1 Introduction

Fiber Reinforced Plastics (FRP) have many advantages over conventional metallic materials such as lightweight, high strength and non-corrosive. Nevertheless, the low out-of-plane thermal conductivity of Fiber Reinforced Plastics (FRP) limits their application where heat has to be dissipated through the thickness such as heat exchangers or electronic enclosures.

Collaborative effort between the Institut für Textiltechnik (ITA) of RWTH Aachen University, Germany, and the Center for Composite Materials (CCM), University of Delaware, USA, has shown that the thermal conductivity of FRP can be increased an order and more. The use of approximately 5.5 % pitch-based carbon fibers in out-of-plane direction can increase the thermal conductivity in this direction to 8 W/mK [1].

One goal is to understand the material behavior to achieve a FRP with a maximal thermal conductivity in out-of-plane direction. Previous attempts showed that a high surface TC – in-plane TC – is advantageous to achieve high out-of-plane values. Hence, also the in-plane TC has a high influence on the out-of-plane properties. Novel research results from ITA and CCM demonstrate that the in-plane TC can be increased to 13 W/mK using different yarn architectures out of pitch- and polyacrylonitrile (PAN) based carbon fibers. These high TC results of FRP’s enable new applications and ways of lightweight engineering.

Within this research project PAN-based carbon fiber preforms are reinforced with pitch-based carbon fibers in in-plane and out-of-plane direction. Afterwards the Vacuum Assisted Resin Transfer Molding (VARTM) technique is used to infuse the preforms with epoxy resin. Specimens for mechanical and thermal test are cut out of the Carbon Fiber Reinforced Composites (CFRP) and the results are discussed.

2 Thermal conductivity

The TC (often referred as k) is a material’s ability to conduct heat and is defined as the heat flux generated over a distance due to a steady state temperature difference [2]. Aluminum has a TC of 237 W/mK whereas copper – one of the highest thermally conductive materials – has one of 399 W/mK. Normally CFRP have compared to these metals low TC values around 4-5 W/mK in in-plane and around 1 W/mK in out-of-plane direction. This is caused by both components of FRP – the matrix and the fibers. Epoxy matrix systems do have a TC of around 0.2 W/mK. Glass fibers have a low TC of ~1 W/mK whereas PAN-based carbon fibers have a TC of ~9 W/mK. However, some pitch-based carbon fibers have up to 800 W/mK a higher axial conductivity than copper.

The thermal conductivity is measured with two different devices. The ITA uses the LAMBDATEST equipment from the Technical University in Liberec, Czech Republic to measure the TC in in-plane direction. Therefore specimens with the dimension of 170 mm [6.7 in] by 50 mm [2 in] are required with a variable thickness. UD-CCM uses a guarded heat flow meter, according to ASTM E 1225 – 04 to provide out-of-plane measurements of circular samples with a diameter of 5 mm [1]. The thickness is also variable. In both cases the measurement accuracy increases with the specimen thickness. Thus values of 4-8 mm [0.16-0.31 in] enable a low measurement error of less than 5 %.
3 Pitch-based carbon fibers
Pitch-based carbon fibers are carbon fibers obtained from pitch precursor fibers after stabilization, treatment, carbonization, and final heat treatment. This precursor is mainly made out of coal tar pitch that is a residue produced by distillation or heat treatment of coal tar [3].

For this research project several pitch-based carbon fibers from Nippon Graphite Fiber Corporation, Tokyo, Japan, and Mitsubishi Plastics Incorporation, Tokyo, Japan, have been selected (Tab. 1). The fibers are brittle with very high tensile modulus and very low elongation capability. The material brittleness make it hard to process on textile machinery. Low bending angles must be avoided because this causes a break of all filaments of the pitch roving (Fig. 1). A bigger loop does not cause filament breakage in the first place (Fig. 1 - 1). If the loop becomes smaller (Fig. 1 - 2) the first filaments start to break. The knot (Fig. 1 - 3) is already broken. Thus, only a small amount of force is required to pull the filaments apart (Fig. 1 - 4). Hence, from the bobbin to the final preform the pitch has to be handled with extreme care to avoid filament breakage.

Stitching and tufting are well established processes in the textile industry. Stitching is used to fix layers together whereas tufting is used in carpet production. Both processes insert fibers perpendicular to the surface and are useful to reinforce 2D preforms in out-of-plane direction. In case of thermally conductive FRP’s the out-of-plane reinforcement can conduct heat away from the surface of the component. The fiber brittleness hinders a stitching or tufting and thus makes it unable to further process those fibers. Thus new ways of fiber modification are required to stabilize the pitch-based carbon fibers for the stitching and tufting processes. Today ITA is able to manufacture 3D preforms and to manufacture FRP parts with three dimensional thermally conductive behavior.

4 Specimens
In a first step CFRP plates with ten layers of 411 g/m² biaxial non-crimped fabrics (± 45°) out of PAN-based carbon fibers (Torayca T700SC from Toray Carbon Fibers, Abidos, France) are manufactured. The thickness of these plates are measured to be 4 mm (0.16 in), based on the requirements from the standards DIN EN ISO 14125 and DIN EN ISO 14126.

In a second step two pitch-based carbon fibers are selected as out-of-plane and two as in-plane materials. The in-plane reinforcement is realized with two different types of Unidirectional (UD) layers. Pitch-based UD-layers are not available on the market. Thus, UD is manufactured by ITA and fixed with a Polyamide (PA) non-woven with 12 g/m² on one side of the UD.

The first UD is made out of XN-90-60S fibers with an areal density of 496 g/m², the second out of XN-80-A2S with an areal density of 423 g/m². The UD is used instead of one biaxial as top layer or the UD is used on both sides instead of one biaxial respectively (Fig. 2). The presented results represent specimens with YSH-50A-60S fibers in out-of-plane direction. The out-of-plane reinforcement is realized by stitching through all ten layers of the 2D preform (Fig. 3). The distance between stitches is approximately 10 mm. Thus, basic thermal effects of the 3D reinforcement can be observed.

Plates with the dimension of 230 mm x 430 mm (9.06 in x 16.93 in) are manufactured using the Vacuum Assisted Resin Transfer Molding (VARTM) process. Two glass molds are used to control a homogeneous thickness of 4 mm (0.16 in). The epoxy system EPIKOTE™ Resin MGS® RIMR 135 and EPIKURE™ Curing Agent MGS® RIMH 137 from Momentive, Duisburg, Germany, is used as the matrix material. The FRP plates are cut into several specimens to measure the TC in in-plane and out-of-plane direction, and to achieve pressure and three-point bending specimens.

5 Thermal Conductivity Results
Fig. 4 shows a schematic of the z-reinforced preform. Type I demonstrates a preform without pitch-fiber reinforcement. Type II has a UD layer on one side, whereas Type III has an out-of-plane reinforcement with pitch-fibers. All other preforms are multiples of the Types I-III.

5.1 In-plane TC
To evaluate the expected heat transfer selected types are manufactured. The expected increase for a combination of UD-layers and out-of-plane reinforcement is shown in Fig. 5. The reinforcement of a PAN-based preform with out-of-plane fibers does not increase the TC significantly (Type I). However the TC increases between
Type V and V* when the specimen surface is flipped during TC measurement. The heat induction and the transfer through the specimen can be raised, if the surface of the heated specimen side is thermally more conductive. This effect is increased for Type VI where both specimen sides are reinforced with an UD-layer. Thus the TC can be increased by medium thermally conductive pitch-fiber reinforcements having a total fiber volume fraction of only 25% by nearly four times. These investigations do not take matrix modifications into account.

5.2 Out-of-plane TC
The results in out-of-plane- differ from the ones in in-plane direction (Fig. 6). Here only slight increases of the TC can be measured for all specimens. This is due to very low fiber volume fraction of fibers in out-of-plane direction with ~1% in total. Surface grinding of the specimens increases the TC therefore by 30%. This effect is caused by removing the rich resin areas on both sides of the specimen, caused in the VARTM process. Grinding is performed down to the surface of the pitch fibers in out-of-plane direction. The cause for the lower TC result of Type V* is unknown at this point.

6 Mechanical Results
Compression tests according to the standard DIN EN ISO 14126 are performed to analyze the mechanical influence of the knitting thread in stitching direction (0°) and perpendicular (90°) (Fig. 7). The results of the Type III material show that there is a decrease in the compressive strength of around 45% in 0° and around 65% in 90° direction compared to the Type I specimens. The Type I specimens show a complex failure according to the standard whereas the Type III specimens in 0° fail by splitting and in 90° by shear failure. The shear is expected to start at the pitch fibers in out-of-plane direction. The influence of the pitch thread on top and bottom of the preform causing thread eyes is not fully investigated yet. Aside three point bending tests according to the standard DIN EN ISO 14125 are performed. All specimens failed by bending. A shear failure mode can be identified although the pitch fibers in out-of-plane direction cause a high residual strength. Tests with different fiber volume fraction in- and out-of-plane are still ongoing and effects are under investigation.

7 Conclusion
The reinforcement of PAN-based CFRP with pitch-based carbon fibers increases the thermal conductivity in in-plane-direction four times and in out-of-plane direction by 1/3 in case of the presented results. Ongoing research of ITA and CCM shows that the TC can further be increased by higher pitch fiber volume fractions as well as by matrix modifications. The mechanical properties like compressive and bending strength decrease with out-of-plane reinforcement.

8 Acknowledgement
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Tab. 1: Selected PAN and pitch based carbon fibers
Fig. 1: Pitch fiber knot test

Fig. 2: 2D preform

Fig. 3: Reinforcement in out-of-plane direction

YSH-50A-60S (120 W/mK) Preform with 10 layers Stitching direction

Fig. 4: Expected heat transfer for different preform configurations

Fig. 5: In-plane TC

Fig. 6: Out-of-plane TC
INFLUENCE OF THE PITCH FIBER REINFORCEMENT OF CFRP ON THE MECHANICAL AND THERMAL CONDUCTIVITY PROPERTIES

Fig. 7: Compressive strength in different test directions

References

