Integrative Simulation. When short-fiber reinforced thermoplastics are injection molded, it is often not possible to avoid the formation of weld lines. The specific mechanical and directional properties of these weld lines must be factored into the structure simulation.

Simulating Weld Lines in Short-Fiber Reinforced Thermoplastic Parts

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As a result of endeavors to extract maximum efficiency from component materials, the stresses which occur in service are pushing materials closer and closer to their limits. This makes it necessary to factor additional aspects that affect part strength into simulations. At the Institute of Plastics Processing (IKV), Aachen, Germany, an integrative simulation based on the finite elements method (FEM) has been developed which factors the weld lines into the virtual design of chopped-strand-reinforced thermoplastic parts.

Weld Lines and Fibers

There are two basic types of weld lines: the stagnant and the flowing [1]. Stagnant weld lines are formed when melt streams meet head-on. Flow lines arise when at least two melt fronts meet at an acute angle to each other and then continue to flow in a combined front.

In fiber-reinforced materials, aside from generally weakening the polymer matrix, local fiber orientation exerts a significant influence on the mechanical properties of the weld area. Within this area, each basic type of weld has a characteristic fiber orientation. In the case of the stagnant type, the melt fronts solidify shortly after meeting. The effect of this is that the fibers remain oriented in the direction of the source flow. In other words, the fibers more or less orient themselves transversely to the direction of flow [2]. In the area of flow lines, the fibers align themselves with the flow direction due to the continued flow of the combined flow fronts. This means that they are mainly aligned parallel with the weld line [3].

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Experimental Studies

The mechanical properties of weld lines in a chopped-strand-reinforced thermoplastic were characterized by performing material studies on semicrystalline polyamide 6.6 with a fiber content of 15 and 30 weight percent (PA6.6-GF 15/30, grade: Durethan AKV 15/30 H2.0, manufacturer: Lanxess Germany GmbH, Leverkusen, Germany) in the freshly molded state and the standard conditioned state in accordance with DIN EN ISO 1100. The studies involved two different specimen geometries that make it possible to selectively incorporate weld lines into the specimen. The specimen for characterizing stagnant weld lines is shown in **Figure 1 (left)**. Flow lines were studied on tensile rods removed at different positions from injection-molded slabs **(Fig. 1, right)**.

The aforementioned specimens were subjected to short-term tensile studies in a universal testing machine (type: Z100; manufacturer: Zwick GmbH & Co. KG, Ulm, Germany) in order that the tensile strengths of specimens with and without weld lines could be determined. **Figure 2** shows the experimental tensile strengths for PA6.6-GF 30 for both basic types of weld. The results demonstrate the influence of fiber orientation on the strength of the material. Thus, injection molded →

The integrative simulation chain can detect the weld lines of a connecting rod made from PA6.6-GF 15 (photos: IKV)

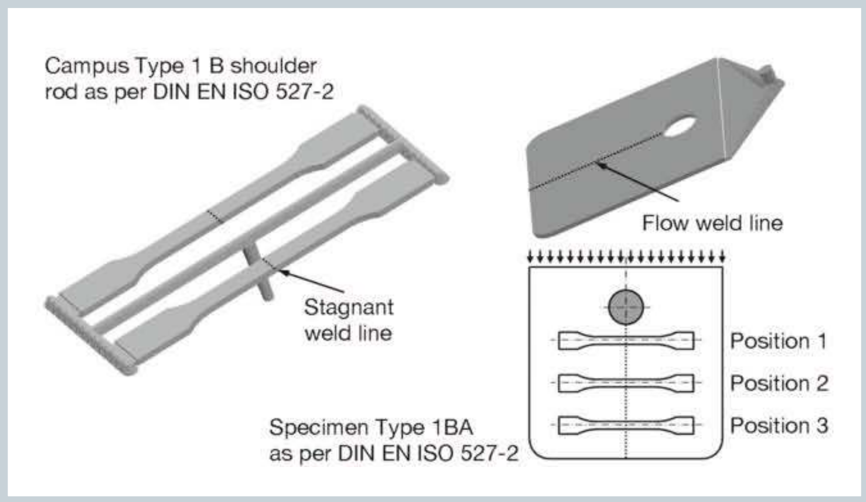

Fig. 1. The mechanical behavior of weld lines was determined on specimens of different geometry

tensile rods without weld line have a marked longitudinal orientation while those removed transversely to the flow direction in slabs have a high transverse orientation. It can be seen that weld lines have lower strengths than a pure transverse orientation. This is due to additional weakening of the matrix polymer.

Developing a Simulation Chain

In the structure simulation, weld lines are taken into account by constructing an integrative simulation chain (**Fig. 3**). Fluid-mechanics simulation software (type: Sigma Soft; provider: Sigma Engineering GmbH, Aachen, Germany) is used to simulate filling processes during manufacturing. The filling simulation determines fiber orientations and weld positions and maps them to the finite element mesh of the structure simulation. The structure simulation is performed with a FE program (type: Abaqus; manufacturer: DS Simulia Corp. Rhode Island, Providence, RI, USA) that was expanded with a material description which was developed at the IKV. The material description simulates the nonlinear and anisotropic stiffness of the fiber/matrix composite [4]. For this, the composite is considered to be a macroscopically homogeneous material, whose properties are determined from the individual parameters of fiber and matrix via micro-mechanical models [5].

Sigmasoft features a weld line parameter which detects the weld lines by assessing the likelihood of the presence of a weld at the respective position in the model. The parameter is good at localizing stagnant weld lines, whereas it tends to return spuriously short flow line lengths.

On account of their characteristic fiber orientation, weld lines constitute an anisotropic vulnerability. Therefore, a directional failure criterion is needed so that weld line failure may be described. The weld line parameter does not provide such directional information as it is described by a scalar quantity only. The directions that describe a weld line plane, however, can be reconstructed retrospectively from the characteristic fiber orientation in weld lines. Consequently, the anisotropic strength both of weld lines and the unstressed composite can be described by a common strength criterion with appropriately assigned strengths. In this regard, a non-differentiating failure criterion of Tsai/Wu [6], which uses a failure function to describe material loading, serves as anisotropic failure criterion. A value greater than one indicates failure.

First, the computational method is validated for a simple geometry. This is done by simulating tensile tests on specimens that were removed at different angles

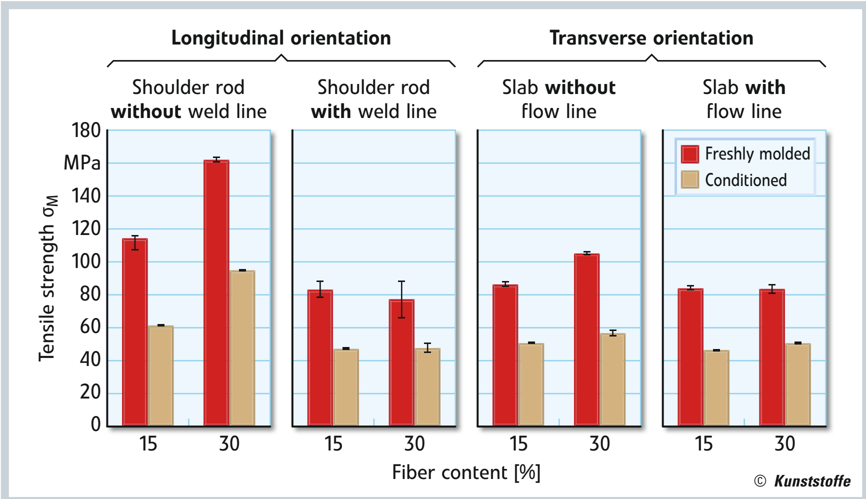

Fig. 2. The results of the short-term studies demonstrate the influence of fiber and moisture content on tensile strength

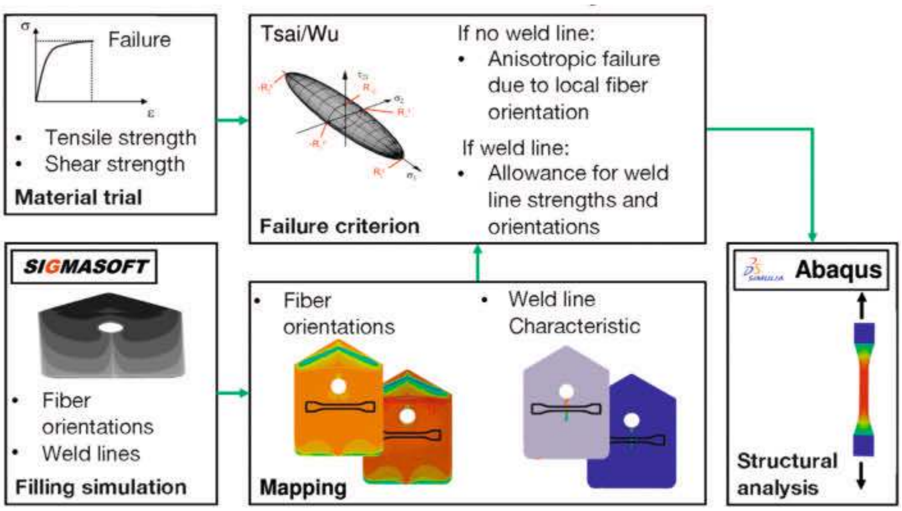

Fig. 3. To take account of weld lines in the structure simulation, an integrative simulation chain is being developed

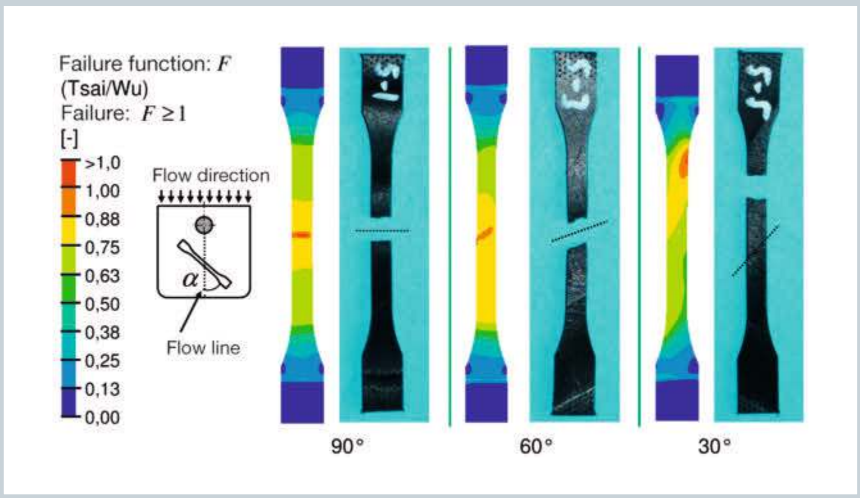

Fig. 4. Comparison of simulated failure pattern and failure location reveals good agreement

from injection molded slabs. **Figure 4** compares the simulation results with the experimental results for different angles. Clearly, there is very good agreement, especially with regard to localization of the failure.

Second, the computational method is validated for a complex geometry. This is done by performing tensile tests on the connecting rod of an electric hand tool made of PA6.6-GF 15, which is a series component made from another material. Since the injection point is located in the center of the part, weld lines form at each end of the flow path in the connecting rod "eyelets". At these points, there are two overflow cavities which permit these weld lines to be perfused and thus help boost strength.

Figure 5 shows both a failure pattern and the visualized material stress from the simulation. Here, the material stress is shown left with weld line detection and right with the weld line ignored. In the latter case, the failure is thus determined solely on the basis of fiber orientations; matrix weakening is ignored. In the studies, the failure pattern shown in **Figure 5** occurred sometimes; however, it also occurred exclusively in the weld line in some cases. In the simulation, the most stressed areas are outside the weld line. This suggests that the failure in the unstressed composite tends to be detected prematurely by the failure criterion employed. Aside from that, however, the simulated material stresses on the weld show good agreement with the experimental results.

Conclusion and Outlook

Studies performed on special test specimens can identify tensile strengths which serve as material parameters for characterizing weld lines. An integrative simulation method makes it possible to map weld line positions from a filling simulation to a structure simulation and to depict anisotropic material stress there. A parameter serves to localize the weld, while the spatial position of the weld can be reconstructed from the fiber orientations. Application of an anisotropic failure criterion enables possible part failure to be predicted on the basis of locally and directionally variable strengths.

The simulation method which has been developed is being validated in experimental studies and is good at depicting the anisotropic properties of both weld lines and flow lines. As a way of further improving the failure description, especially of the unstressed fiber/matrix composite, in the future, the non-differentiating failure criterion should be replaced by a more complex criterion. This should differentiate between matrix and fiber damage and also depict the plastic behavior of the matrix material. ■

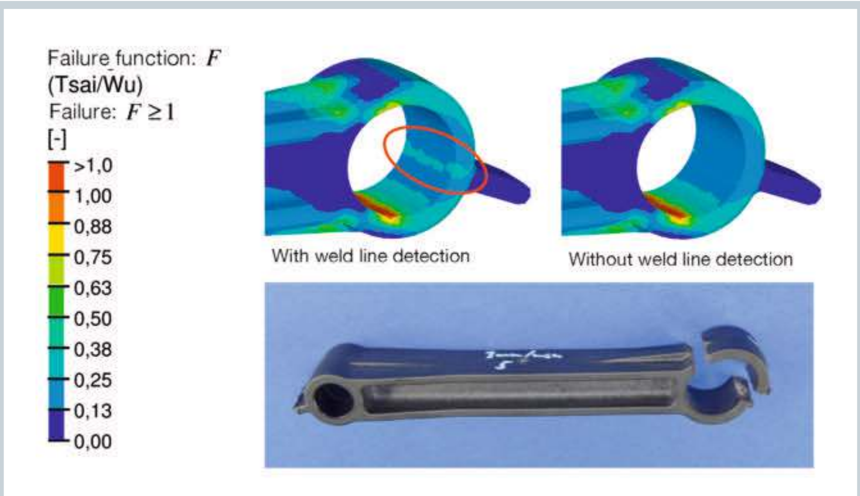

Fig. 5. The connecting rod failure patterns generated in the simulation are in good agreement with the results of the tensile test

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