1. Introduction

Resin transfer molding (RTM) has become a standard manufacturing process for composite materials. After the placement of the fiber reinforcement (fiber preform) in the mould, it is sealed and a vacuum is applied. The resin is injected by means of a pressure level ranging from 6 (standard RTM) to 200 bar (high pressure RTM). Both, the pressure level and the dimension of the component define the size of the clamping unit to keep the tool closed. Normally steel is used for the tool to sustain the load of the clamping unit. This situation makes it very difficult to control the resin flow in the mould, which is of great interest to minimize manufacturing defects. Furthermore, knowledge of the resin flow in closed moulds can help to apply simulation technique to optimize the cycle time. Different approaches are available to monitor injection and cure of resins of RTM processes [1 to 6]. Optical fiber sensors, pressure transducers and plate capacitors are used to measure the progress of the resin front in composite manufacturing. The sensors are positioned in the fiber preform or at the mould surface.

Concerning this paper a new method was investigated using carbon fiber sensors having capacitive properties. One advantage of this method is that this sensor can be placed in the fiber preform. Due to the material conformity the fiber sensor will not influence the resin flow. Using this method the resin flow can be measured continuously in the plane of the fiber preform. Another method of measurement is a step change of the output signal. In the past the carbon fiber sensor has been investigated successfully as piezoresistive sensor to measure strain levels and monitor the crack density in composite structures [7].

2. Theory

The resin has an electrical conductivity of almost zero. In order that the resin behaves like a moderate electrolyte, we add a little lithium ions. They contribute to the transmission of charge carriers in the resin through their movement and dielectric polarization under electric voltage.

According to Fig.1 two carbon fibers having a specific distance create a small capacitor in addition with a parallel resistance. Each fiber is electrically connected at one ending. The resin as medium between the fibers influences the electrical field.

Fig. 2 shows the principal of the electrical circuit. The capacitive carbon fiber sensor and a resistance are connected in series. Contact surface between resin and carbon fibers rises with the increase of the immersion depth. Therefore the emerging capacitor ascends, but the parallel resistance decreases in opposite. For this reason a small current flows through the circuit. Thus a high amount of voltage falls off across the series resistor and the voltage drops across the carbon fibers. Immediately the displacement of phase between the source voltage and the voltage across the carbon fibers changes. By means of measuring these changes we can determine the resin flow in the mould.

3. Experimental

3.1 Fundamental study

The preparation of the carbon fiber (Toray, T300-B1k) is described in [7]. The manufacturing process of the carbon sensor includes three basic steps: Pre-curing of the carbon fiber, preparation of the electrical connection und embedding of the sensor fiber into the fiber preform.
The pre-curing process is used to stabilize the carbon fiber roving and to align the filaments of the roving. For this purpose the twisted carbon fiber roving is impregnated by a resin with low viscosity and cured by using a special tooling. Good results for the impregnation of the carbon fiber roving are obtained by using epoxy resin EP301 (HBM) and a twist of 20 turns per meter. Spring elements provide a constant tension force along the roving during the curing process at 180°C for 1.5 hours.

For the preparation of electrical connections a galvanic process is applied based on a nickel electrolyte. In order to attain a homogeneous nickel coating of the filaments the resin must be removed at the fiber ending. An applied current of $40\,\text{mA}$ for 30 seconds leads to an excellent nickel coating. The end of sensor fiber can be provided with soldered pins.

The sensor fiber is stowed to the preform by means of the stitch yarn (Fig. 1).

In a first step the behavior of the carbon fiber sensor is studied by using 50cm long fibers which are dunked into a cylinder filled with the resin (Hexion RIM935) with 11.5 gr/l lithium trifluoromethanesulfonate. The lithium dissolves completely in the resin. Its influence on the viscosity of the resin can be neglected due to its small amount. A function generator is used for power supply. The change of the voltage is measured by an oscilloscope (Tektronix 2014) depending on the wetting of the fiber. In order to get the maximum sensitivity a principal study is performed. The frequency varies in the range from $50\,\text{Hz}$ to $1\,\text{MHz}$. The resistance is adapted to get a maximum change of voltage. In addition the influence of the distance between the two fibers on the electrical signal is studied. Two approaches are applied:

- A linear correlation between the voltage and the wetting length of the fibers (continuous monitoring of the resin flow).
- A step change of the output voltage for the case, if any wetting is along the fiber (discontinuous monitoring of the resin flow).

For both monitoring methods a frequency of $100\,\text{Hz}$ is found to be effective. The behavior of the circuit can be controlled by the resistance. $35\,\text{k}\Omega$ to $1\,\text{M}\Omega$ are applied for the continuous and the discontinuous method, respectively.

Fig. 3 shows a typical curve for the continuous changing of the potential difference of the sensor. This calibration curve is a result of the fundamental study. The distance between the two carbon fibers is 2.5mm and a resistor of $35\,\text{k}\Omega$ is applied.

3.2 Application

In a second step the approach is verified by the impregnation of a glass fabric (40 × 50cm).

In this case an injection pressure of 1bar is applied. A transparent plate can be used to close the tool and to correlate the sensor signal and the resin flow by visual inspection (Fig. 3). Four carbon fiber pairs in the resin flow direction and four sensors in the transverse direction are accommodated in the mould. A small polymer strip is applied to avoid short circuit at the crossing points of the sensors.

4. Results

4.1 Results of the fundamental study

Fig. 5 demonstrates the potential drop of the carbon fiber sensors as a function of the injection length and the series resistance as parameter. This result shows that two approaches can be realized to monitor the resin flow: Continual output signal using a low resistor and a step change using a high resistor.

With increase of the resistance a high amount of voltage falls off across the series resistor. Thus the voltage of the carbon fibers drops speedy. If the series resistance is high enough, the potential drop of the sensor fibers appears for the most part when the resin touches the carbon fibers.

Due to the waviness of the carbon fibers the distance between the fibers of every sensor may vary $±0.5\,\text{mm}$ along the length of the fibers.

Fig. 6 demonstrates the potential drop of the carbon fiber sensor as a function of the injection length and the distance between the carbon fibers as parameter. A resistor having $61\,\text{k}\Omega$ is applied.

With decrease of the distance between the carbon fibers the transmission of charge carries increases in the resin. Therefore the capacity between two carbon fibers rises. The parallel resistance of the capacitor sinks in opposite. Thus a higher amount of voltage
falls off across the series resistor and for this reason the curve is less steep.

4.2 Simulation

Through the computer simulation of the equivalent electrical circuit by the use of the software Matlab/Simulink the results of the experiment can be analyzed concerning further parameters. The fundamental study and the computer simulation show that by means of the comparison of the experimental results and the theoretic conclusions the location and the velocity of the resin in the mould may be appreciate accurately. With increase of the number of the carbon fiber sensors the experimental results appropriate the simulated conclusions and the desired parameters can be captured more precisely.

The circuit of Fig. 2 corresponds to a voltage divider and in accordance with the Ohm’s law the current through the series resistor can be calculated:

\[ i_{Rs} = \frac{v_{FG} - v_{CF}}{R_s} \quad (1) \]

\( v_{FG} \) is the voltage of the function generator, \( v_{CF} \) is the voltage across the carbon fiber sensor and \( i_{Rs} \) the current through the series resistor. This current also flows through the carbon fibers capacitor \( C_{CF} \) and its parallel resistance \( R_p \). The voltage across the carbon fibers capacitor \( u_{CF} \), which is time dependent, can be determined by using Kirchhoff’s current law and the differential equation for the capacitor. The current through the series resistor is equal to the sum of the current through the carbon fibers capacitor and the current through the parallel resistance:

\[ i_{Rs} = i_{CF} + i_{R_p} \quad (2) \]

In accordance to the differential equation for the capacitor and Ohm’s law it follows:

\[ i_{Rs} = C_{CF}\frac{du_{CF}}{dt} + \frac{u_{CF}}{R_p} \quad (3) \]

By using the Laplace transformation equation 3 gives:

\[ I_{Rs}(s) = sC_{CF}u_{CF} + \frac{V_{CF}(s)}{R_p} \quad (4) \]

The voltage across the capacitor as a function of the input current can be determined:

\[ V_{CF}(s) = R_p \frac{1}{sC_{CF}R_p + 1} I_{Rs}(s) \quad (5) \]

In accordance to the equations (1) and (5) the transfer function from the input voltage to the voltage across the carbon fibers capacitor can be calculated:

\[ \frac{V_{CF}(s)}{V_{FG}(s) - V_{CF}(s)} = \frac{R_p}{R_s sC_{CF}R_p + 1} \quad (6) \]

The simulation circuit is based on equation (6). The value of the series resistor can be determined by means of Fig. 5, depending on whether the continuous monitoring or discontinuous measuring should be conducted. The values of the mathematic equivalent-to elements of the carbon fiber capacitor and the parallel resistor may be determined by the mathematic calculations. However, the calculated results must be verified experimentally.

The function generator supplies a pulse wave. The impulse response for the voltage across the carbon fibers capacitor is the inverse Laplace transformation of the corresponding transfer function. That represents the response of the simulation circuit on the input voltage. The impulse response of the capacitor between the carbon fibers is:

\[ \frac{v_{CF}(t)}{v_{FG}(t) - v_{CF}(t)} = \frac{R_p}{R_s C_{CF} R_p} e^{-t/C_{CF} R_p} \times H(t) = \frac{R_p}{R_s C_{CF} R_p} e^{-t/\tau} \times H(t) \quad (7) \]

Where \( H(t) \) is unit step function and \( \tau \) time constant. This function is shown in Fig. 8 Fig. 9.

Fig. 7 shows the simulation circuit to describe the experiment. The series resistor, the capacitor between the carbon fibers and its parallel resistance are replaced by the mathematic equivalent-to elements.
Fig. 8 demonstrates the results of the simulation for the continuous changing of the potential difference of the sensor, before and after the contact of the resin with the carbon fibers. The contact has been emulated by the adoption of the values of the mathematical components. It is clear that the change of the voltage signal is very low (ca. 1V), because the total potential difference has to be distributed continuously during the impregnation.

Fig. 9 shows the outcomes of the simulation for the discontinuous changing of the voltage difference of the sensor, before and after the simulated contact of the resin with the carbon fibers. In this case the decrease of the sensor signal is higher (ca. 4V) in comparison with the continuous measurement of the resin flow. Thus the sensor signal remains almost constant if the impregnation proceeds. The impregnation has been emulated by the changes in the mathematic equivalent- to elements for the capacitor und its parallel resistor between the carbon fibers sensor.

4.3 Continuous measuring of the resin flow

A calibration is performed by means of the test configuration shown in Fig. 2. Fig. 10 shows the calibration curve (CC) determined for the preferred sensor configuration. Figures 7 to 9 show the results of the experiment concerning the impregnation of the glass fabric (40 × 50 cm) and the continuous measurement of the resin flow.

Fig. 10 shows the measured signal of three carbon fiber sensors (S1-3) during the experiment. The measured changes of the sensor signal are plotted versus the injection length determined by visual inspection. In addition the results are compared with the calibration curve (CC). The carbon fibers distance is 3 mm and a 61 kΩ resistor is applied. The differences between the three measured sensor signals are quite small. Furthermore there is a good fit between the sensor signals und the calibration curve. The maximum difference between the sensor signal und the calibration curve is 0.25V.

Fig. 11 shows the injection length of the three sensors (S1-3) as a function of the injection time. The diagram demonstrates that the resin in the closed mould flows erratically. In order to predict the velocity and the location of the resin, the resin flow of every sensor must be compared with the resin flow of the calibration experiment.

Fig. 12 shows the comparison of the injection length measured by the carbon fiber sensor no. 2 (S2/m) and the injection length determined by visible inspection (S2/v). The comparison is performed every 2.5 minutes. The calibration curve having a carbon fibers distance of 3 mm and a 61 kΩ resistor (Fig. 10) was applied to calculate the injection length. The maximum difference between the calculated injection length and the injection length determined by visible inspection is less than ±2 cm. The result shows that two parallel CFs can be used as flow sensor to monitor the injection length. From the data the flow sensor to monitor the injection length. From the data the flow velocity of the resin can be calculated (Fig. 13).

Fig. 13 demonstrates that however the injection velocity (S2/v) is not constant but directly proportional to the measured voltage changes (S2Vc). In this manner the flow velocity and the location of the resin can determined during the experiment. As visible the flow velocity ranges from 0 to 4.3 cm/min and the voltage change ranges from 0 to 1.2 V per time step.

4.4 Discontinuous measuring of the resin flow

Fig. 14 demonstrates the potential drop of the four vertical carbon fiber sensors (SP1-4) during the course of the process. At the beginning all sensors have the starting signal of 2.8 V. Once a sensor pair is wetted by the resin the electrical field between the carbon fibers is affected and a signal drop of about 1 V is measured. The potential drop of the sensor takes about 10 minutes, which correlates to an increase of the injection length of about 8 cm. The solid line indicates the progress of the resin front, which was monitored visually. The dashed lines indicate the sensor voltage (SV), whereas the dotted lines show the sensor position (SP).

The measurement accuracy is indicated by the circles. The maximum difference between measured and observed resin flow is less than ±2 cm.

5. Summary

The study indicates that two parallel carbon fibers as electrodes and the resin with the dissolved lithium
ions as electrolyte behave like a low capacitor. The distances between the carbon fibers is 2 to 3mm and 11.5 gr/l lithium trifluoromethanesulfonate are used. This capacitive sensor can be used to monitor continuously and discontinuously the resin flow in closed moulds used for composite manufacturing. The carbon fiber sensor measures the resin flow in the plane of the fiber preform. A step change or a continual output signal can be obtained by means of a low or high serial resistor, respectively.

It has been demonstrated that many interesting process parameters like resin flow velocity and resin location can be determined concerning monitoring of the resin flow. A prediction accuracy of ±2cm may be achieved. The estimated quality depends on the sensor arrangement and the complexity of the tooling. The data generated can be applied to control the quality of the manufacturing process. In a next step the usage of the sensor will be investigated to monitor the curing of resins.

6. References


7. Figures

![Fig.1: Capacitive carbon fiber sensor](image)

![Fig. 2: Schematic of the electrical circuit](image)
Fig. 3: Continuous measuring of the resin flow for the continuous monitoring method

Fig. 4: Visual monitoring of the resin flow during the injection

Fig. 5: Influence of the series resistance and the injection length on the output signal of the sensor

Fig. 6: Influence of the carbon fibers distance and the injection length on the output signal of the sensor
CARBON FIBER SENSORS TO DETERMINE THE RESIN FLOW

Fig. 7: Computer simulation equivalent circuit diagram

Fig. 8: Simulated results for the continuous changing; above sensor signal before the wetting, below sensor signal after the wetting

Fig. 9: Simulated results for the discontinuous changing in comparison with Fig. 8

Fig. 10: Measured signals of three sensors (S1-3) and the calibration curve (CC)
Fig. 11: Injection length determined by the three sensors voltage outputs (S1-3) versus the injection time

Fig. 12: Injection length determined by the sensor no. 2; comparison between the measured (S2/m) and the observed injection length (S2/v)

Fig. 13: Injection velocity determined by the sensor no. 2; and the voltage changes of this sensor during the experiment

Fig. 14: Course of the experiment of the sensors orientated in the transverse direction of the resin flow