materials, such as fiber-reinforced composites with the current-conducting tensor and the distribution of heat generated by the electric field. The correlation they describe, which weighs the conductivity of the individual layers with the surface of the layer, can be characterized by the electrical potential in any layer order. Based on these, the electric field, charge density and the amount of heat generated can be predicted. From these data, they modelled the temperature distribution and they verified it with a heat camera recording taken during the heating of various layers of specimens.

In CFRP, heat is generated by induced current as well. Yarlagadda *et al.* [33] focused on the question, what phenomena causes heat in the closed loop formed in the CFRP. They detected two sources of heat: one was the current flowing through the fibers generating Joule heat, and the other source was the junction of the fibers; for the latter, there are two possible causes depending on the connection of the fibers (Figure 1).

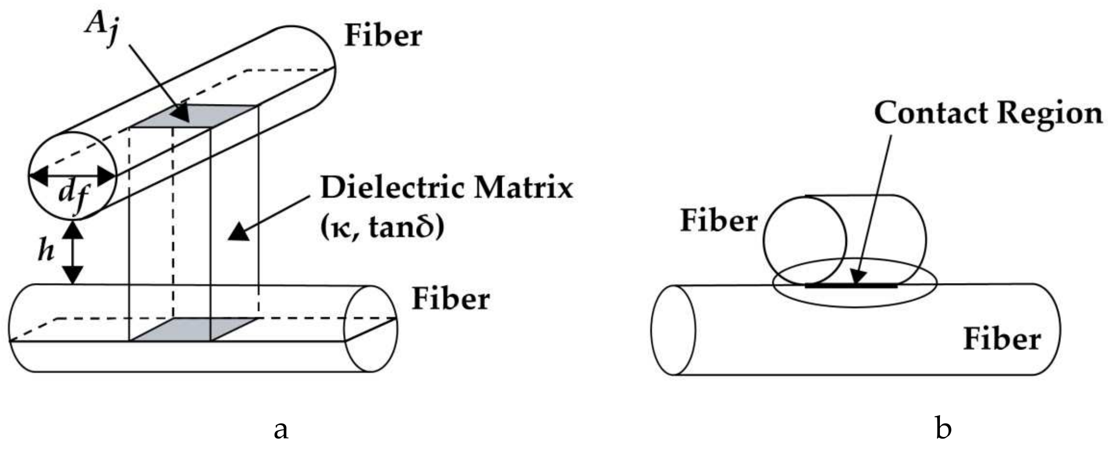


Figure 1. Area of heat generation due to induced current: in the dielectric matrix between carbon fibers (a) and at a fiber contact (b) [33]

If the fibers do not come into direct contact (e.g. UD prepregs are placed in different directions), dielectric loss heat is generated due to the dielectric properties of the matrix. In the case of direct contact (e.g. woven structures) heat is generated by contact resistance. They found that a significant part of the heat generated by induction is due to dielectric hysteresis loss at the junctions, which is not dominant in composites reinforced by conventional carbon fiber fabric (direct contact between the fibers).

The two electric heating methods (direct connection to the circuit, induction heating) described above can be used *in situ* for the heating of the matrix material to induce crosslinking. In direct resistance heating, some of the carbon fiber layers are directly connected to the power supply, which results in Joule heat that heats the environment locally. Joseph and Viney [24] clustered carbon fiber prepregs between copper blocks and then heated the prepregs up to the temperature needed for crosslinking by current flowing through the copper blocks. Although the bending strength of the specimens produced by this method was lower than that of specimens treated in an oven, their elongation and energy absorption increased. Athanasopoulos *et al.* [38] investigated the temperature distribution at different temperatures during resin infusion, heat treatment and crosslinking. When evaluating the results, they found that heat production was even in the laminate (deviation was less than 3 °C), and according to their recommendation, the process can be also used for vacuum bagging, vacuum injection or prepreg manufacturing techniques. Hayes *et al.* [20] also studied temperature distribution; they analyzed the method of connecting the current and the surface distribution of the temperature. They came to the conclusion that, with manufacturability taken into account, the best distribution can be achieved if the copper foil electrodes hold all layers or all layers except the outermost ones (Figure 2).

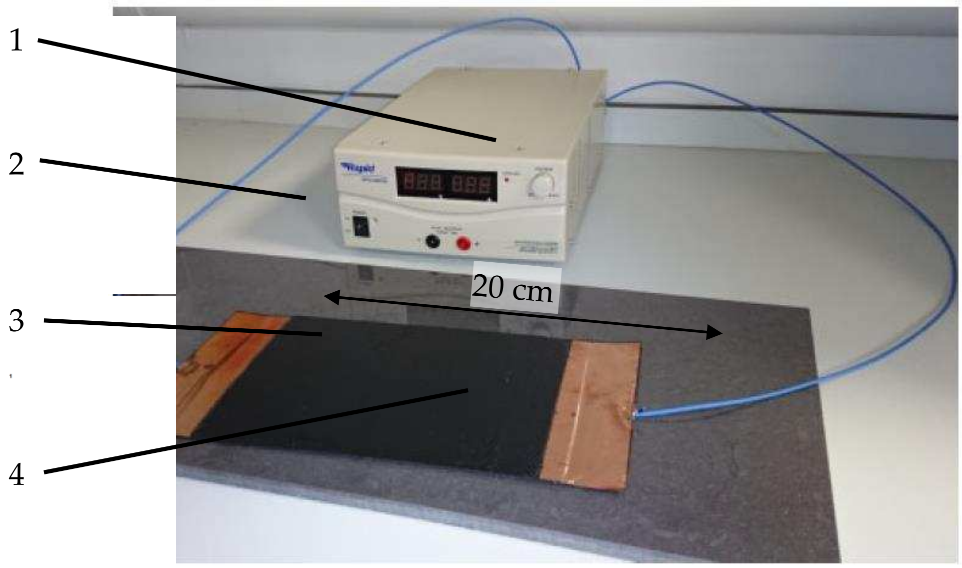


Figure 2 Measurement arrangement for crosslinking with electric heating. Power supply (1), electric wire (2), copper foil (3), CFRP laminate (4) [20]

With the use of a copper foil, the center of the specimen is approximately the same temperature, but at the edges there can be a difference of up to 10 °C. During manufacturing, this part would be removed anyway for the sake of accuracy of size; therefore resistance heating can be suitable for the useful area.

Theoretically, induction heating can also be used for curing the resin, although heat distribution is not as even as in the case of the direct method. The reason is that induction requires a closed loop in the composite, but loop formation is unpredictable and difficult to design. Such a loop can be created by crossing carbon bundles or by filling the resin with a conductive material (metal particles, graphene, carbon nanotubes) [30]. However, because of the size of the induction coils and the properties of the magnetic field in the material, this procedure can only handle a small area at a time and cannot be applied well to the edges of the material. Due to these physical limitations, the researchers only used induction heating to cure minor defects and for the heat treatment of two-component adhesives [30,31,35,39].

With the help of electric heating, products can be crosslinked *in situ;* the heat is applied directly to the matrix material, therefore heating is fast (up to 200 °C/min) and heat distribution can be even [40]. Compared to conventional heating methods, such as oven or autoclave heat treatment, almost the same degree of curing can be achieved with the help of electric heating, and as a result, the mechanical properties of the composite are the same in the case of autoclave and electric heat treatment [20]. Resistance heaters can reduce the energy and the time required for heating.

It is a disadvantage of crosslinking by electric heating that proper electrical connection is necessary between the carbon fibers and the power source; otherwise contact resistance is too high and so is the voltage drop on the contact, therefore the energy need of the process increases and the heat generated by the connection is wasted. A further difficulty is to achieve accurate regulation.

Another application of resistance heating is the welding of thermoplastic polymer matrix composites [41]: the heat required for welding can also be generated by a current flowing through carbon fibers. In their study, Eveno and Gillespie [25] showed that due to the good adhesion of the matrix and the fibers, specimens made with the help of multifunctional carbon fibers have better mechanical properties after welding than those joined by gluing, ultrasound welding or wire mesh heating. During experimenting, the carbon fibers were directly connected to the circuit and used to heat the matrix while they analyzed the effects of different parameters. They found that the even temperature distribution required for high-grade welded joints can be achieved only by slow and long heating but this is not a productive method. McKnight *et al.* [42] studied larger welded joints. Size plays a significant role in the success of the technology, since more heat (i.e. more electrical power) is needed in the case of a larger surface, furthermore it is more difficult to achieve an even distribution of heat. They first studied different heating methods (constant temperature or constant power). To avoid overheating, and thus the degradation of the matrix, they maintained a constant temperature with a temperature measurement feedback circuit. To reduce the electrical power required for welding, they divided the surface into three parts and heated them in a specific order. The three-step seams were compared to the one-step seams by ultrasonic surface scanning and mechanical testing. According to the researchers, the three-step process resulted in a bigger seam surface area and at the same time, the shear strength of the joint was higher, though more time was required because of sequential heating.

Similarly to crosslinking, the heat required for welding can also be generated by induction. In this process, shorter cycle time and higher productivity is usually achieved by continuous welding, with a moving work piece or coil. Alternating current can be induced in different materials, therefore metallic mesh, carbon fabric and ferromagnetic particles can be used to influence the location of Joule heat within the material. This process usually heats the surface more than the inside of the material, but active cooling of the surface can reduce the temperature difference [30]. Pappadà *et al.* [32] used carbon fiber induction heating to form a typical aerospace welded joint. The experimental parameters (induction coil geometry, distance from the composite surface, required electrical power) were determined with a finite element model. The overheating of the surface was prevented by air blown on it, while a tempered cylinder provided the required pressure and cooled the seam (Figure 3).

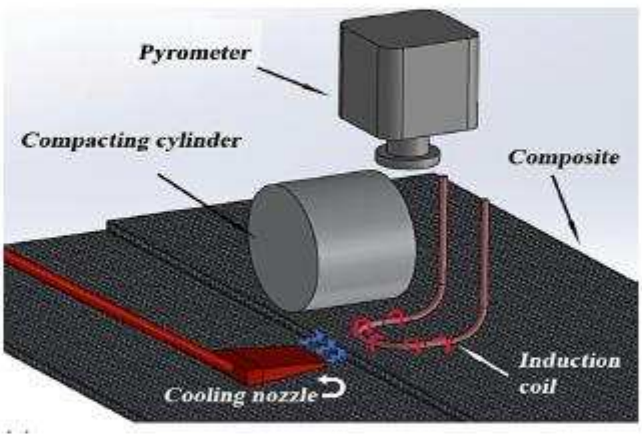


Figure 3. The conceptual outline of induction welding of carbon fiber thermoplastic composite [32]

The strength of the welded specimens were in accordance with the regulations of the aviation industry and therefore the authors intended to extend the procedure for more complex geometries [32].

Heating materials locally resulted in novel applications. Tridech *et al.* [43] treated the reinforcing carbon fibers with a polyacrylamide coat and then created an epoxy matrix composite. During a three-point bending test, they applied current to the fibers, which heated the thermoplastic material over its glass transition temperature (T_g) but lower than the T_g of the matrix. This resulted in a weaker interface between the fibers and the matrix resulting in a significantly lower bending stiffness. The stiffness change was reversible by cooling down the specimens.

The Joule heat generated in carbon fibers can be used for the activation of shape memory or morphing composites, therefore multi-shaped reinforced material can be electrically activated. Gong *et al.* [44] used carbon fiber felt (CFF) reinforced, epoxy-based shape memory polymer (SMP). In order to achieve the shape recovery effect, they heated their specimens up to 130 °C by resistive heating of the electrically conductive carbon fiber felt. They also investigated the heating performance of the CFF/SMP material at different great flux densities. With high power density, the needed temperature (130 °C) can be achieved in 15 s. The authors highlighted that with different lay-ups the temperature distribution within a part can be tailored. Wang *et al.* [45] printed different patterns of carbon fiber reinforced polyamide66 composites. They designed the layout in order to have programmable deformation. They controlled the deformation by Joule-heating the carbon fibers: increasing the amperage in carbon fiber results in higher temperature, which causes a higher change in the shape.

Park *et al.* [26–28] used the heating capability of carbon fibers to create self-repairing composites. Mendable polymers can be classified in different ways; the type referred in their articles was based on the Diels-Alder reaction: during the thermally reversible process, crosslinking occurred by energy transfer (e.g. heat). When the material is damaged, the double bonds break apart but reconnect again if heated [46]. Park *et al.* [26–28] first created cracks in the healing polymer, then the carbon fiber reinforcement was electrically heated. Intact and healed specimens were tested with a DMA bending test and the efficiency of healing was over 90%. The authors also produced larger-size specimens, which were tested by conventional three-point bending until the appearance of the first instance of delamination, and then testing was continued until complete damage.

The authors declared that delamination can be healed if the carbon fibers are heated electrically, but efficiency decreases if the fibers break: a damaged circuit cannot supply even heating. A number of other research projects have focused on heating CFRP with an electric current. Ezekiel *et al.* [47] heated carbon fiber by resistance heating to 2900 °C to graphitize the carbon fiber. Hung *et al.* [2] developed a heated composite component that can prevent icing on aircraft wings or remove an already formed ice layer from the wing. Bode in his patent [48] described a heating arrangement that uses stretch-broken short-fiber carbon fiber for seat heating on motorcycles, for medical fixing and healing bonds, and for die heating. Le *et al.* [49] researched the self-healing in rubber blends filled with carbon nanotube (CNT). They showed that healing can be accelerated by localy Joule heating the conductive composite.

3.2. Electromagnetic shielding

Electrically conductive materials such as carbon fibers are also suitable for electromagnetic shielding. This can have a role in telecommunication where a source of electromagnetic radiation may cause interference in data transmission wires. Typically, short fiber reinforced polymer matrix composite insulation is used for shielding, and it can be effective even with a fiber ratio of 20% [50].

In the case of airplanes, it is expected that the structure will be electromagnetically shielded, as described in different standards. Possible shielding materials include carbon fibers as well as carbon-based materials such as CNTs, graphene and graphite. For example, a fuselage made conductive with the aforementioned reinforcing and filler materials protects passengers and cargo from electromagnetic fields, as it works as a Faraday cage. A disadvantage of reinforced, non-filled materials is their low thermal conductivity, which causes the composite to heat up by the heat released by the lightning strike, which may even burn the structure (Figure 4) [51].

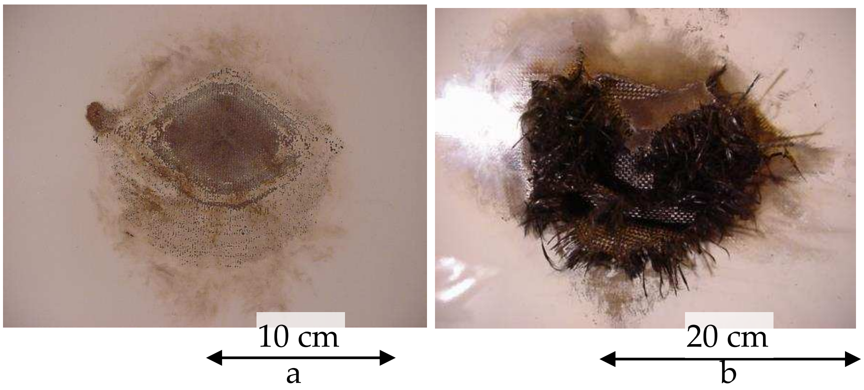


Figure 4. Composite specimen exposed to thunderstrike with protection (a) and with no protection (b) [52]

Li *et al.* [4] investigated the effect of the layer order on the integrity of the composite after lightning strikes. They presented that in the case of unidirectional reinforcement, the reinforcing materials are damaged in a large area, the matrix burns out and the delamination of layers can happen. The degree of damage can be reduced when the reinforcing fibers are used as woven fabrics. They also carried out mechanical tests on both the original and the damaged specimens, and found that a lightning strike reduces the modulus of elasticity and tensile strength, depending on the layer order, down to approx. 90% of the original value. Molnár *et al.* [53] added CNTs and carbon nanofibers to carbon fiber reinforced epoxy matrix composites to improve their thermal and electrical conductivity. The purpose of their research was to develop a material that could substitute copper mesh to protect aircrafts against the effects of lightning. They found that a carbon nanoparticle filled layer as a top layer can improve the thermal and electrical conductivity of the component (20% in the fiber direction) without compromising the mechanical properties of the composite. Other articles [3,54] focus on the numerical modelling of lightning strikes, which makes it possible to understand better the heat distribution and the path of the current in the material. Based on all this research, today's metal mesh protection can be completely replaced with a properly positioned carbon fiber structure.

3.3. Energy storage

A further possible application of the electrical properties of carbon fiber is energy storage in structural elements. Shirshova *et al.* [5] used a special layer order: carbon fabric – glass mat – carbon fabric and a suitable polymer electrolyte, thus forming a composite structure that functions as a capacitor in addition to its load-bearing properties. This multifunctional material is called structural supercapacitor. They tested several types of electrolytes and reinforcing fibers but they could not achieve good mechanical properties and good energy storage simultaneously. In their further research, Shirshova *et al.* [6] provided the carbon fibers with a special, so-called aerogel coating. Due to this coating, the specific surface area increased, resulting in higher storage capacity (capacitances of up to 55 mFg^{-1}.).

The structural supercapacitor can be an effective alternative in areas where large energy storage and low mass can be important. Such an area is the automotive industry: one of the obstacles to the spreading of electric and hybrid vehicles is the amount of energy that can be stored in the car, in other words, the maximum range available with a single charge. Volvo has been researching the possibility of using a structural supercapacitor. They made trunk lid and body stiffening prototypes from CFRP. The body stiffener replaces three parts: the plenum cover, the rally bar and the start-stop battery [55]. Integrating the components this way, the company reduced the weight of the car and was able to increase space by removing the starter battery. When carbon fiber is used as a supercapacitor, the following problems have to be solved: increasing capacity density, creating electrical insulation (to avoid short-circuiting after a collision), and connecting loads and generators to the system.

3.4. Improving mechanical properties

According to several researchers, the electrical or magnetic field around carbon fiber or CFRP components has an impact on the mechanical properties of the component. Sierakowski *et al.* [56] examined whether the current flowing through the carbon fiber has any impact on collision damping. In their experiments, the effects of several parameters (current, duration) were studied with impact tests. It was found that higher impact forces can be achieved with a larger current in unidirectional CFRP specimens. They highlighted that a current flowing for a long time can heat up the specimen, therefore the electric circuit was closed just before the impact. Barakati and Zhupanska [57] studied how the dynamic mechanical properties of the CFRP at low-velocity impact test are affected by an electromagnetic field or flowing electric current. The mechanical behavior of CFRP tested with low-velocity impact when it is not in an electromagnetic field is described elsewhere [58]. Barakati and Zhupanska [57] claimed that if the test is carried out in an electromagnetic field, the mechanical damping of the specimen is greater, and the oscillation of the specimen will disappear sooner. The current flowing through the test piece only had an influence in the presence of an electromagnetic field. In that case, the electrified composite had greater mechanical damping and smaller deflection at the moment of impact.

3.5. Structural health monitoring sensors based on the measurement of the resistance of carbon fiber

A structural state-monitoring sensor can be created by measuring the electrical resistance of carbon fiber. This system can detect changes (e.g. deformation, crack propagation, etc.) in the composite part from manufacturing to the end of the lifetime of the product.

Todoroki [59] tested CFRP with epoxy matrix specimens during production: alternating current was coupled to carbon fibers and the capacity change was measured. The capacity depends on the dielectric constant of the epoxy matrix which changes during crosslinking, thus the degree of curing can be measured.

Examining the electric properties of carbon fiber used as a reinforcing fiber, Owston [60] found that the resistance of fibers is directly proportional to mechanical stress. Schulte and Baron [36] studied this effect with different loads (static, as well as cyclic pull and bending tests). The static tensile tests showed that at the beginning, correlating with the geometric change, resistance increases linearly, while at larger deformations, with the breakage of the fibers, resistance increases suddenly. In their cyclic experiments, it was observed that a different load level equals different resistance, and with the breaking of the fibers, resistance increases dramatically. They pointed out that an electric current in fibers generates heat, and also that the heat generated by cracks affects the accuracy of the measurement. They also mentioned an application example: in their opinion, the test layout can be used to create a multifunctional airplane wing that monitors loads and fractures (Figure 5).

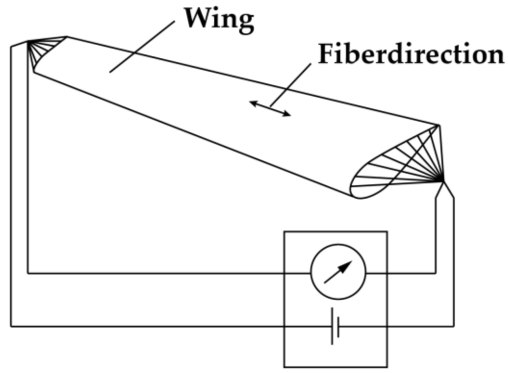


Figure 5. Layout of an airplane wing-mounted state monitoring sensor [36]

Prasse *et al.* [61] also studied the electric resistance change of carbon fiber during cyclic loads. They found that in the case of increasing loads, when the load level reaches the maximum of the previous cycle, there is a break in the change of the electrical resistance. This is caused by the cracks formed while loading-up, which then close during unloading, as during a new cycle, the earlier cracks open up first, though that is barely seen in the change of the electrical resistance. As stress increases further, new cracks open, but these cause an intensive resistance change. As they investigated the load cycles further, they found hysteresis in the change of the resistance, due to the viscoelastic behavior of the polymer matrix. Abry *et al.* [62] inspected their specimen during cyclic bending tests. For the monitoring of CFRP pieces, direct and alternating currents were both used. They found that direct current is more sensitive to the breakage of the fibers, as the resistance of the system significantly increased. However, with alternating current they were able to show the cracks in the matrix more accurately because the capacity of the system increased. Vavouliotis *et al.* [63] tested quasi-isotropic carbon fiber reinforced epoxy composite specimens for fatigue fracture, where the resistance of the carbon fibers was measured. As a result of their experiments, correlations were reported between the load level, the number of cycles and the change in resistance, which can be used to predict the failure of the specimen.

The main reason for increasing volume resistance in a CFRP during a fatigue tensile test is the separation of the layers, i.e. delamination. In dynamic tests (e.g. falling weight impact test), besides delamination, fiber breakage appears near the imperfection, which further increases volume resistance. There are several methods to measure delamination between composite layers. One of them is based on through-thickness and volume resistance change, so a twosided arrangement of the electrodes is required, allowing conduction across the entire cross section. If the electrodes are placed on two surfaces of the specimen in multiple rows and columns, the size and location of delamination can be inferred by selecting electrode pairs and measuring the resistance between them [21].

Another method is to measure the longitudinal or surface resistance of the test specimens. Angelidis *et al.* [64] measured the electrical potential of a composite sheet both before and after a falling weight impact test. The delamination resulting from the impact affects the electrical potential; the change in the potential of the damaged plate indicates the size and location of the failure. Todoroki *et al.* [59,65,66] calculated the size and location of failure from the change in resistance caused by delamination. Resistance was measured in different pairs of electrodes on one side of the test piece. They also investigated the effect of the test method (double or four-wire arrangement [67]) and the effect of the distance between the electrodes on the precision of measurement. They found that the four-wire method can more accurately measure the resistance and requires densely placed electrodes in the case of high fiber content.

There is a third method, called the crossover method. It requires a special conducting layer. Wang *et al.* [68] worked out the theory of this method: at some point the crossing of carbon fiber layers is permitted (this will be the area under study), while others are isolated from each other (Figure 6).

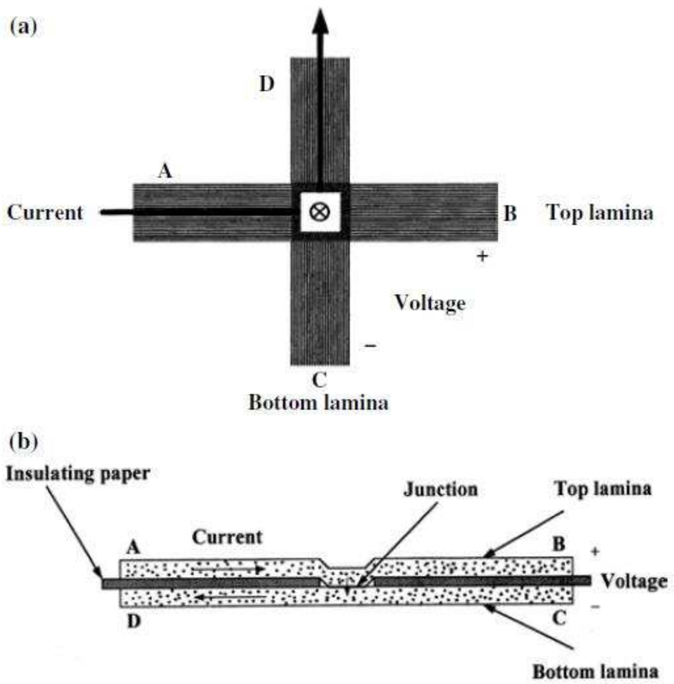


Figure 6. Experimental layout for cross-over (a) and unidirectional (b) carbon fiber layers. "A" and "D" are the locations of current supply, "B" and "C" are the locations of voltage measurement [68]

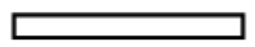
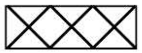
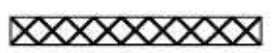
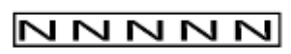
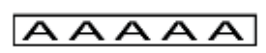
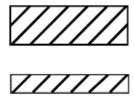
The electric circuit was designed in such a way that the current has to pass through the contact area in any case. Delamination increases the contact resistance, which can be detected by measuring the resistance of the system. This method can be effective if there are known vulnerable points in the product (such as a region of inserts) where there is a greater likelihood of delamination [68].

Besides deformation and delamination, carbon fibers can also be used to measure changes in their environment. Chung *et al.* [68–70] described relationships between the thermal load, the environmental impacts (humidity, temperature) and the resistance of the fiber during production. In their experiment, a node similar to the delamination test was created, where two carbon fiber layers were in contact. As a result of temperature increase, the electrons move more easily from one layer to another. If humidity is high, the epoxy matrix binds water and swells, thereby distancing the carbon fiber layers from each other. These changes can be detected by measuring contact resistance.

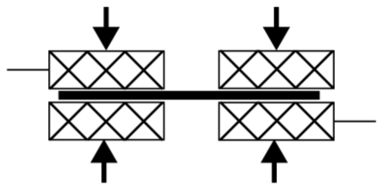
Damage to a composite component can be detected not only by measuring resistance but also with the help of the heat generated by an electric current flowing through carbon fibers. Grammatikos *et al.* [71] modified a non-destructive procedure, active thermography, by *in-situ* generating the heat by Joule heating the carbon fibers. The amount of heat and its change was measured with a thermal camera and the evaluation of the shots showed the defects in the material.

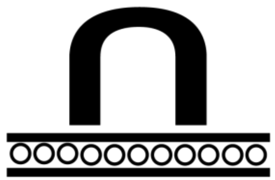
The reliability of carbon fiber used as a sensor is increased if the matrix material is conductive. This can be achieved by adding CNTs. This requires that filler concentration should reach the so-called percolation threshold, the amount of the filler at which a continuous conductive network develops from the contacting particles [72]. Gallo and Thostenson [22] added nanoparticles into CFRP in two different ways: mixed with epoxy or injected on the reinforcing fibers. In case of injecting the nanoparticles, surface treatment should be carried out on the fibers [73]. After Gallo and Thostenson [22] manufactured the specimens, the elongation value from cyclic tests calculated from the resistance change was compared to the values measured with standard strain gauges. They found that the measurement of the resistance of nanotubes not only detected breaks in specimens, but also the inter-cycle changes caused by microcracks. In their experiments, Grammatikos and Paipetis [74] used a multi-layer carbon structure and examined the electric resistance of a carbon fiber reinforced, CNT-filled epoxy composite. They came to the conclusion that adding CNTs increased the sensitivity of the system because the resistance of the specimen noticeably changed even in the case of smaller deformation.

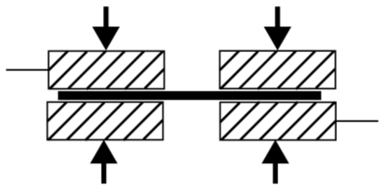
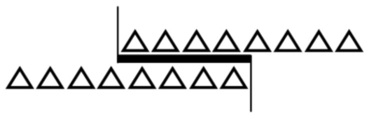
Multifunctional polymer composites with regard to the electrical properties of carbon fiber are detailed in Table 1. In the table, we grouped the research and application examples described above according to the secondary function of the carbon fiber reinforcement. The authors used different materials (reinforcement structure, matrix, supplementary materials) in their experiments, and electrical connection was implemented in different ways. These features and the physical layout of electrical connection are also detailed in the table.

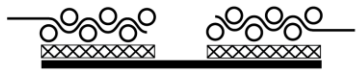
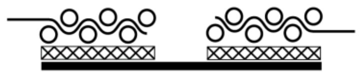
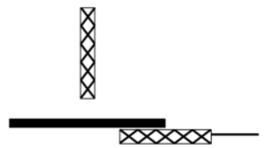
Legends				
electric wire	 carbon fiber reinforced thermosetting matrix composite	 carbon fiber reinforced thermoplastic matrix composite	 glass fiber reinforced composite	 thermoplastic polymer
 adhesive	 silver filled electrically conductive paint	 silver filled electrically conductive adhesive	 fastener, clamping force by bolt	 induction coil
 copper block	 copper foil	 nickel foil	 gold foil or evaporated gold film	 metallic block or foil (not stated in the article)

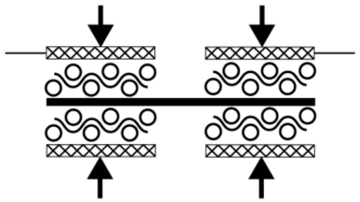
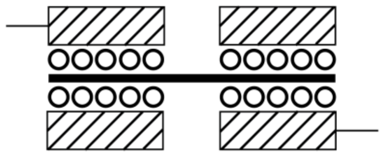
Application examples

No.	Function	Carbon fiber reinforcing structure *	Matrix**	Supplementary materials ***	Electrical contact	Physical layout	Properties of the electric circuit	Measured quantities	Note	Ref. no.
1	graphitization of carbon fiber	carbon fiber							- the carbon fiber was graphitized in inert atmosphere due to the electric heating of the fiber	[47]
2	curing	carbon fiber prepreg (914c TS 6K)	epoxy		carbon fiber ends wrapped in aluminium foil and clamped		15 A 6-6,4 V	temperature	- a good quality crosslinked sample can be manufactured from prepreg	[24]

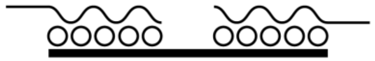
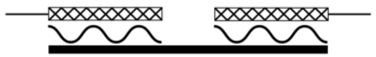
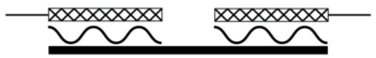
					between copper blocks				- adequate electrical connection between the electric circuit and the carbon fibers	
3	curing	carbon fiber pre-preg (Cycom 950-1)	epoxy		copper foil (Rogers R-Flex 20FRNP)		max. 40 A max 30 V	temperature	- uniform temperature distribution in the specimen - high degree of cure	[20]
4	curing	Carbon fiber mat, prepreg (UD Sigrafil/E0 222, UD T700S)	Epocast 52		copper wire			temperature	- well-adjustable temperature profile - can be used with different manufacturing technologies - the degree of cure and mechanical properties are similar to those achieved by conventional methods	[38]
5	bonding	carbon fiber prepreg	epoxy	Loctite EA 9394 adhesive	induction coil		max 30 kHz max 15 kW	temperature	- high strength bonded joints can be achieved with the locally cured adhesive	[31]

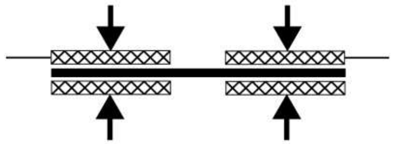
6	welding	graphite fiber pre-preg (AS4)	PEEK		metal clamps fastened by screw		208 V max. 12 A	temperature, pressure	- to demonstrate correlation between welded surface size and processing parameters (power, energy, time) - a more uniform temperature distribution can be achieved at a lower power and longer curing time	[25]
7	welding	carbon fiber (AS4)	PEEK		silver-filled adhesive		18,3-42,8 V 14,8-59,1 A 633-1081 W	temperature	- with multi-stage heating, better results can be achieved for large-scale products	[42]
8	welding	carbon fiber prepreg (T300, Toray)	PPS		induction coil		600 kHz 220 V 0,5-3,5 kW	temperature	- optimized induction loop and technological parameters - created joint passes the industry standards	[32]
9	active stiffness control	carbon fiber (unsized, AS4, Hexcel)	epoxy (Araldite LY556 with XB3473 hardener)	PAAm coating on carbon fiber			15 V, 0.6 A (9W) to heat up to 110 °C, 20 V, 0.7 A (14 W) to heat up to 130 °C	bending stiffness	- the stiffness can be modulated by applying current to the reinforcing fibers	[43]

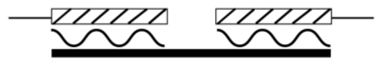
10	shape memory	carbon fiber felt (Kaifen Pengyuan Glassfiber Products Co.)	epoxy	epoxy-based shape memory polymer	overlapped copper foil, conductive nanosilver glue (HS-100RF, Kunshan Hisense Electronic Co.)		5-30 V 180-9676 W/m^2	shape recovery	- the activation time can be decreased by direct heating the carbon fibers	[44]
11	de-icing (resistive heating)	graphite fiber (brominated, P-100, Amoco Co.)	epoxy (My720 with HT976 hardener, Ciba-Geigy)		nickel foil		6-20 A 0,563-0,65 V		under laboratory conditions, relative rapid heat-up and de-icing can be carried out on an aircraft wing like specimen	[2]
12	self-healing	carbon fiber (AS4)	epoxy, mendomer 401		copper plating, silver filled adhesive			temperature, voltage	- mechanical properties can be restored up to 90% after healing - microcracks and delaminations can be repaired	[26–28]
13	lightning protection	carbon fiber (T700SC-12K UD, Toray)	epoxy (AIRSTONE 760E/766H)		copper plate, copper spike		22-38 kA		- damage to matrix can be reduced by a better dissipation of the heat generated by lightning strike	[4]

14	energy storage	carbon and glass fiber (Tissa Glasweberi AG)	epoxy (MVR444 MTM57, with VTM266 hardener, Cyctec Industrial Materials)	CNT sizing on carbon fibers, EMITFSI and LiTFSI filler in epoxy					- a structural element capable of storing electrical energy can be created	[5,6]
15	improving mechanical properties	carbon fiber (AS4)	epoxy (3501-6)		copper blocks glued to the edge of the specimens with silver-filled epoxy (Duralco 120)		40 V 0, 25, 50 A	impact energy, amplitude and damping of vibration	- direct current coupled to fibers can increase impact resistance - the electromagnetic field reduces the vibration of the specimen and increases the damping during impact test	[56,57]
16	structural health monitoring	carbon fiber (RAE Farnborou gh type)			bonded to metal surface clamps			resistance	- deformation sensing - with small elongation, the resistance changes linearly - in the case of greater elongation, due to the breaking of the fibers, the change	[60]

									increases progressively	
17	structural health monitoring	carbon fiber (HTA7)	matrix (6376, Ciba Geigy)		evaporated gold electrode		75 kHz	complex impedance	- for cyclical loads, the failure can be predicted	[61]
18	structural health monitoring	carbon fiber (HTA7)	epoxy (913 type, Civa Geigy)		evaporated gold electrode onto the burnished surface of carbon fiber		10 mA 100 kHz 500 mV	resistance or complex impedance	during cyclical loads, direct current is more sensitive for fiber breakage, alternating current is more sensitive for matrix cracks	[62]
19	structural health monitoring	carbon fiber (Wela)	epoxy (Araldite LY564/Aradur HY2954 type, Huntsman Advanced Materials)	multiwalled carbon nanotube (MWCNT, Arkema)				resistance	in case of cyclical loads, the failure can be predicted	[63]
20	structural health monitoring	carbon fiber	epoxy					surface and volumetric resistance	- delamination sensing separation of layers and fiber breakage increases the volume resistance	[21]

21	structural health monitoring	carbon fiber prepreg (TR340M150ST type, Mitsubishi-Rayon Co. Ltd)	epoxy		copper foil placed before curing		1 kHz	longitudinal resistance	- delamination sensing - separation of layers and fiber breakage increases the longitudinal resistance the location of the imperfection can be localized by a special electrode layout	[59,65,66]
22	structural health monitoring	carbon fiber prepreg (t300, Hexcel)	epoxy (914)		copper wire bonded with epoxy, covered with silver-filled paint		100 mA	electric potential distribution	- delamination sensing - the impact of a drop-off test is measurable by electrical potential distribution measurement	[64]
23	structural health monitoring	carbon fiber prepreg (ICI Fiberite)	epoxy	insulating paper between layers	burnt carbon fibers wrapped in copper foil with silver-filled paint			contact resistance	- delamination sensing contact resistance is increased by delamination of the contacting conductive layers	[68]
24	structural health monitoring	carbon fiber prepreg	epoxy, PPS	insulating paper between layers	in the case of epoxy, the matrix was burnt out and the fibers		5 V	contact resistance, temperature	- detection of environmental impacts - temperature variation changes	[68–70]

					wrapped in copper foil with silver-filled paint. The PPS matrix wasn't burnt out.				carbon fiber resistance and contact resistance due to the change in humidity, the matrix binds water, so the conductive layers separate	
25	structural health monitoring	carbon fiber (43280, Hexcel)	epoxy (Epocast 52 A/B , Huntsman International LLC)	0,5 m/m% CNT	burnished carbon fibers coated with silver-filled paint and bonded with silver-filled adhesive tape		10 A	temperature distribution	- the distribution of Joule heat in carbon fibers changes due to injuries and is measurable by active thermography	[71]
26	structural health monitoring	carbon fiber (IM7, Hexcel), E-glass fiber (Jamestown Distributors)	epoxy (862, Momentive Speciality Chemicals)	MWCNT	carbon fibers clamped between copper electrodes		10 mA	change in longitudinal and volumetric resistance	- damage and microcracks can be detected - the sensitivity of the system can be increased - by adding nanoparticles, insulating composites can be tested by resistance measurement	[22]

27	structural health monitoring	carbon fiber (G0947 1040, Hexcel)	epoxy (Araldite LY 564/ Aradur 2964, Huntsman International LLC)	0,5 m/m% MWCNT (Arkema)	burnished carbon fibers coated with silver-filled paint and bonded with silver-filled adhesive tape			change in resistance	- by adding nanoparticles, the interference with Poisson effect can be reduced - by adding nanoparticles, the sensitivity of the system can be increased	[74]
28	structural health monitoring	carbon fiber (TZ-307, Taekwang Co.)	epoxy (YD-128/YD-127, Kukdo Chemical Co.)	MWCNT (Iljin NAnotech Co.), carbon black (Korea Carbon Black Co.), carbon nanofiber (SDK)	silver filler paste			resistance	- CNT and carbon nanofiber can provide more efficient state monitoring than carbon black - in small amount, with CNT better sensing can be obtained than with carbon nanofiber	[75]

*** the type and producer of the fiber are marked if it was available in the article.**
**** the type and producer of the matrix are marked if it was available in the article.**
***** filler and excipient materials were used in some cases, the materials were marked in those cases**

Table 1. Application examples based on the electrical properties of reinforcing carbon fiber

4. SUMMARY AND OUTLOOK

Lightweight and compact structures can be designed by merging different functions of carbon fiber reinforced composites. Carbon fibers, besides their mechanical load-bearing capability, can be used for secondary tasks based on their electrical properties. Examples are given in Table 1 and are categorized according to their function. One of the most important aspects in choosing a secondary role is the material used. In most examples, long carbon fiber reinforced epoxy matrix composites were used. In some cases, however, a thermoplastic matrix proved to be a better choice. In order to improve efficiency, nano-sized carbon particles, such as carbon black, CNTs or carbon nanofibers were added to the composite.

Two different methods for connecting the composite part to the electric circuit exist: induction or direct physical contact. The effect of induction is local; therefore, it is suitable for the heat treatment of the joints (e.g. bonds and welds). By direct contact whole composite parts or structures can be electrified; in this case, low contact resistance is needed between the carbon fibers and the electrical circuit. For this, the fibers first have to be exposed either during fabrication (a dry fiber bundle sticking out, or a laminated conductive foil) or after curing (matrix burning or grinding). For the sake of good contact, usually a metallic block or foil (copper, nickel, gold) is pressed against the fibers or another conductive layer (evaporated gold, silver-filled paint or adhesive) is applied on the fibers.

Table 1 is a useful tool from two aspects. Firstly, it helps the designer of a multifunctional structure to choose a secondary function. Secondly, the necessary layout and materials can be determined with it. The roles, based on the electrical properties of carbon fibers, cover the whole life of a composite part. These multifunctional structures can be used in manufacturing (graphitization of carbon fiber, matrix curing, process control), assembly (bonding, welding) and application (deformation, temperature and humidity sensing) until failure (micro cracks, delamination, fiber breakage), besides structural load bearing.

Resistance-based state monitoring is proven to work well with CFRP, but can be used in insulating glass fiber reinforced composites or even in existing structures. Several researchers [22,76–79] investigated electrically insulating glass fiber reinforced epoxy composite sheets by measuring their resistance. To make the test specimens conductive, they added nanoparticles (multiwalled carbon nanotube, carbon black). They proved that a basically insulating material could be modified to measure the electrical resistance of the samples, thus continuous and *in situ* structural state monitoring can be achieved. As a consequence, failure can be predicted. In the case of finished parts, state monitoring can be performed by applying a conductive film layer [79].

In order to meet the efficiency standards of the energy and transportation industry, lightweight structures are essential. Merging functions, creating and using multifunctional materials promote weight reduction in these industries. Weight can be reduced significantly with the use of the electrical properties of the CFRP to substitute electrical instruments. Adding energy storage functions to body parts (e.g. trunk lid, body stiffener) creates a structural supercapacitor, which merges functions and creates free space in the underhood area [55]. In a car a serious amount of wires are used to operate devices or to gather information from sensors. The reinforcing carbon fibers could be used to transmit electrical signals, therefore a reserve network can be formed, or cable cords could be replaced completely [80]. Adding sensing capability as a secondary function converts conventional materials into raw materials for Industry 4.0 and autonomous vehicles, which will need increasing amounts of multifunctional carbon fiber reinforced composites.

5. ACKNOWLEDGEMENTS

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