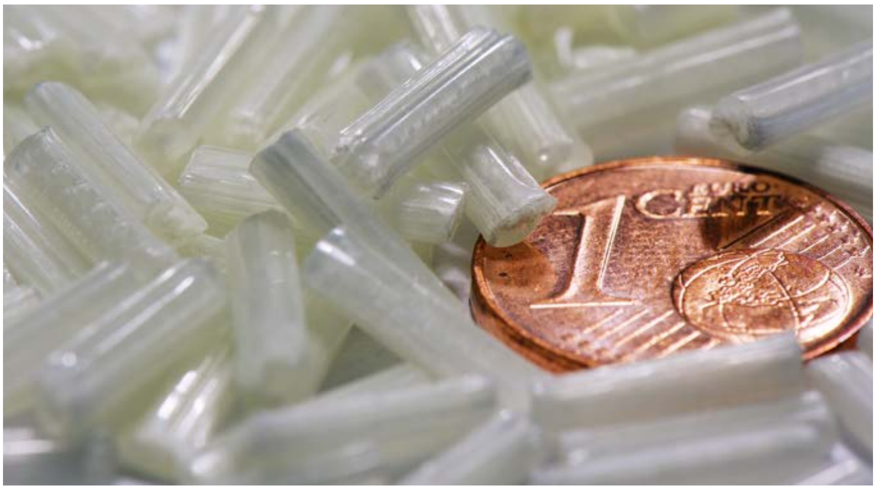
Simulate "Longer"

A New Calculation Model Allows the Prediction of Strength of Long Fiber-Reinforced Thermoplastics by means of Integrative Simulation

While the dimensioning of short fiber-reinforced thermoplastics is now established as state of the art, the dimensioning of their long fiber-reinforced counterparts (LFT) is an unresolved issue for developers and designers. First answers are provided by an integrative simulation method now developed at the Institute of Plastics Processing for predicting the strength of injection-molded LFT parts.



Pultruded long fiber granulates allow the economical processing of long fibers by the use of injection molding (© IKV)

The use of long fiber-reinforced thermoplastics (LFT) in injection molding is continuously growing, also in the field of highly stressed structural components. Because of their specific properties, these materials occupy the niche between short fiber-reinforced thermoplastics, which are often manufactured in the injection molding process, and continuous fiber-reinforced materials with mostly thermoset matrix systems, which are not suitable for injection molding. Compared with short fiber-reinforced thermoplastics, LFTs offer advantages of higher strength, impact resistance and reduced creep. Unlike thermoset materials with continuous fiber reinforcement, there are primarily economic benefits that can be achieved in the processing of long-fiber granulates (LFG) or by direct processes (D-LFT) in the conventional injection molding process [1].

The potential of LFT has not yet been fully exploited. In order to open up new applications, the availability of a reliable calculation method is one of the basic requirements. Integrative calculation methods already available for short fiber-reinforced materials can only be applied to a limited extent for the calculation of LFTs because of simplifications in the mathematical models that are no longer valid for long fibers. This involves primarily the prediction of fiber orientations and certain assumptions that are made about the microstructure of discontinuously fiber-reinforced composites. In a publicly funded research project, the Institute of Plastics Processing (IKV) at RWTH Aachen University, Germany, has developed an integrated simulation method to predict the strength of injection-molded LFT components under quasi-static loading. The simulation method is based on previously developed calculation methods for short fiber-reinforced thermoplastics.

Process Influences in LFT Are Diverse

To achieve this aim, the specific differences between short and long fiber-reinforced materials were first identified. For this, a LFG of polypropylene with 40 wt.% long glass fibers (PP-LGF40, grade: Celstran PP-GF40-0414 P10; manufacturer: Celanese GmbH, Sulzbach, Germany) was manufactured by injection molding. Additionally an LFT with 20 wt.% long glass fibers (PP-LGF20) was also studied. The PP-LGF20 was produced by adding a straight PP copolymer (grade: Tipplen K199; manufacturer: TVK, Tiszaujváros, Hungary) to the PP-LGF40 by means of in-line blending. The initial fiber length in the pellets was 10 mm.

Analytical studies on injection-molded 2.5 mm thick sheets show that some effects that are less relevant for short fibers are more visible with increased fiber length: In the processing of injection-molded LFTs, excessive attrition of the initial fiber length can occur through mechanical stressing of the fibers. This can lead to a wide distribution of fiber lengths, covering not only long fibers but also the range of short-fiber reinforcement [1]. An increase in the fiber weight fraction and an accumulation of longer fibers along the flow path are also observed (**Fig. 1**).

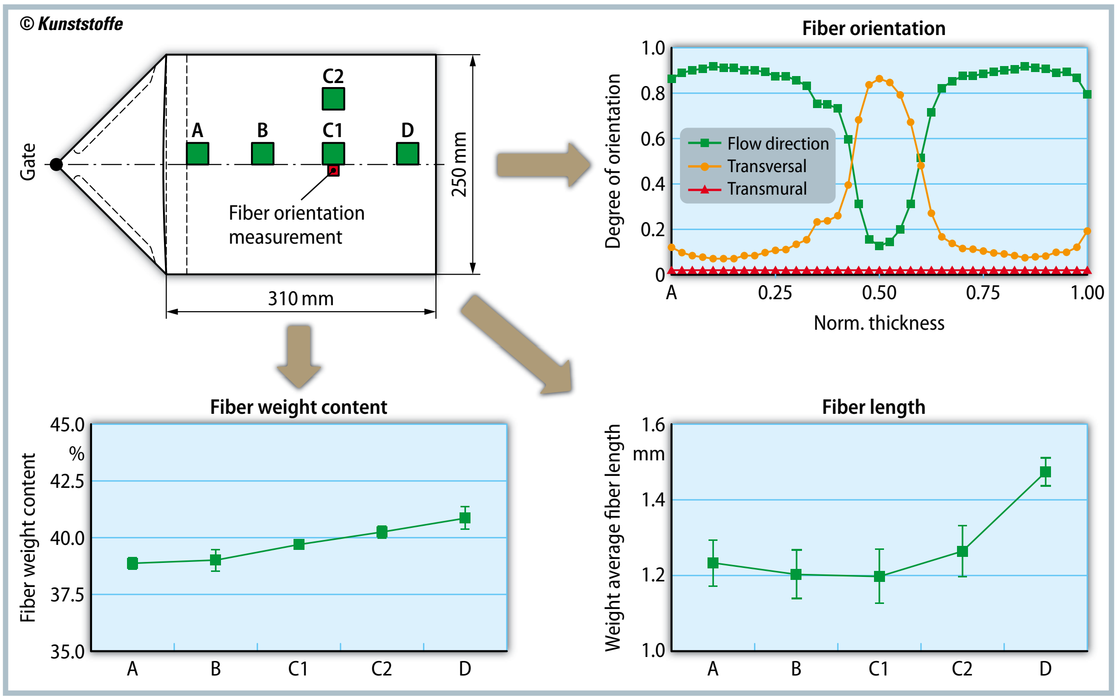


Fig. 1. Various influences on the microstructure of a PP-LGF40 caused by the injection molding process can be shown by measuring local properties (source: IKV)

Fiber weight content and fiber lengths were determined by ashing the PP matrix at 500 °C. For measuring the fiber lengths, an analyzer of the type Fasep (manufacturer: xyz high precision, Darmstadt, Germany) was used [2]. Both the increase in fiber content and the transport of long fibers to the end of the flow path can be traced back to a transport mechanism in which the surface layers that freeze early are deprived of fibers while the longer flowable core layer is enriched with these fibers [3]. With increasing fiber length, this mechanism is more pronounced.

In addition, long fibers are oriented in the melt more slowly than short fibers. As a rule, this leads in LFT to the core layer being oriented more transversely to the flow direction than with short fiber-reinforced materials [4]. To determine the fiber orientation, studies were carried out with micro-computer tomography. The measured local fiber orientations and a characteristic fiber length distribution are taken into account when modeling the material properties of LFT.

Efficient Calculation by Homogenization

Due to current limitations in computing power, the explicit modeling of the microstructure of fiber-reinforced materials for complete parts is hardly possible. Therefore, homogenization can be used to model the composite's properties caused by the microstructure on a macroscopic level. Such approaches have established themselves in the simulation of short fiber-reinforced materials. Based on a micromechanical model approach [5, 6], a material model has now been developed according to the requirements for LFT (**Fig. 2**).

The constitutive model uses a two-stage homogenization procedure [7, 8]. The basic idea is to break down the composite material into so-called "pseudo-grains", which, in their form and orientation, possess homogeneous inclusions. With this procedure, both an orientation distribution function (ODF) and the distribution of the fiber lengths can be considered. These two distributions are discretized by a finite number of orientation and length classes.

The material behavior of the matrix material is modeled using an elasto-plastic material model with isotropic »

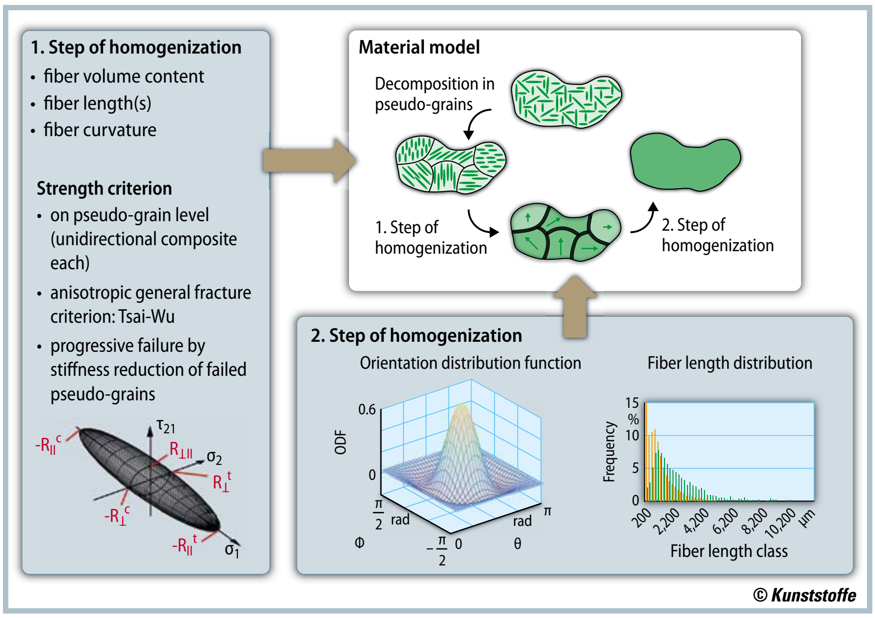


Fig. 2. Homogenization allows a prediction of the non-linear anisotropic material behavior of LFT within practicable calculation times (source: IKV)

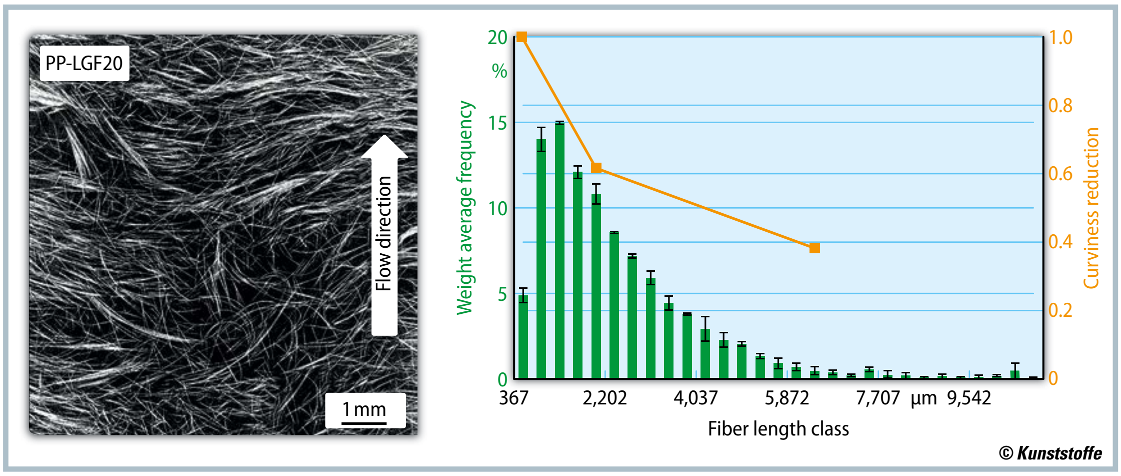


Fig. 3. CT scans illustrate the curvature of the fibers within LFTs. Since fiber curvature leads to a significant stiffness reduction, the material model takes into account the influence of fiber curvature phenomenologically (source: IKV)

hardening, which makes it possible to map the nonlinear material behavior until failure. The fibers are modeled as linear elastic in line according to their significantly more brittle material properties. The strength of the composite material structure is assessed individually for each pseudo-grain [10], based on an anisotropic general fracture criterion [9]. This approach also makes it possible to model the progressive failure of LFT, which is shown by a reduction in the contribution to the stiffness made by already damaged pseudo-grains. The described constitutive model for LFT was implemented in the FE program Abaqus/Standard (supplier: Dassault Systèmes S.A., Vélizy-Villacoublay, France) by using a user-defined material (UMAT).

Fiber Curvature Must Be Taken into Account

When modeling discontinuous fiber-reinforced materials using micromechanical models, the properties of the material's microstructure can be greatly simplified. Usually, the shape of a fiber is described as an ellipsoid having a characteristic aspect ratio. This goes along with the assumption of perfectly straight, uncurved fibers. While this simplification holds true for short fiber-reinforced materials, such an assumption for LFT is no longer valid. CT images clearly show the curvature of the fibers in LFT (**Fig. 3**). Because this fiber curvature lowers the attainable stiffening effect from longer fiber lengths [11], the curvature must be suitably taken into account in a simulation method for LFT.

For this reason, the concept of the equivalent inclusion stiffness [12] was taken up and the stiffness of long, curved fibers was accordingly reduced by a certain factor. In this way, the assumption was made that longer fibers bend more than short fibers. The newly included factor thus defines the reduction of the inclusion stiffness as a function of fiber length.

The model parameters were determined on the basis of tensile tests on specimens by means of computational optimization. For this, tensile specimens of type 1B (DIN EN 527) were used, which were taken from injection molded plates at defined angles to the flow direction. Similarly, the distribution of the fiber orientation and the fiber lengths were determined experimentally. Because, however, the unidirectional strength of LFT cannot be determined in practice experimentally, the described strength criterion is calibrated with the help of the maximum strength that could be detected in real tensile tests. For both materials, the model shows very good conformity with the experiments (**Fig. 4**).

Dimensioning of LFT Parts by Integrative Simulation

To calculate complex LFT parts, an integrative simulation chain was developed, taking computationally predicted fiber orientations into account. The injection molding process was simulated with the filling simulation program Autodesk Moldflow (supplier: Autodesk Inc., San Rafael, California, USA). For predicting the fiber orientations, the ARD-RSC model was used [13], which was specially developed for LFT. For the transmission of data between the different programs of the simulation chain, an interface developed at IKV was used.

In order to validate the calculation method, a model flange was tested under 3-point bending up to failure. This

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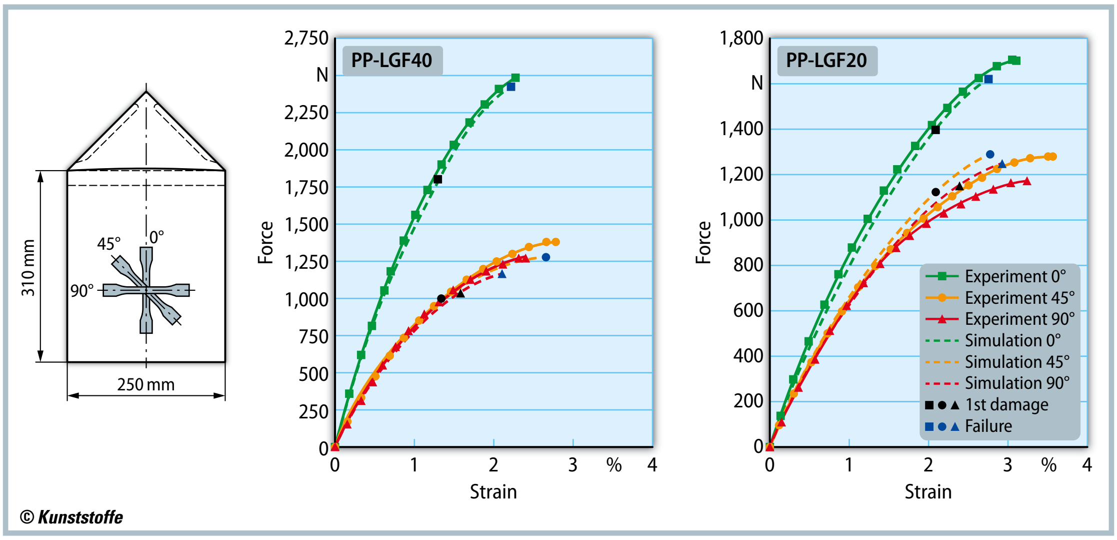

Fig. 4. The material model reproduces the material behavior of PP-LGF40 and PP-LGF20 with great accuracy (source: IKV)

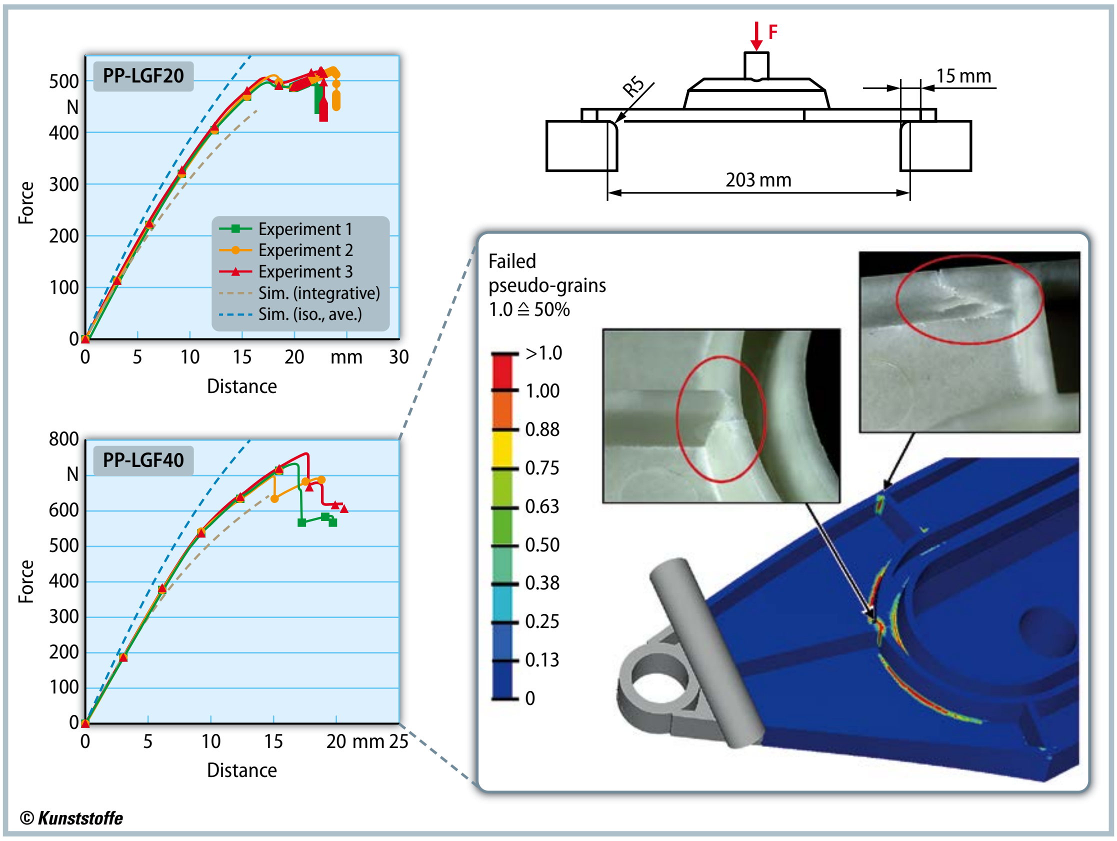

Fig. 5. Successful validation of the material model by simulating an LFT component. For this purpose, a model part was first tested in a 3-point bending mode until failure and this test was subsequently simulated (source: IKV)

test was also virtually recreated and the results compared to the experiments (**Fig. 5**). The potential of the integrative simulation method was demonstrated also by comparing simulations with an isotropic elastoplastic material card for a pre-determined quasi-isotropic property level. This property level was obtained by averaging the stress-strain response from the 0° and 90° tensile tests. Regardless of a meaningful failure prediction – which is almost impossible with the isotropic model – the integrative method shows a much better representation of the overall stiffness compared to the experiment. The locations of failure are also predicted with a high level of accuracy.

Outlook

The newly developed integrative simulation method already allows an accurate prediction of the quasi-static material behavior of LFT. In addition to the local fiber orientation and the characteristic distribution of the fiber lengths, the fiber curvature is shown to be another important factor in the realistic modeling of the constitutive behavior of LFT.

In further studies, the general failure criterion currently used to evaluate the strength is to be developed further so that the influence of fiber length and fiber curvature on the strength of LFT is explicitly taken into account in the modeling. Further investigations are ongoing at IKV on modeling the creep and relaxation behavior of LFT. ■