INTEGRATIVE SIMULATION METHOD FOR THE PREDICTION OF ANISOTROPIC AND TIME-DEPENDENT MECHANICAL BEHAVIOR OF INJECTION MOLDED FIBER-REINFORCED FAN IMPELLERS – CREEP MODELLING

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SUMMARY

Based on experimental approaches the anisotropic and time-dependent creep behavior is investigated and modelled in this paper. The Findley power law is used to represent nonlinear viscoelastic creep curves and compared to time stress superposition principle. Both methods are applied to predict the creep behavior, based on short-term creep curves. Finally, an integrative simulation method is outlined for an application in fan design.

INTRODUCTION

Injection molded fiber-reinforced plastics are widely used as structural or functional parts in fan applications. Due to the possibility of insert integration in injection molding and the short cycle times without the need of subsequent machining, injection molding is a cost-efficient process for producing large numbers of complex parts [1], e. g. for the production of fans. Adding to this, the high flexibility in design can be used to achieve lower noise emissions, higher efficiency factors, and weight savings in aerodynamic applications [2]. For the latter option, a number of aspects need to be considered. Besides the operating loads and conditions, flow-induced static and dynamic loads on the surface of the fan can occur. Thus, the process-induced anisotropic, time-dependent mechanical behavior needs to be included to ensure the long-term use of the parts.

During the injection process the thermoplastic material underlies flow induced shear and elongation among other influences. Depending on the material viscosity, a corresponding flow velocity profile exists and leads to a characteristic fiber orientation. At the mold boundaries, the fibers are oriented in flow direction due to a high shear rate. In the middle section the fibers are oriented perpendicular to the flow direction [3, 4] (Figure 1).

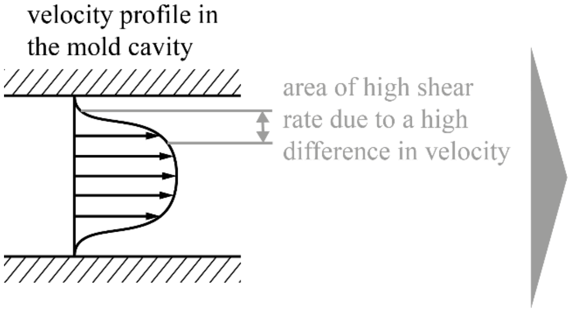

Figure 1: fiber orientation in injection molding due to the shear rate in polymer flow

When applying a constant load on a polymer part an initial strain ε_0 occurs. The strain increases with ongoing time, which is known as creep and is caused by nonlinear viscoelastic polymer behavior. Several models are proposed to describe nonlinear viscoelastic polymer behavior (e. g. [5, 6]). In order to avoid the difficulties with non-linear theoretical formulations, engineering approaches based on empirical expressions are often used. An empirical approach proposed by Findley [7] is widely used to model creep behavior of fiber reinforced composites [8]. The creep strain ε_c at time t can be written as

$$\varepsilon_c(t) = \varepsilon_0 + m \cdot t^n \tag{1}$$

with ε_0 as initial strain, m as a function of stress, and n as a material constant. For a given specific thermomechanical condition, the Findley equation can be rewritten as [9]

$$\varepsilon_c(t,\ T,\ \sigma) = \varepsilon_0(T,\ \sigma) + m(T,\ \sigma) \cdot t^n \tag{2}$$

To determine polymer creep behavior, different accelerated testing methods exist. The time stress superposition (TSS) principle is similar to the more common time temperature superposition (TTS) principle. Instead of increasing temperature, the TSS method accelerates the measurement by increasing the stress at a constant temperature. Compared to creep test measurements, this method reduces the test duration to predict the time dependent material behavior. Moreover, a temperature chamber is not necessary to perform the tests, which is an advantage over the TTS method. The measured creep modulus at a constant stress and a short time interval, is equivalent to the measurement at a lower stress but at an expanded time scale. By the shift factor *log a*, the short time creep curves can be put together (Figure 2). Similar to the time temperature superposition, the expression of the time stress superposition principle can be expressed as

$$\varepsilon(\sigma_1, t) = \varepsilon(\sigma_2, t \cdot a_\sigma) \tag{3}$$

where σ_1 and σ_2 are the applied stresses and a_σ is the stress shift factor. Taking this relation as a basis, a master curve can be constructed.

Several authors applied and investigated this principle. The nonlinear creep of high-density polyethylene was investigated by Lai and Bakker [10] with short- and long-term tensile creep tests. The authors described that an acceleration of creep can be realized by applying high stresses. For the application of the time stress superposition to the neat material, the obtained master curve correlated well according to the authors. Hadid *et al.* [11] reported an excellent superposition of curves in the bending creep behavior of a 43 % by weight glass fiber reinforced polyamide 66. The method used by the authors showed an increase in the master curve, which could be assimilated to the third stage creep. Nevertheless, the data was not compared to long-term creep data. Moreover, the master curve was not only obtained by a horizontal shift, but also a rotation of each curve with respect to the next curve, as the curves did not have the same slope [11]. Eftekhari and Fatemi [12] investigated the creep behavior and modeling of short glass fiber reinforced thermoplastics with time stress superposition. The presented results of the TSS method predicted creep data satisfactory. The use of TSS method is limited for the prediction of creep behavior in elevated environmental temperatures [12].

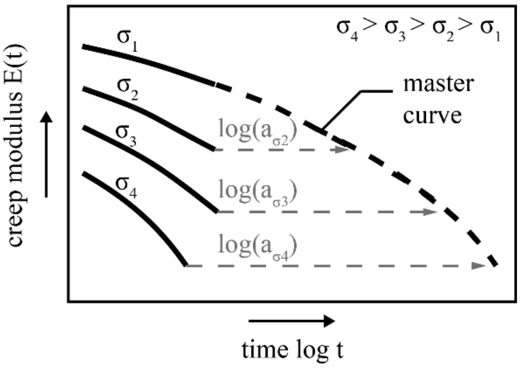

Figure 2: time stress superposition – schematically

In this work the anisotropic and time-dependent creep behavior is investigated and modelled based on experimental approaches. The Findley power law is used to represent non-linear viscoelastic creep curves and compared to the TSS principle, which is applied to predict the creep behavior, based on short-term creep curves. At the end of the paper, the integrative simulation methods are outlined to determine the total and local strains of a fan impeller.

MATERIALS AND METHODS

In this study, a semicrystalline 40 % by weight short glass fiber reinforced polypropylene (Altech PP-H A2040/159 GF40 CP, ALBIS Plastic GmbH) was used. It features high stiffness and tenacity, which is why it is used for technical applications, e. g. for fan impellers.

To investigate the mechanical behavior in dependence of the fiber orientation, plate shaped test specimens (115 mm x 115 mm) with different thicknesses (1 mm, 2 mm, 4 mm) were injection molded with an ARBURG Allrounder 370V/800-315. A three-zone screw with a diameter of 35 mm was used. Except for the holding pressure all parameters remained constant for the different specimen thicknesses. The nozzle temperature was 260°C, mold temperature 40°C, injection speed 40 mm/s, holding pressure time 20 s, and cooling time 40 s. The holding pressures was set to 350 bar for the samples with 1 mm and 2 mm thickness. For the sample of 4 mm thickness a holding pressure of 450 bar was applied. For mechanical analysis, test specimens were prepared by milling, and different mold directions were considered as shown in Figure 3.

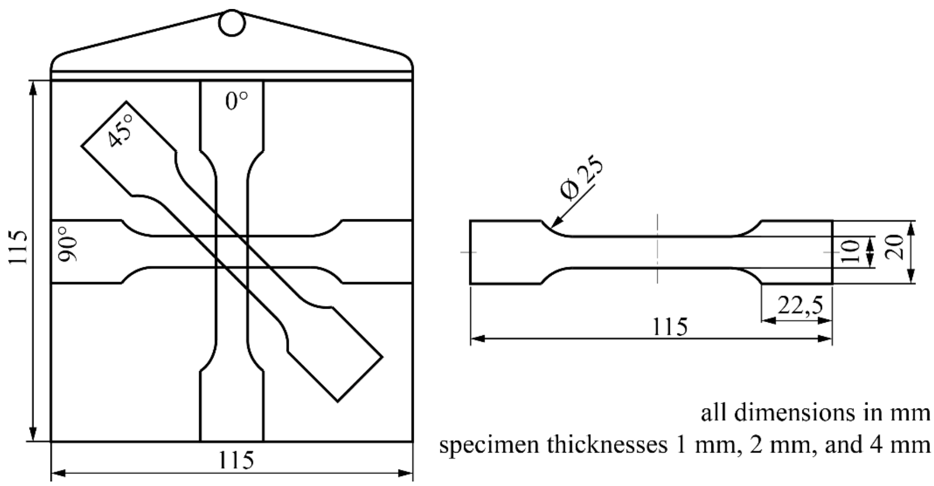

Figure 3: test specimens used for mechanical analysis and the different mold directions

The mechanical properties were characterized by short term tensile tests according to EN ISO 527. A strain rate of 0.6 mm/min (determination of Young's modulus) or 3 mm/min were used respectively with an universal tensile testing system (Zwick Roell). Moreover, the Poisson's ratio was determined in 0° and 90° direction under tensile load. T-rosette strain gauges type FAET-A6194N-35-SXE (Vishay Precision Group) with a nominal resistance of 350 Ω were applied on the specimens.

Tensile creep tests were performed with a constant stress at an ambient temperature of 23°C according to EN ISO 899. The applied stresses were 15 N/mm², 20 N/mm², 25 N/mm², and 30 N/mm². The creep tests had a duration of 1000 h. For the creep measurements linear strain gauges type FAE-25-35-SXE-G (Vishay Precision Group) with a nominal resistance of 350 Ω were used in half-bridge configuration with temperature compensation. The data was logged with a Spider8 (HBM) with a data acquisition rate of at least 0.1 Hz. The tests were performed for 0° and 90° mold direction. Both plate thicknesses of 2 mm and 4 mm were analyzed.

To characterize the different fiber orientations, polished cross sections were prepared in 0° mold direction and observed under a microscope with Zeiss Axio Imager.M2m.

For TSS, test specimens with a sample thickness of 4 mm were investigated in 0° and 90° mold direction. The observed time interval was about 2 h and 45 min (10^4 s). The results were used to model the long term tensile creep behavior. With the shift factors a creep master curve was exemplarily built for 15 N/mm². Findley's power law model was applied to predict long term creep behavior. The shift factors for the applied stresses σ_i were determined according to the following expression

$$a_{\sigma i} = \frac{t_{i,e}}{t_{i+1}} \tag{4}$$

with $t_{i,e}$ being the end time of the investigated time period (10^4 s) of the short-term creep tests, and t_{i+1} is the time which fulfills the condition shown below.

$$\varepsilon(\sigma_i, t_{i,e}) = \varepsilon(\sigma_{i+1}, t_{i+1}) \tag{5}$$

RESULTS AND DISCUSSION

The injection molded samples of different thicknesses show the typical fiber distributions induced by polymer flow in the mold (Figure 4).

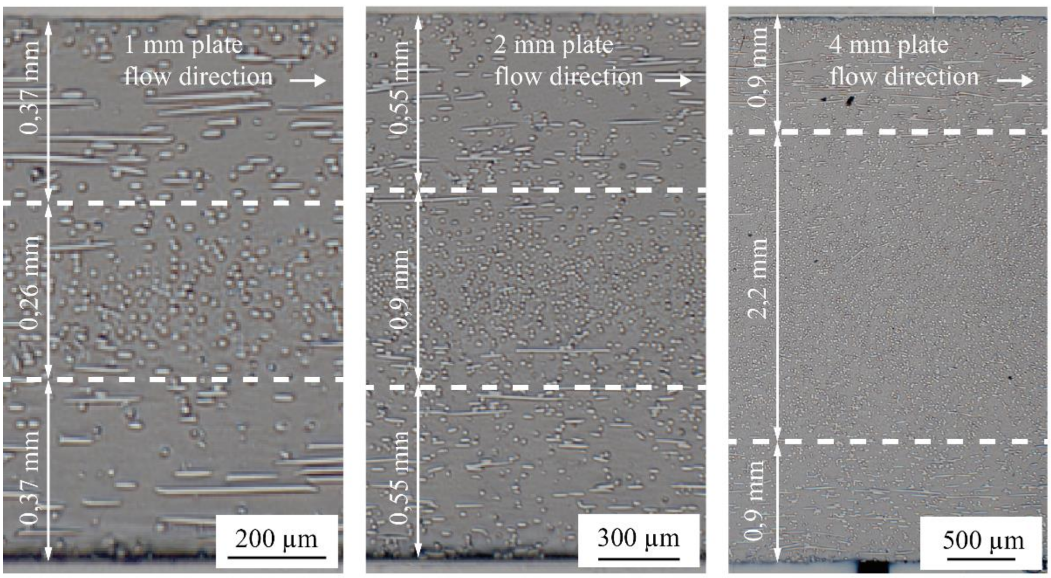

Figure 4: glass fiber orientation and layer formation in 1 mm, 2 mm and 4 mm sample

The percentage of the surface layer with the fiber orientation into flow direction decreases with increasing plate thickness. A reason for this are the higher velocities and shear rates for smaller plate thicknesses. In particular, this applies when the same injection speeds are present.

As the fiber orientation directly influences the mechanical properties, clear differences can be identified in the tensile tests (Figure 5). Due to the highest percentage of oriented glass fibers, the highest tensile stress and tensile modulus occur for a plate thickness of 1 mm in 0° direction. These values decrease with increasing plate thickness. For the test direction perpendicular to the injection direction (90°) this effect is reversed. The same observations can also be made for the Poisson's ratio (Figure 6, right).

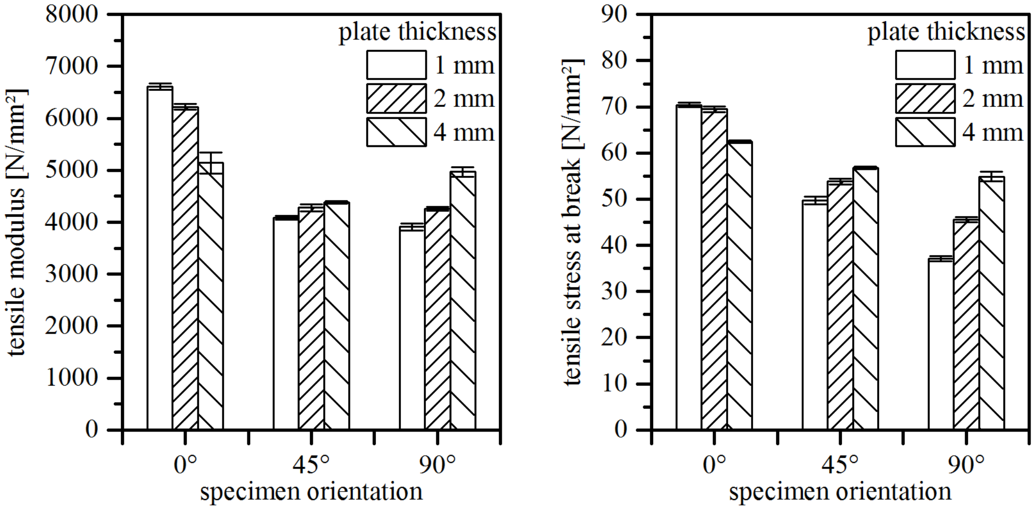

Figure 5: tensile modulus (left) and tensile stress (right) in dependence of the plate thickness and specimen orientation

A different behavior occurs for the elongation at break. The elongations rise with increasing plate thickness. Moreover, the highest elongation at break are achieved for the tensile direction of 45° (Figure 6, left). As most fibers are oriented in an angle of 45° to the tensile direction, the fibers cannot directly transfer the forces into tensile direction, thus allowing for a higher shear deformation of the matrix. Overall, a high anisotropy is detected for a plate thickness of 1 mm, while the anisotropy for a plate thickness of 4 mm is significantly lower and nearly quasi-isotropic. This means that part thickness and geometry have to be taken into account in order to determine the mechanical properties for a simulation.

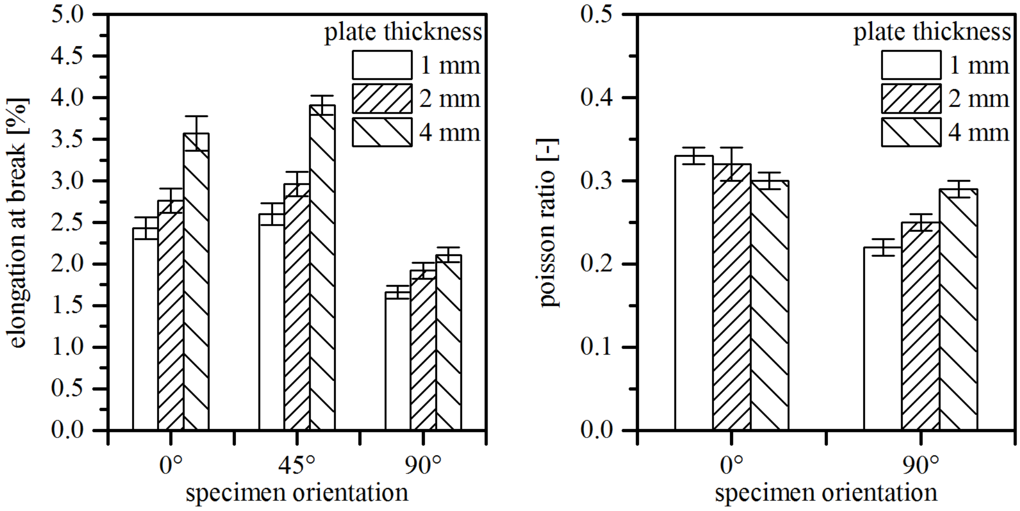

Figure 6: elongation at break (left) and Poisson's ratio (right)

The anisotropic behavior and thickness-dependence are also present for the long term creep tests (Figure 7 and Figure 8). Moreover, the load dependency is clearly visible and the creep strain increases for higher stresses. In case of the specimen direction of 90° this leads to failure at 30 N/mm² after only 6 h and 36 min, at 25 N/mm² after 83 hours and at 20 N/mm² after 920 hours for the 2 mm samples. Therefore, the creep strain is lower than the maximum elongation at break measured in the tensile tests.

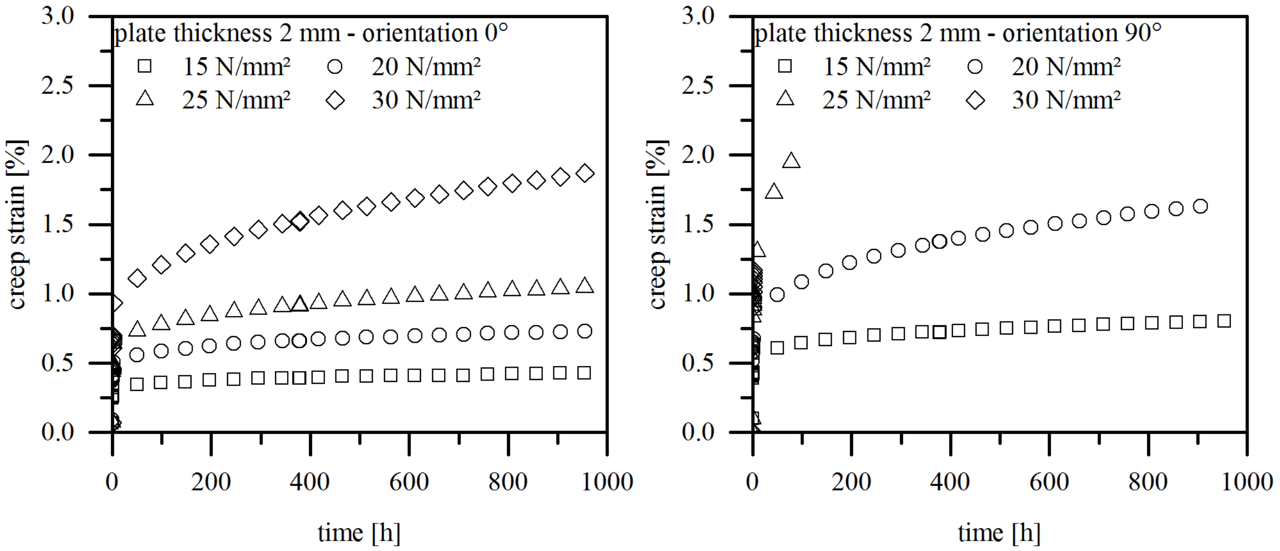

Figure 7: creep strain of test specimens with 2 mm thickness into flow direction 0° (left) and perpendicular to flow direction 90° (right)

For the test specimens of 4 mm thickness, only the highest stress of 30 N/mm² leads to failure. In contrast to the samples of 2 mm thickness, the failure corresponds to the elongation at break of the tensile tests. Although the tensile modulus of 0° and 90° specimens are almost equal, no failure occurs for the creep tests in flow direction. This could mean that the fiber orientation in the surface layers might play a significant role in the failure of the parts.

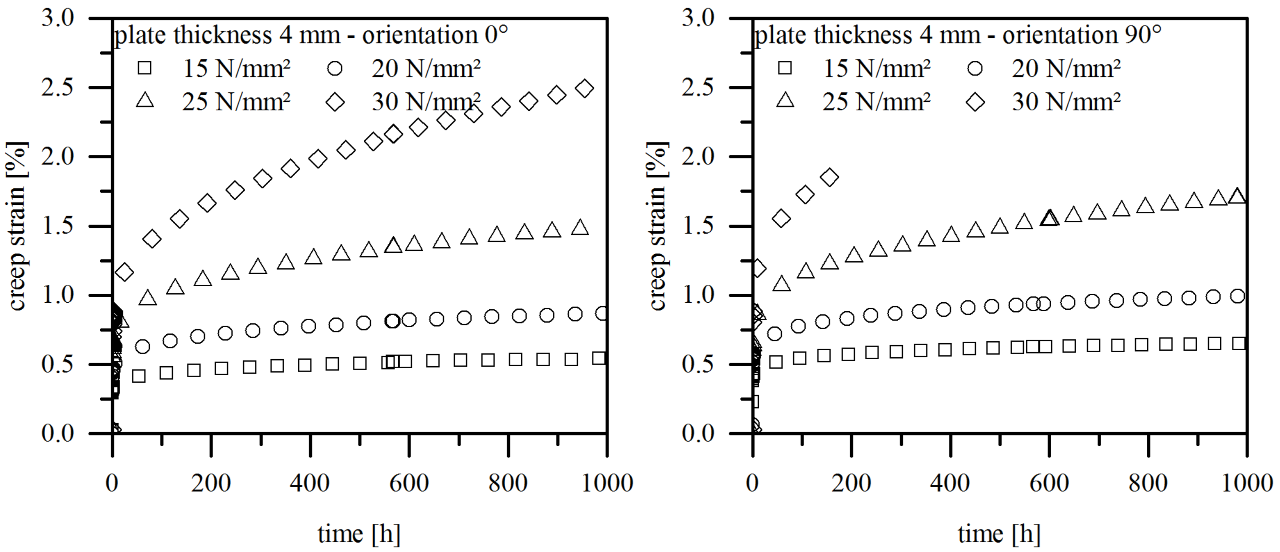

Figure 8: creep strain of test specimens with 4 mm thickness into flow direction 0° (left) and perpendicular to flow direction 90° (right)

The short creep strain curves for TSS principle are illustrated in Figure 9. To obtain the master curves, the curves were shifted along the time axis as described in equation (4) and (5).

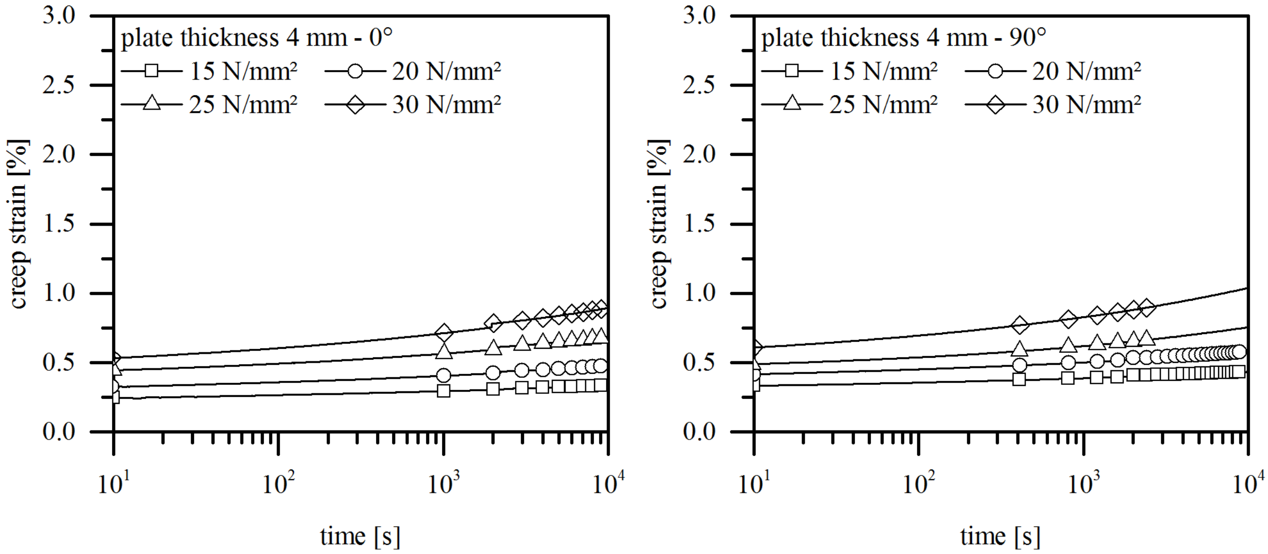

Figure 9: short creep strain curves for with constant stress 15 N/mm², 20 N/mm², 25 N/mm² and 30 N/mm² for specimen orientations of 0° (left) and 90° (right);

Figure 10 exemplarily shows the creep master curve for a constant stress of 15 N/mm² in 0 ° and 90 ° direction constructed from the experimental data given in Figure 9. In general, a good superposition of the curves is achieved and the obtained time interval increases to more than 1.000 h. The curvature at the end of the master curve demonstrates the non-linear behavior of the material. Nevertheless, as the slope of the curves in Figure 9 is not identical, slight discontinuities can be seen in the master curves. To prevent this, a rotation of each curve with respect to the next curve is described in [11]. A rotation gets justified by the authors on the basis of the stress sensitivity of the power law exponent. Regardless of that, the physical theory is not consistent, the basis on which the rotation is performed. The shift factors for the applied stresses are shown in Figure 10, right. Higher shift factors are obtained for the directions of 0°, which can be attributed to the lower creep ability.

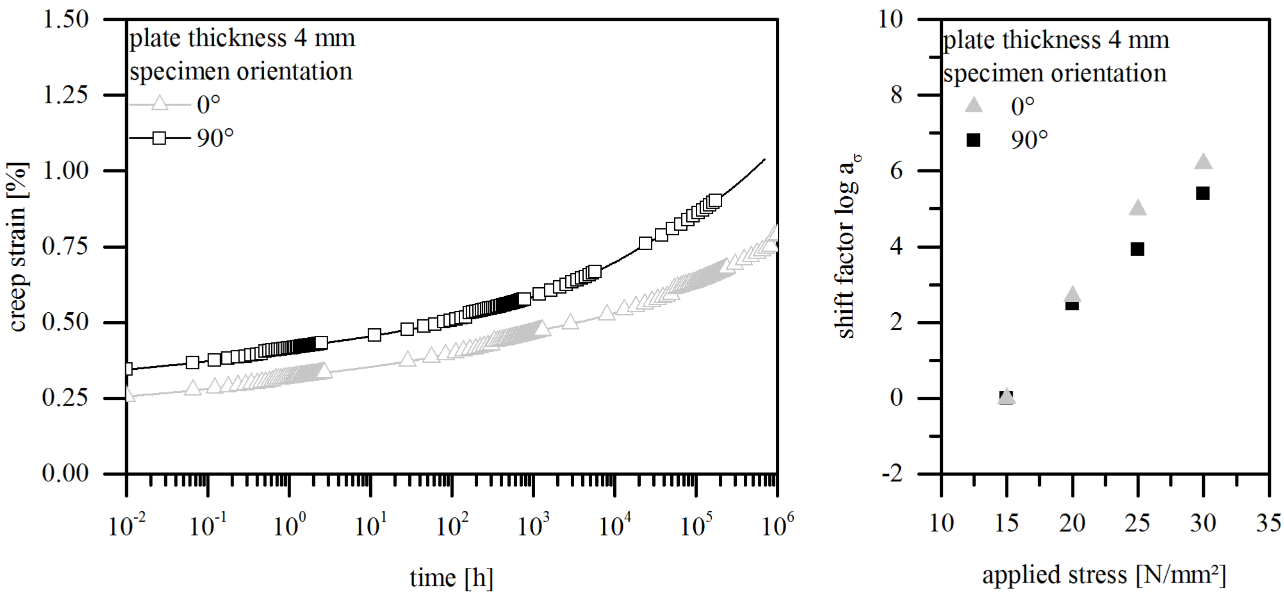

Figure 10: creep master curve for stress of 15 N/mm² (left) and shift factor vs. stress (right)

In comparison to the experimental data and the curve obtained by the Findley model, the creep strain of TSS is significantly lower for both test specimen directions (Figure 11). The creep strain results for TSS after 1000 h deviate more than 10 % from the creep strain curve. For the Findley model the results differ by 1 %. These results can be applied to predict the long term creep behavior in simulations.

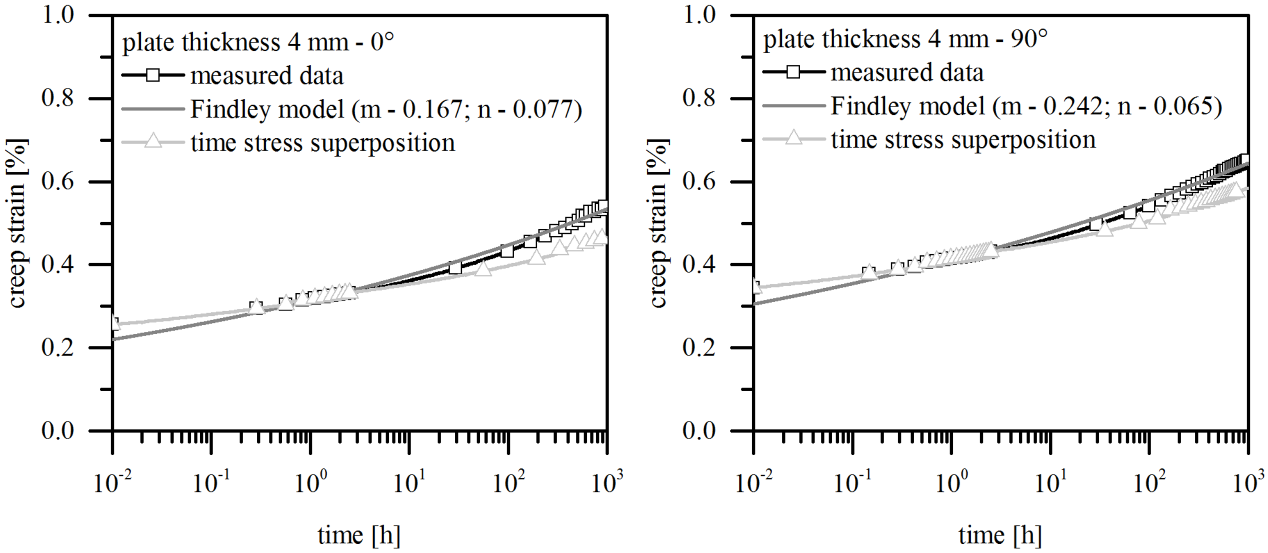

Figure 11: creep curves with experimental data, Findley model and time stress superposition for stress of 15 N/mm² and test specimen directions of 0° (left) and 90° (right)

INTEGRATIVE SIMULATION OF FAN IMPELLER

To predict the long-term and time-dependent stresses and strains of a fan impeller, an integrative simulation method is outlined in the following.

Figure 12 illustrates the integrative approach. At the beginning the fan geometry is generated and read in the flow simulation and injection molding simulation software. For the flow simulation the conveying volume, pressure increase, and rotational speed are considered for the simulation. To simulate the injection molding process the thermal and rheological properties of the material, e. g. the viscosity, heat capacity, heat conductivity, and pressure-volume-temperature behavior are measured and included. Moreover, the process parameters are taken into account. As a result of the flow and the injection molding simulation, a pressure profile on the fan surface and the fiber orientation, as well as weld lines within the fan are obtained. The results of the flow and injection molding simulation are mapped onto the mesh of the structure simulation. Additionally, the operational loads induced by the rotational speed and the anisotropic creep behavior are taken into account. As the Findley model correlates very well with the experimental data, this model is implemented to describe the creep behavior of the used fiber reinforced polypropylene.

The simulations are accompanied by experimental validations, specifically, for the fiber orientation and the total and local deformations of the fan impeller in use.

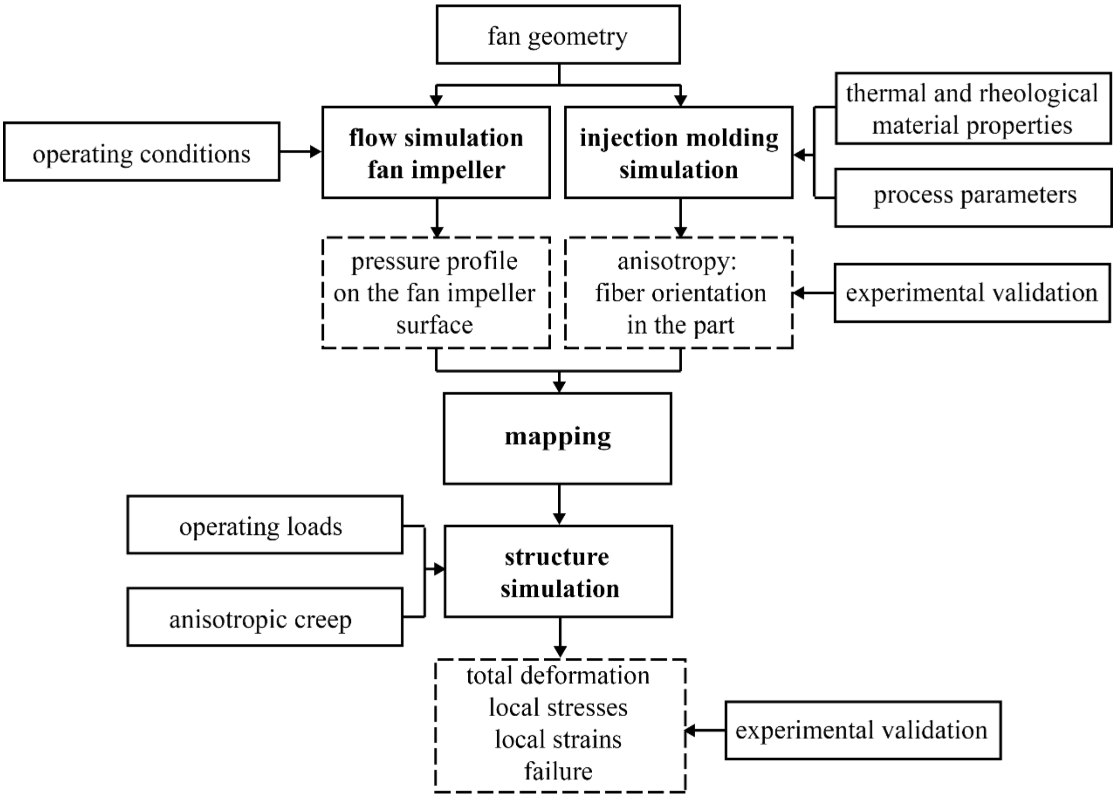

Figure 12: integrative approach to determine the time-dependent and anisotropic creep behavior of fan impellers

CONCLUSIONS

Based on the observed behavior of the used material, the following conclusions can be drawn.

- In addition to the intrinsic anisotropic behavior of fiber reinforced thermoplastics, the process and part geometry influences the anisotropy significantly. The smaller the flow cross section the higher the occurring anisotropy. This point should already be considered during the part design.
- For the investigated fiber reinforced polypropylene, the creep strain shows the same effects of anisotropic behavior as the short term tensile tests. In longitudinal mold direction less strain occurs than in in the transverse direction.
- The Findley power law model describes the creep behavior very well. With TSS method, a master creep curve is obtained with much less time effort compared to long-term creep measurements. Nevertheless, the horizontal shift carried out is not able to predict the creep behavior sufficiently from short term creep data. Additionally to a horizontal shift, a rotation of each short term creep curve might help to predict the creep behavior better. Nevertheless, there is no physical basis on which the rotation is performed and a rotation was not carried out.
- With the integrative simulation method a cohesive approach is presented, considering the different influences onto the deformations and stresses for a fan impeller in use. By applying such an approach at the beginning of the development process, iteration loops can be minimized, and the fan efficiency can be increased by making use of the material properties.

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