CF/AR/thermoplastic hybrid yarns for requirement-based thermoplastic composites with outstanding, scalable stiffness, strength, crash and impact property combinations (Yarn Engineering)

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Introduction, problem definition and aim

Fiber-reinforced plastic composites are designed according to required stiffness and strength or impact and crash properties. Complex, overlapping load scenarios are only taken into account to a very limited extent. There are first practical approaches for realizing composite components, e.g. the B-pillar of an automobile [1]. In which composites (e.g., carbon fiber prepregs) are combined with metallic components (e.g. steel sheets) in order to achieve the necessary damage tolerance along with high weight-specific stiffness and strength. In such concepts, hybridization takes place at the macro (structural level) or meso (yarn level) level and requires extremely complex and cost-intensive manufacturing processes [2-4]. Furthermore, these components also have highly pronounced interlaminar interfaces, where complex stresses generate high shear stresses. As a result, premature structural failures occurs due to delamination [5-8]. In order to overcome these disadvantages and for use in future developments, a concept is developed and implemented in the project presented here. The approach provides the design of the combination of various fiber components by hybridization at the micro-level (within a yarn/fiber level), thus maximizing their property potentials. The use of recycled high-performance fibers also results in significant advantages over conventional composites in terms of sustainability, resource efficiency and cost-effectiveness.

The project aims to create a new three-component class of materials hybridized at the micro level for thermoplastic lightweight applications. By combining the reinforcing fibers such as carbon and aramid, it is possible to combine high stiffness and strength with high crash and impact properties by varying the reinforcing fiber proportions and fiber makeup in a way appropriate to the load case. Fig. 1a schematically shows the properties of state-of-the-art CF/AR hybrid composites (Fig. 1a bottom, highlighted by an ellipse) according to state of the art, from engineered yarns to be developed (top, area within the dashed lines) and the theoretical material potentials (top, colored lines), each depending on the fiber volume fractions. The systematic investigation of the influence of the material-specific fiber volume fractions for a scalable composites design was carried out in five stages (CF/AR or rCF/rAR: 50/0 %; 40/10 %; 25/25 %; 10/40 %; 0/50 %).

The development work focused on three main areas. The first focus was the further development of the process technology so that the composites based on engineered yarns exhibit high strength and stiffness due to low fiber damage, high uniformity and high fiber orientation. The second focus was the first-time implementation of the homogeneous blending of three fiber materials at the micro-level. The third focus was designing the engineered yarns so that outstanding, scalable stiffness, strength, crash and impact property combinations can be set explicitly for a wide range of requirements (Fig. 1a).

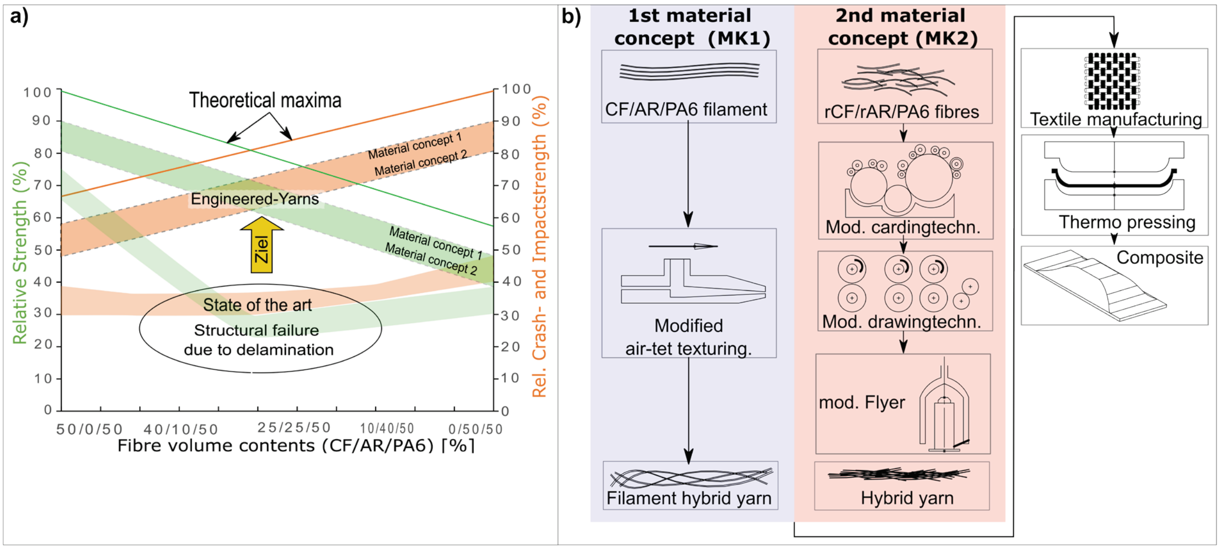

Figure 1: a) Schematic representation of the relative strengths and crash or impact properties of CF/AR hybrid composites as a function of the fiber volume fractions; b) Schematic representation of the process chain for realizing the material concepts.

For the concrete realization of the desired goal, CF/AR/PA6 or rCF/rAR/PA6 hybrid yarns were developed using two material concepts (Fig. 1b) based on two yarn formation technologies (Fig. 1a) for the production of thermoplastic composites with outstanding, scalable stiffness, strength, crash and impact property combinations. The interrelationships between process parameters and material-yarn composite properties were analysed. A sound knowledge for the material-dependent design of the engineered yarns could be achieved. Furthermore, the best possible material and process parameters for specific applications was derived and a process guide was prepared for the control of the manufacturing processes for the SMEs. A detailed description of the development work can be taken from the final report.

Development and production of engineered yarns based on the 1st material concept (MK1): filament-filament using advanced air texturing technology

With the MK1 concept (based on advanced air texturing), engineered yarns were developed from different filament yarns, specifically with homogeneous mixing and low fiber damage for composites with the high structural and mechanical properties. Based on ITM's extensive experience in developing two-component hybrid yarns consisting of reinforcing and thermoplastic filament yarns on the basis of air texturing technology, process investigations were first carried out with carbon and thermoplastic filament yarns. Based on the results of the process investigations, extensive developments were carried out for the first-time realization of homogeneous, intermixed three-component engineered yarns with low fiber damage according to MK1 from carbon, aramid and thermoplastic filament yarns. For this purpose, a heated spreader device for gentle pre-opening of the filament yarns was constructed and integrated into the air-texturing machine (Fig. 2). The unique innovation here is the significant reduction of the adhesion of the filaments to each other through the simultaneous mechanical spreading and thermal softening of the sizing. This significantly reduced fiber damage in the process (fiber damage in the yarn ≤ 5 % compared to at least 30 % previously) and significantly increased homogeneous blending. To realize the defined yarn properties, machine parameters such as overfeeds, delivery speed and air pressure were varied and suitable transparent air jets based on the interlacing principle were analyzed using high-speed video technology. After successful development, five different engineered yarns with fineness between 300 tex to 500 tex and each with a resulting volume content combination CF/AR/PA6 (50/0/50 %; 40/10/50 %, 25/25/50 %, 10/40/50 % and 0/50/50 %) were implemented in the composite. The engineered yarns exhibit high intermixing and fiber orientation with low damage (increased pre-opening degree allows air pressure reduction from current min. 3.5 bar to max. 2 bar). These yarns were characterized and used to produce the fabric structure, composites and a demonstrator.

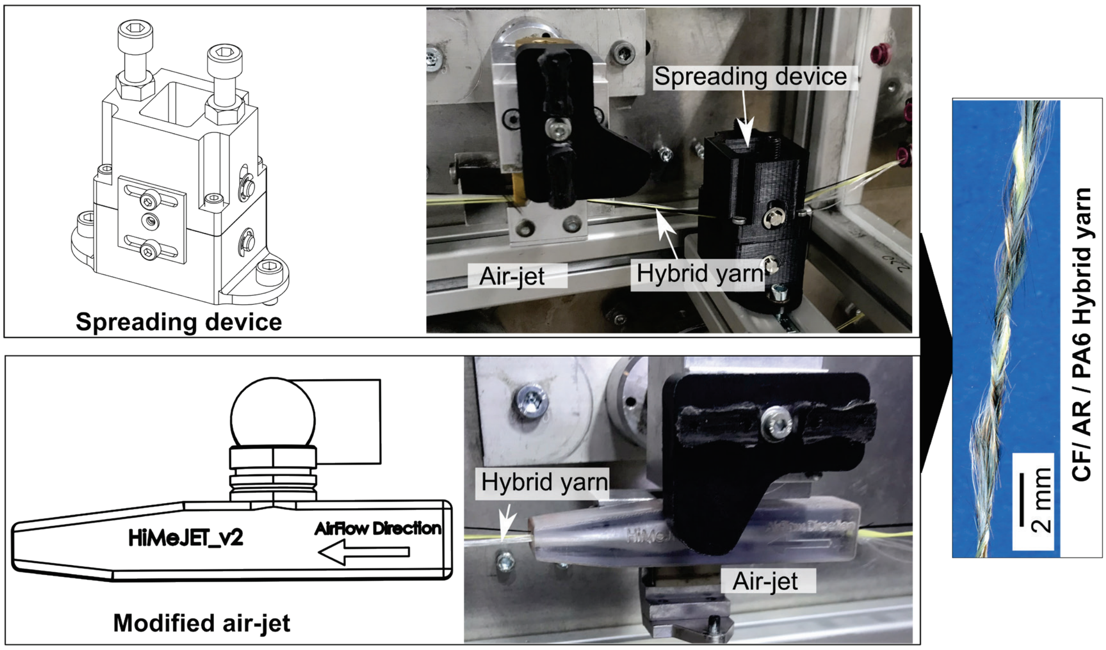

Figure 2: Developments on the air texturing system according to concept MK1

Development and production of engineered yarns based on 2nd material concept (MK2): staple fiber-staple fiber using advanced roving frame technology

The schematic process chain for implementing the MK2 "Engineered yarns based on staple fibers" is shown in Fig. 3. The MK2 concept allows the production of low-twist engineered yarns for composites from staple fibers with the best ratio of structural-mechanical performance and costs using an advanced roving frame technology. Various technological and design developments were made based on ITM's extensive experience in processing rCF and thermoplastic staple fibers. The roving frame's drafting system was further developed in order to keep the fiber damage as low as possible by modifying the roller surfaces (smooth surfaces). Furthermore, the best possible roller pressure was determined. High drafting uniformity could be achieved by determining the best textile-technological parameters. Furthermore, a methodology for the realization of a low-twist rCF/rAR/PA6 yarn was developed. For this purpose, a new thermos fixation module for inline heat setting was designed, developed and implemented based on an infrared emitter system available at the ITM (Fig. 3). The new module was integrated at the roving frame immediately after the drafting system exit and tested regarding the process control and realization of reproducible yarn properties. Yarn twists and different temperature levels as well as heating durations, were investigated. Finally, five engineered yarns from rCF/rAR/PA6 with fineness between 900 tex to 1500 tex with the high degree of intermixing, high fiber orientation, low degree of damage for a resulting volume fraction in the composite (50/0/50 %; 40/10/50 %, 25/25/50 %, 10/40/50 % and 0/50/50 %) was produced and characterized. They form the basis for the production of the fabric surface structure and composites as well as the demonstrator.

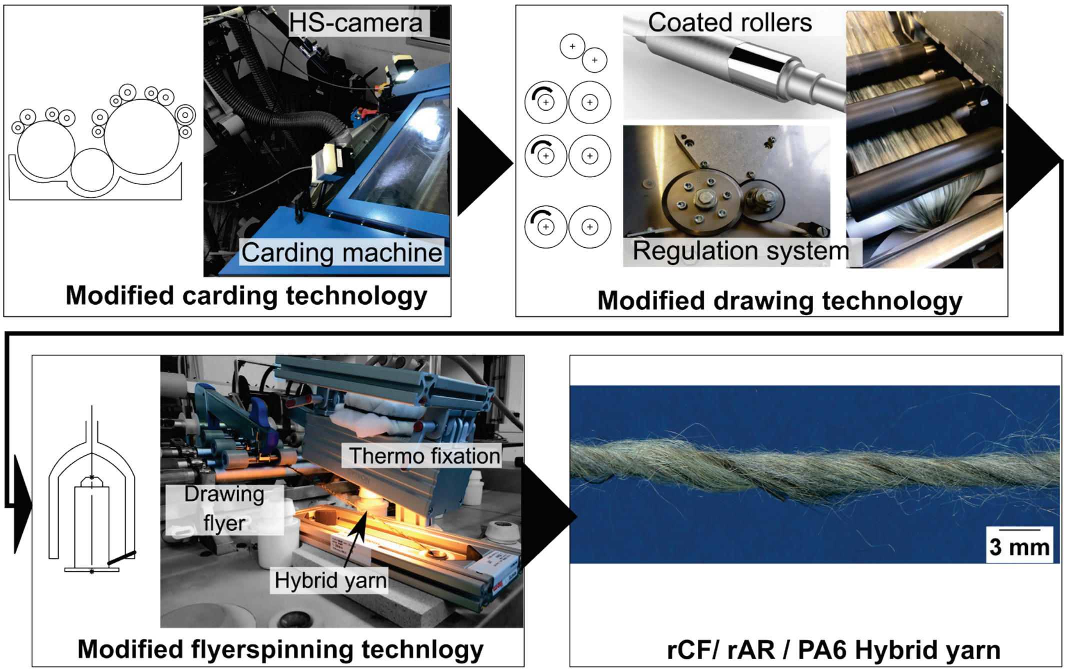

Figure 3: Modifications, investigations and hybrid yarn of the material concept MK2

Results (Selection)

The technological developments and textile-technological investigations within the scope of this work enable the processing of CF, AR and PA6 filament yarns based on air texturing technology (MK1) and rCF, rAR and PA6 staple fibers based on roving frame technology (MK2) into thermoplastic hybrid yarns with a high degree of blending and low fiber damage. The filament yarns based on MK1 have periodic alternating compact and bulky areas due to the principle and the staple fiber yarns based on MK2 show a uniform twist with crimping. The tensile and impact properties of the composites produced from the hybrid yarns can be adjusted in a defined way via the proportion of CF/rCF and AR/rAR depending on the requirements (Fig. 4b). The property profiles differ according to the selection of the material concept used (Fig. 4a). The use of staple fibers according to MK2, for example, allows higher impact strengths compared to MK1, and thus higher impact properties. On the other hand, composites made with MK1 exhibit higher tensile and flexural stiffness. The variable fiber volume fractions and the material concepts thus allow a wide range of properties to be set and permit the specific design of the composites to meet the requirements (strength, stiffness and impact or crash).

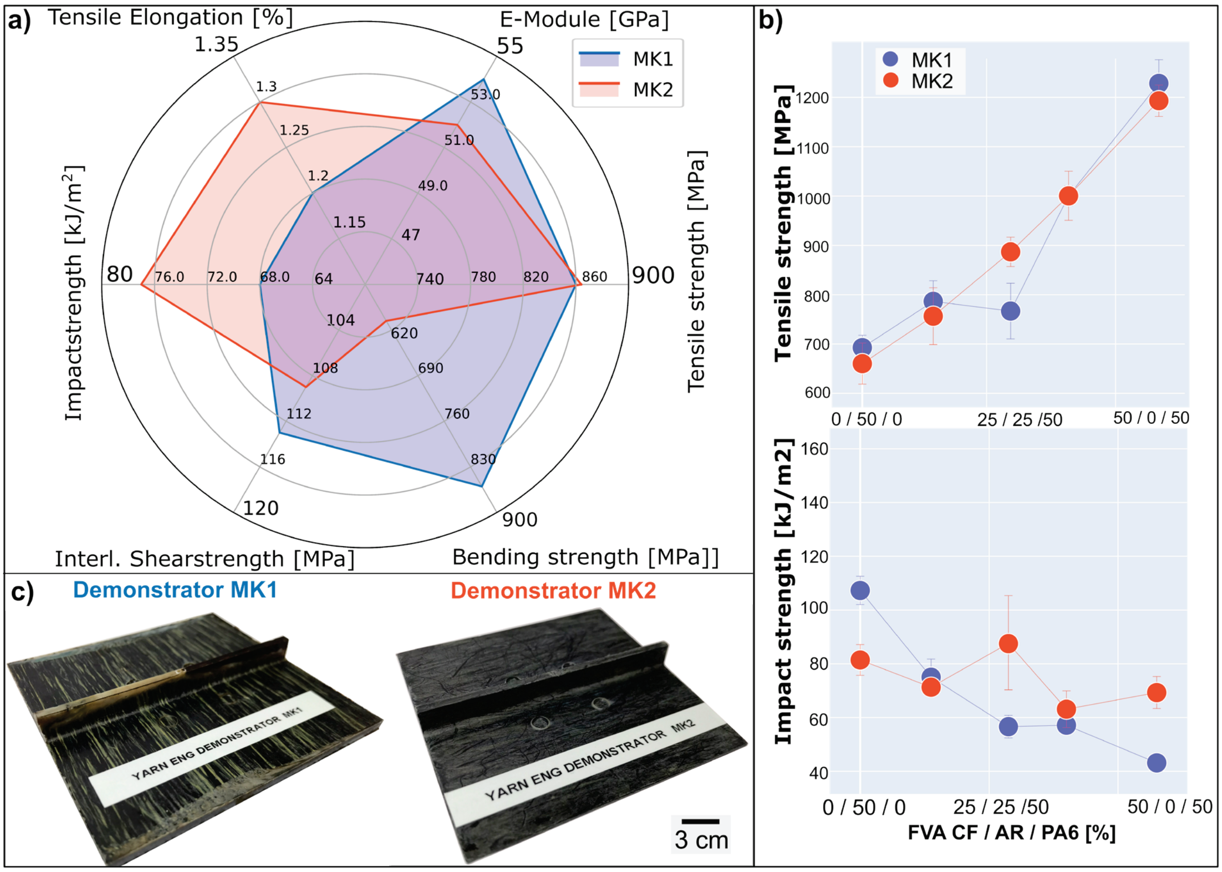

Figure 4: **a) Property profiles of the composites based on different material concepts; b) Dependence of the composite properties on the fiber volume fractions; c) Demonstrators based on MK1 and MK2**

Finally, a CF/AR/PA6 or rCF/rAR/PA6 hybrid yarn with properties that meet the requirements was selected and successfully processed into a complex thermoplastic demonstrator component (Fig. 4 c).

Summary

Within the framework of the IGF research project (21004 BR/1), material concepts based on two yarn formation technologies were realized at the ITM and CF/AR/PA6 and rCF/rAR/PA6 hybrid yarns for thermoplastic composites meeting requirements with outstanding, scalable stiffness, strength, crash and impact property combinations were produced. The influence of carding, draw frame and roving frame (MK1) and air texturing unit (MK2) parameters and fiber volume fractions on the mechanical properties were analyzed to develop requirements-based and defined engineered yarns and composites based on them. The investigated yarn formation technologies complement or partly compete with each other, but thereby also represent a broad technology spectrum. This generates a broad effect for the application of the results for product development in numerous German and often on few technologies specialized SMEs of textile technology.

Acknowledgement

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