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Targeted Manipulation of Fibre Orientation Through Relative Movement in an Injection Mould

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Abstract. The injection moulding of fibre-reinforced plastics leads to a flow related characteristic microstructure with fibres aligned in flow direction in the shell layers and fibres aligned transversely to the flow direction in the core layer. The combination of a design related gate location and the flow related microstructure can lead to an unfavourable fibre orientation. For example, the flow direction for rotationally symmetric parts under internal pressure is often in axial direction and therefore the main fibre orientation is transversely aligned to the critical tangential tension. This leads to high wall thicknesses, increase in weight and material inefficiency. This paper shows first results of the targeted manipulation of the fibre orientation for long and short fibre reinforced thermoplastics through relative movement. The relative movement of opposing mould surfaces is realised through a rotating core in the injection mould and allows the reorientation of the fibres in tangential direction through shearing of the melt. The evaluation of this process is done by mechanical tests, microscopic investigations and computed tomography scans and shows a significant increase of transversely aligned fibres.

Keywords: Injection moulding · Fibre-reinforced plastics · Fibre-orientation · Rotating core

1 Introduction

Due to good weight-specific mechanical properties and cost-efficient injection moulding more and more metallic components are being replaced by fibre-reinforced plastics (FRPs). Thus, necessary weight reductions can be achieved for example in the automotive sector. Examples of applications include media-carrying components in the engine compartment, for which the plastics must not only fulfil the high temperature but also the mechanical requirements like internal pressure [1, 2].

For the highest possible material efficiency of fibre-reinforced plastic parts, the majority of the fibres should be oriented along the load path. The fibre orientation of short and long fibre-reinforced plastics in the injection moulding process, however, depends on the flow conditions and the gate location. The wall adhesion of the polymer melt causes a parabolic velocity profile during the injection process (see Fig. 1).

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The resulting strain of the melt in tangential direction and shearing in radial direction cause a symmetrical layer structure of the fibres [3, 4]. In this structure the fibres in the core layer orient themselves perpendicular to the flow direction and in the outer layers parallel to the flow direction. The characteristics of the layers depend, among other things, on the wall thickness, the fibre content and the process parameters [5].

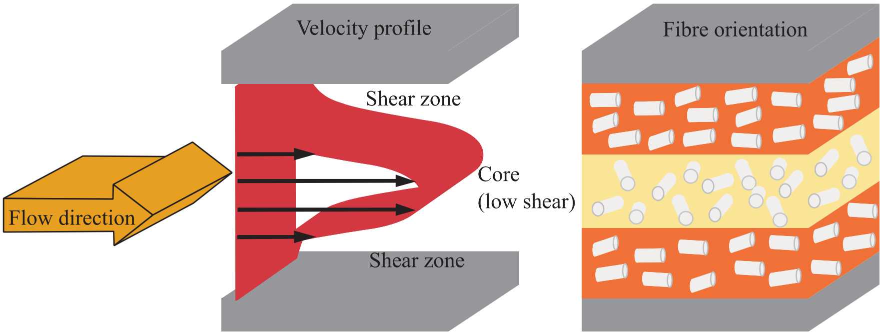

Fig. 1. Velocity profile and resulting fibre orientation over the cavity cross section according to [3]

For rotationally symmetrical components under internal pressure, the tangential stress σ_t is twice as much as the axial stress σ_a (see Eq. 1).

$$\sigma_t = 2 \cdot \sigma_a \tag{1}$$

In order to realize an optimum use of the material, the majority of the fibres in fibre-reinforced components under internal pressure should therefore be oriented in the tangential direction. Due to their demouldability and for prevention of weld lines, such components are often injected in axial direction. As a result, the majority of the fibres are oriented in the same direction. According to Eq. 1, this results in oversizing of components in axial direction if they have to withstand a certain internal pressure.

A rotating tool core can be inserted into rotationally symmetrical components to orient a large part of the fibres in the loading direction. The rotary motion causes a relative movement of the opposite cavity surfaces, which leads to a shearing of the polymer melt. The superposition of this relative movement with the shear flow of the melt during the injection process allows the reorientation of fibres into the tangential direction.

[6–9] show first investigations to this technology. [6] shows the possible reinforcing effect on unreinforced polyolefins. [7, 8] prove that the bursting pressure strength of a rotationally symmetrical cylindrical component made of glass fibre-reinforced PA and PPS can be increased by the rotating core. [9] shows the practical application of this method on a carburettor housing, where the burst pressure strength and the impact strength in the area of a weld line could be improved.

This technology itself was not further scientifically investigated or practically implemented by [6–9] in the following. The investigations shown in this paper have taken up this technology again, investigated it scientifically and furthermore applied it to long-fibre-reinforced materials.

2 Process Implementation and Experimental Procedure

2.1 Process Implementation

At the beginning of the investigations, a suitable test specimen was developed which, despite its idealized geometry, has a certain practical relevance (see Fig. 2a). The cup-like demonstrator has a length of 100 mm, a final diameter of 57 mm and is evenly filled through a screen gate. Due to the uniform filling the shear exerted by the rotation of the core affects the polymer melt over the entire component length and circumferential direction (see Fig. 2b). Because of the relative movement between the cavity surfaces, the injection-induced velocity profile of the polymer melt is superposed on the shear induced velocity profile caused by the rotation. This superposition leads to a higher degree of orientation of fibres in tangential direction.

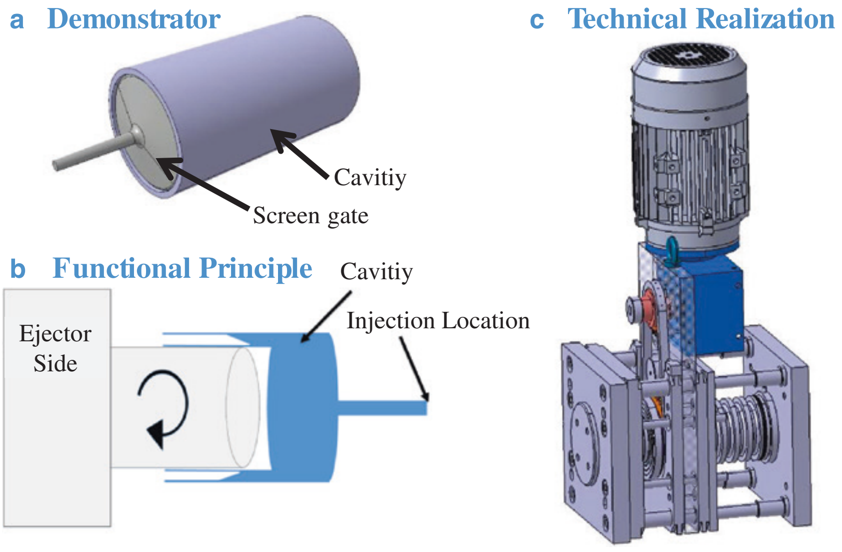

Fig. 2. Demonstrator part, functional principle and technical realization of the injection moulding with a rotating core (source: University of Applied Sciences Osnabrück)

The technical implementation is shown in Fig. 2c. An electric motor mounted on the tool transmits the unidirectional rotational movement via a chain gear to the mounted tool core. A frequency converter, whereby different rotation speeds can be realized, controls the motor. The signal for turning is transmitted to the frequency converter by the injection moulding machine Arburg Allrounder 270 c golden edition, Arburg GmbH + Co KG, Loßburg, Germany. The rotation starts 1 s before the injection process, so that the desired speed is reached at the beginning of injection. The rotation time afterwards is variable.

2.2 Experimental Procedure

The described tool concept was used to investigate a short glass fibre-reinforced polypropylene (PP) with a fibre weight content of 30%, a short glass fibre-reinforced polyamide (PA) with a fibre weight content of 50% and a long glass fibre-reinforced PA with a fibre content of 60% (see Table 1).

Table 1. Overview of the examined materials

Short name	Trade name	Manufacturer
PP GF30	Polyfort FPP 30 GFC K1079	A. Schulman Inc., Fairlawn, USA
PA GF50	Grivory GV-5H EF black 9915	EMS-Chemie AG, Domat/EMS, Switzerland
PA LGF60	Grivory GV FE 16127 black	EMS-Chemie AG, Domat/EMS, Switzerland

The process parameters in the injection moulding process were based on the manufacturer's data from the data sheets. Subsequently the influence of the rotational speed and the influence of the absolute rotational duration on the mechanical properties of the PP GF30 were investigated. The results of this study, especially the optimal settings for the core rotation, are transferred afterwards to the PA GF50 and the PA LGF60.

3 Experimental Results

The influence of the rotary motion on the fibre orientation can be shown in different ways. On the one hand, the reorientation can be quantified indirectly by the mechanical properties of the component in the tangential direction. On the other hand, microscope images of fracture surfaces show a qualitative change in the microstructure. Furthermore, a direct measurement of the fibre orientation with a computer tomograph is possible.

3.1 Mechanical Tests

Two different mechanical tests were carried out as part of these investigations. First, ring tension tests were performed according to ASTM 2995 [10], in which the influence of the rotation parameters was investigated. In addition, burst pressure tests are carried out, confirming the results for a practical load case.

Ring Tensile Test

For the ring tensile test, specimens from the demonstrator at three different positions have been prepared and then tested in accordance with ASTM 2995. The removal position of the specimens and the test setup can be seen in Fig. 3.

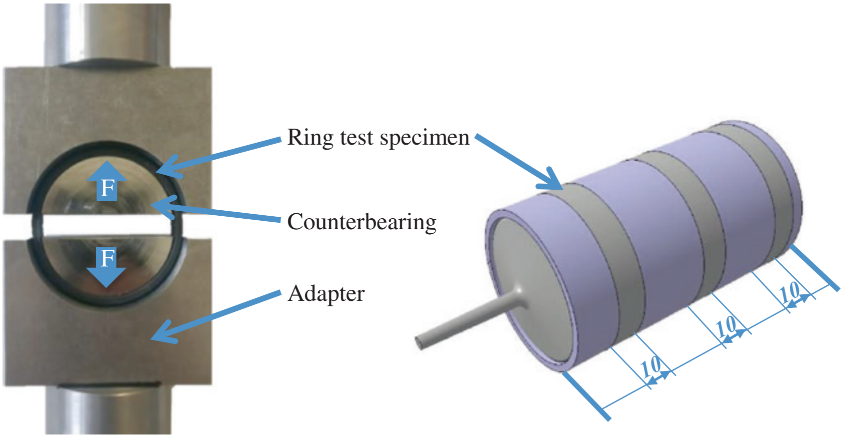

Fig. 3. Test setup for the ring tensile test and sampling position of the test specimens (source: University of Applied Sciences Osnabrück)

Since flexural stresses act to a small extent in addition to tensile stress in this test setup, only the apparent tensile stress $\sigma_{apparent}$ can be determined. This stress results from the ratio of the force F to double the cross-sectional area A of the test specimen (see Eq. 2)

$$\sigma_{apparent} = F / (2 \cdot A) \tag{2}$$

First investigations on the influence of the turning parameters on the apparent tensile strength have been carried out on PP GF30 on test rings from the middle section (see Fig. 4). The influence of the rotational speed of the tool core on the one hand and of the rotational duration on the other hand has been investigated. For the reorientation of the fibres along the entire part, the minimum turning time is equal to the injection time of 2 s. It shows that the apparent tensile strength can be increased by 32% from 45.0 MPa to 59.5 MPa with increasing rotation speed. 1.6 Hz is the maximum rotation frequency with the integrated chain gear, however, based on the increase it can be assumed that further increase in strength are possible with higher speeds.

Furthermore, the influence of the rotation time at a rotation frequency of 1.1 Hz is shown. Here it can be seen that no further increase in strength is achieved with rotation durations of more than 3 s. In Addition, when rotating during the holding pressure phase, a significant increase in standard deviation occurs.

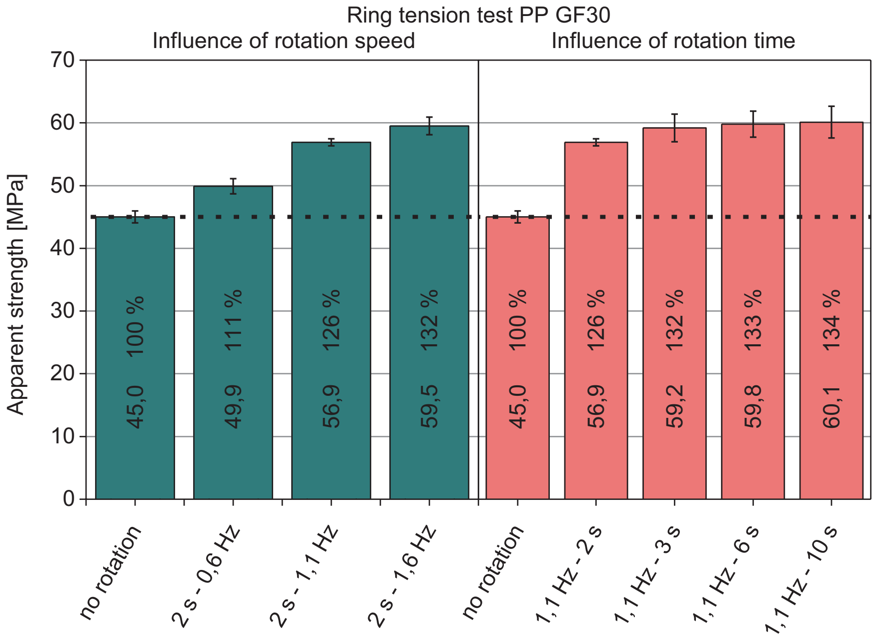

Fig. 4. Apparent strength of PP GF30 – Influence of rotation speed and rotation time (source: University of Applied Sciences Osnabrück)

The influence of the turning time is partly contradictory to the findings from [8]. There it is recommended that the rotation only takes place during the holding pressure phase. With the geometry used, a rotation during the holding pressure phase causes no or only a slight reorientation of the fibres. In this phase, the melt front has already reached the end of the flow path. The solidifying edge layers that cool down on the cold mould wall, touch and enclose the remaining melt (see Fig. 5b). Prior to this contact (see Fig. 5a), the cavity surfaces can be moved freely and the melt can be sheared. After the contact of the solidifying outer layers, the demonstrator rotates on the mould core and no further shearing of the remaining melt takes place. This behaviour prevents damage to the microstructure such as delamination at higher speeds or longer rotation times, because the melt is no longer sheared after a certain rotational resistance.

These findings indicate that the influence of the turning time depends strongly on the geometry. If the sheared area via a rotating core of a component is at the end of the flow path, no reorientation is possible during the holding pressure phase. However, if the remaining cavity, which is not affected by additional relative movements, follows after this area, a further reorientation during the holding pressure phase is conceivable.

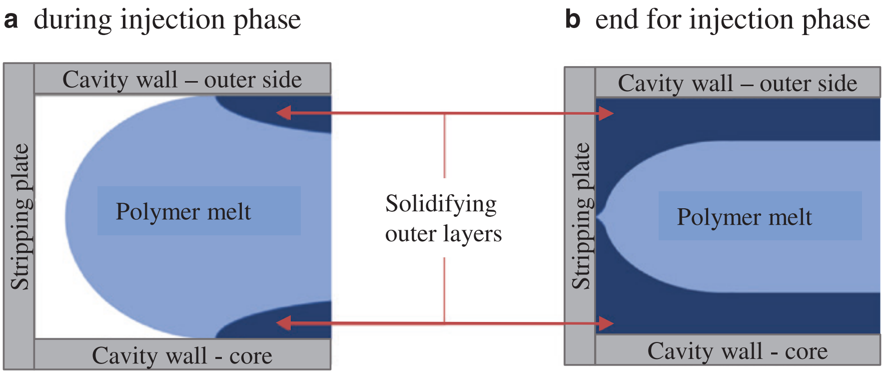

Fig. 5. Free movement of the cavity surfaces relative to each other during the injection phase (a). Solidifying outer layers at the end of the filling phase allow no further shearing of the remaining melt (b) (source: University of Applied Sciences Osnabrück)

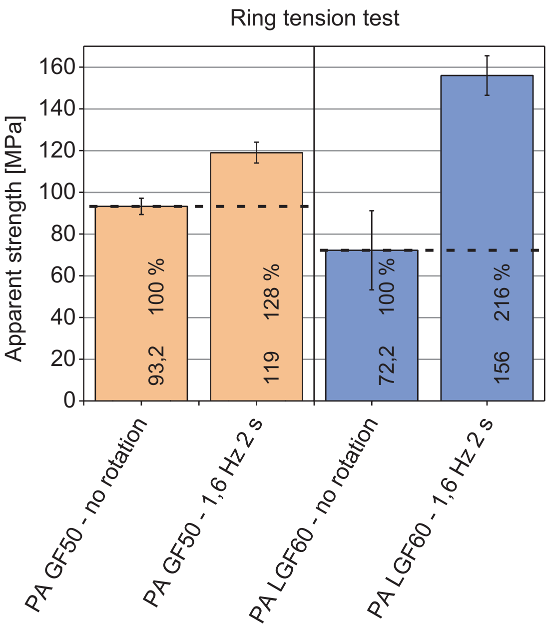

Fig. 6. Apparent strength of non-rotated and rotated test specimens of PA GF50 and PA LGF60 (source: University of Applied Sciences Osnabrück)

A similar increase in strength is possible for PA GF50 (see Fig. 6). Here the apparent tensile strength can be increased by 28% from 93.2 MPa to 119 MPa. The most significant increase in strength can be achieved with long glass fibre-reinforced polyamide. Here, the strength increase achieved is 116%. The high increase in strength of the long fibres can be explained by a rather disordered fibre structure in the non-rotated specimens and a highly oriented fibre network in the rotated specimens. Further investigations regarding the microstructure can be found in Sects. 3.2 and 3.3.

Burst Pressure Test
For the burst pressure tests, a testing device was constructed in which clamping and edge area effects are minimized. In addition, only a defined test area should be loaded during these tests. The schematic realization of this test device is shown in Fig. 7. The test medium can flow into the inner as well as into the outer area of the test specimen. Seals are fitted on the outside at the edge to the test area. This means that out of the test area the pressure applies from outside and inside and thus does not load the specimen. In the test area, the pressure applies only on the inside, which leads to an internal pressure load and ultimately to bursting in this area.

For PA LGF60, the burst pressure strength can be increased from 80.9 bar to 219.5 bar, which corresponds to an increase of 171%. In this test setup, the highly oriented fibre network due to the rotation has an even greater effect on the mechanical properties than in the ring tensile test. The burst pressure test shows that the targeted manipulation of the fibre orientation by relative movements has potential not only for uniaxial loads, but also for practical load conditions.

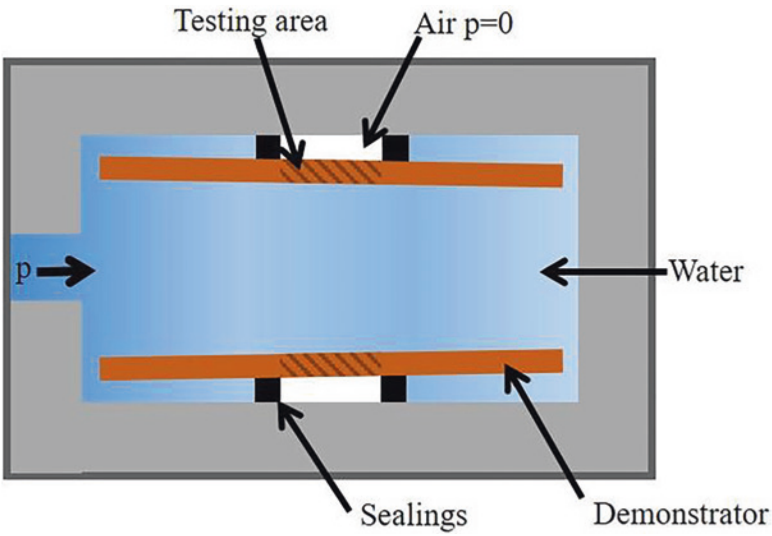

Fig. 7. Schematic realization of the burst pressure testing device (source: University of Applied Sciences Osnabrück)

3.2 Microscopic Investigations

The following microscopic images were taken on fracture surfaces of specimens tested in the ring tensile test. The filling direction in these sections is from right to left. Fibres, which are oriented in axial direction and thus in flow direction, as it is the case in the outer layers, are recognizable as elongated fibres or ellipses. The fibres oriented in tangential direction point out of the image and are therefore only visible as points.

Figure 8 shows the difference between a non-rotated and a rotated sample for the short fibre-reinforced PAGF50. The 3-layer structure known from the literature is clearly visible here (cf. Fig. 1). There are strongly noticeable outer layers and a small core layer no the non-rotated sample. The rotation of the tool core at 1.6 Hz shows a strong change in the microstructure. The outer layers are considerably thinner and do no longer show such a uniform orientation. The amount of fibres that are tangentially oriented and show out of the image has been significantly increased, which is also reflected in the remarkably wider core layer.

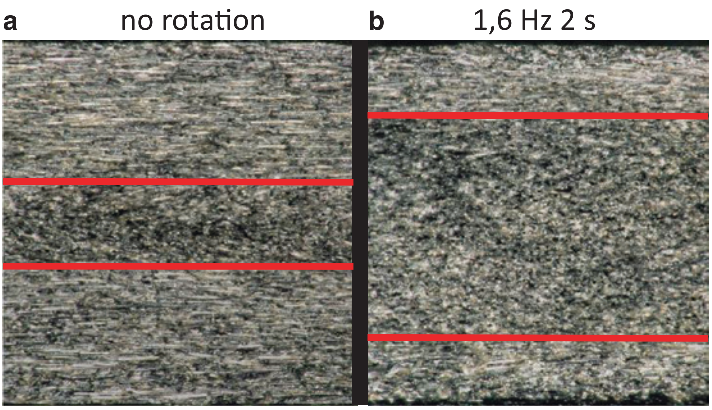

Fig. 8. Microscopic image of the fractured surface of non-rotated (a) and rotated (b) PA GF50 specimens tested in the ring tensile test (source: University of Applied Sciences Osnabrück)

In the case of the long fibre-reinforced PA LGF60, the microscope images confirm the high increase in strength (see Fig. 9). The fracture surface of the non-rotated specimen (a) also shows a layered structure. In the outer layers a large part of the fibres is oriented in axial direction. In the core layer, in contrast to the PA GF50, there is no or only little orientation in the tangential direction. The majority of the fibres in this unorientated layer lies in the axial and radial direction. As a result, a significantly larger percentage of fibres than in PA GF50 can be reoriented by the relative movement, which can be seen in the rotated sample (b). In comparison to the previous microscope images, no clear layer structure can be seen. Both in the outer areas and in the core, fibres with tangential orientation are predominantly present.

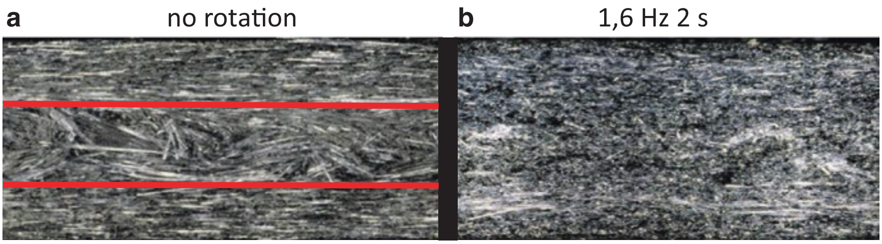

Fig. 9. Microscopic image of the fractured surface of non-rotated (a) and rotated (b) PA LGF60 specimens tested in the ring tensile test (source: University of Applied Sciences Osnabrück)

For the PA LGF60, the core layer with a high axial and radial orientation content in non-rotated specimens means that the strength in the mechanical tests is lower than in the case of the short glass fibre-reinforced PA GF50. At the same time, the process technology with the rotating core can unleash its full potential here and allows a significantly higher increase in mechanical properties.

3.3 Computed Tomography Scan

The mechanical results can also be verified using computer tomographic scans, as Fig. 10 shows. The diagram shows the degree of orientation in axial, tangential and radial direction over the normalized wall thickness for PA LGF60. The non-rotated specimen shows the layer structure known from the literature, which is also partly visible in the microscope images. In the boundary layers, about 80% of the fibres are aligned in the flow direction (axial direction) and only a small amount in the tangential and radial direction. In the core layer, the axial content decreases and the radial and tangential content increases. Here, the tangential component predominates with about 55%, but the orientation is much less pronounced here than in the outer layers. The evaluation of the rotated sample confirms the results of the mechanical and microscopic investigations. There is no noticeable boundary layer left. In the outer areas there are about the same number of fibres orientated in tangential and axial direction. The relative movement results in a highly oriented core layer, which is also significantly wider than that of the non-rotated specimen.

The integral consideration of the fibre orientation shows that the tangential orientation fraction could be increased from 28 to 64%. The axial portion was reduced from 58 to 28%.

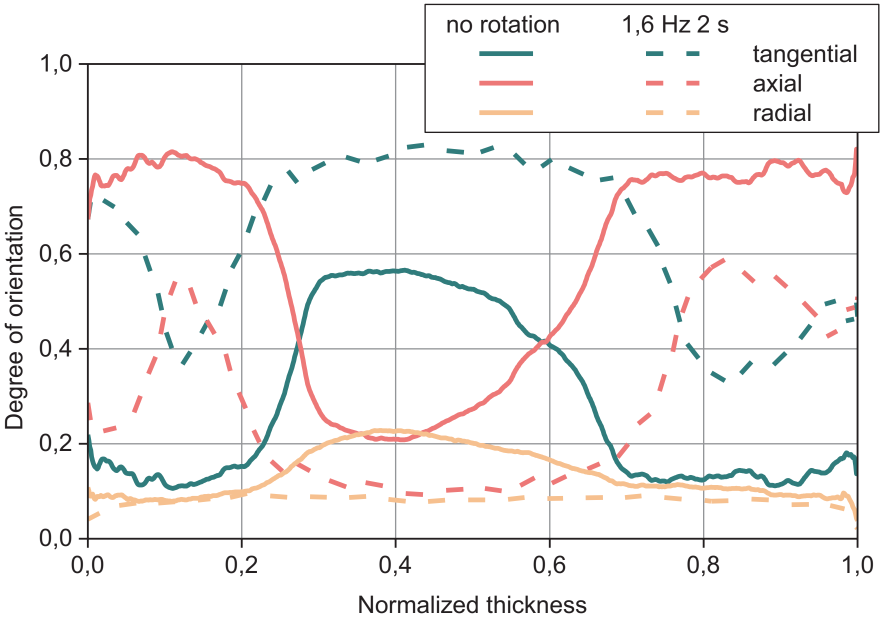

Fig. 10. Degree of fibre orientation over the normalized thickness for non-rotated and rotated PA LGF60 specimens analysed with a computer tomographic scan (source: University of Applied Sciences Osnabrück)

4 Conclusion and Outlook

Within the scope of the investigations, the fibre orientation of reinforced thermoplastics could be manipulated by a concept of a mould system with a rotating core.

Here, the rotational speed has a significant influence on the strength. At higher frequencies, more fibres could be reoriented and the greatest increases in strength could be achieved. It also shows that the maximum has not yet been reached and that higher speeds probably allow a further increase.

Furthermore, it could be shown that with turning times that are significantly longer than the injection time, no further reorientation of the fibres is caused.

Mechanical tests have shown that for PP GF30 and PA GF50 an increase in strength of about 30% is possible. For long fibre-reinforced PA LGF60, the ring tensile strength could be increased by 116% and the burst pressure strength by 171%. These results were verified by microscopic examinations and computer tomography scans.

In the future, the process will be further analysed. Investigations at different wall thicknesses and higher speeds are planned. This results will also be used to develop a design methodology for components that are to be manufactured with a rotating core. These findings will then be transferred to a practical demonstrator component as part of a research project.

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