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Investigation on the Fiber Compounding with a New Type of Compounding Machine

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Abstract. Nowadays, the use of fiber reinforced polymers increases continuously. Endless carbon fiber reinforced polymers are used primarily for products, which require high stiffness and strength while having a minimum weight. The increasing use of these materials results in the issue of production and after lifetime waste recycling. Due to the high costs for carbon fibers the recycling is reasonable from the economic point of view. Currently there are different strategies to reuse carbon fibers. One of them is processing carbon fiber waste in twin screw compounders for the production of short fiber reinforced polymers. One of the main issue during this process is the distributive mixing of the fibers and the fiber degradation of carbon fiber waste which is mostly available as cutted fabric.

In order to achive higher fiber lengths while having evenly distributed fibers in the polymer matrix, a new type of compounding machine typically used for recycling of domestic plastic waste is investigated. In a first step the flow region of the machine is calculated numerically. With a particle tracking method that is based on the numerical flow calculation the distributive mixing behavior is determined. In the experimental part the compounding of glass fibers (chopped strands) in a Polypropylene matrix is investigated. Different pre-mixtures of granulate and fibers with fiber proportions of 20%, 30% and 40% are prepared and processed using different parameter settings. For every processing point the fiber length distribution and the fiber mass proportion in the produced granulate is measured. By analyzing the different results the homogeneity and the fiber breakage is determined. Finally there is a comparison between the material properties of the conventionally produced material in the twin screw process and the material produced with the aforementioned machine.

INTRODUCTION

The last few years have seen continuous growth in the sales of glass fiber-reinforced thermoplastics. The main driving factors for the increasing use of composites are their superior mechanical properties compared to unreinforced plastics. Their density is not much higher than that of unreinforced plastics so if the weight-specific mechanical data are determined, the significant lightweight construction potential of fiber-reinforced plastics becomes evident. Parts made of such composites must, however, not only have high lightweight construction potential, their production needs to be economical as well. Fiber-reinforced thermoplastics have the greatest potential in this area because, compared with matrix polymers that have to be crosslinked, shorter cycle times can be achieved during the processing. [1]

For the compounding of fiber-reinforced plastics, predominantly twin-screw extruders (TSE) are used. The process unit of the extruder consists of a cylinder with two screws whose rotational movement takes place in the same direction [2]. The main tasks of the extruder are conveying, melting and mixing [3].

During the processing of fiber-reinforced plastics a homogeneous distribution of the fibers is achievable by distributive mixing. However, dispersive mixing is not required to break up the fiber bundles, as they decompose into single filaments by distributive mixing when the sizing system is selected properly [4]. Excessive shear, however, leads to a reduction in fiber length. The shearing forces have to be minimized when mixing the fibers. To achieve this aim optimized shear mixing elements are used and the fibers are added at the end of the process length of the extruder [5].

The twin screw process is an established process used to incorporate fibers into a plastic matrix. The big advantage of the system technology is the modular screw and cylinder design, which makes it possible to adapt the system technology to the corresponding compounding conditions [3]. In this paper a different way to compound fiber reinforced polymers is presented, which includes a machine with rotatory moving discs and radial material flow.

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WORKING PRINCIPLE

The main process unit of this machine consists of a rotating and a fixed disc, which both are cooled actively. The geometry of the fixed disc is characterized by a central hole through which a screw conveyor directs solid material into the space between the disc pair. Furthermore, bars are mounted on the disks and grooves are embedded on the surface. These elements contribute to return the material towards the center. The discs have different conicities, so the shear gap reduces radially from the inside towards the outside of the disc pair. The melting of the material is achieved exclusively by the introduced dissipation energy. The molten material is forced outwards by centrifugal forces. A good homogenization of the material is achieved as the bars and grooves constantly convey portions of the material back inwards. As soon as the viscosity of the material drops underneath a specific level, the material is driven outward by the centrifugal forces. At this point it radially exits through the narrow gap between the discs. In general, the material inside the machine is in a transient state between liquid and solid and the material exiting the discs has a non-uniform round shape. The exact flow mechanisms within the disc geometry and the effectiveness of the homogenization of compounds are not clear yet. To describe the exact mixing characteristics of the process CFD simulations are performed.

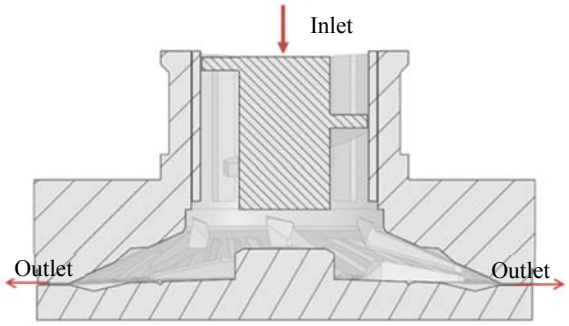

FIGURE 1. Schematic construction of the process area

CFD SIMULATION

During the rotation of the disc the fluid domain geometry changes which results in a transient flow field. The calculation of the flow field is performed with discrete angular positions of 5°, resulting in 72 angular positions per revolution. As the disk geometry features a 60° symmetry, however, the flow field only has to be calculated for a rotation of 60°. During the isothermal simulation the flow properties are modeled using the power-law approach (Eq. 1) for a polyamide 6, (K = 250 Pa * s, n = 0.9). The disc speed is set to 600 rpm.

$$\eta = K * \dot{\gamma}^{n-1} \tag{1}$$

The transition state of the material between liquid and solid is incorporated into the simulation by a higher viscosity of the material compared to usual injection molding grade PA6.

The complex flow is described by a separate analysis of the individual velocity components in cylindrical coordinates (Figure 2). This procedure is used to simplify the complex three-dimensional material flow into single components, especially to analyze material flows which cause mixing. However, the consideration of an axial section only shows a small section of the entire model domain and is therefore only of limited suitability for a comprehensive description of the flow processes or their mixing behavior. An appropriate approach for the consideration of the entire flow domain are isolines. If a certain flow velocity is predetermined, this results in a three dimensional surface in the model space which encloses a flow region with the predetermined minimum velocity. From the location and the relative position of these areas qualitative conclusions about the occurring flows can be gained. The limit values for the three dimensional surfaces are 100 mm / min (red) and -100 mm / min (blue) for axial and radial velocity components (figure 3).

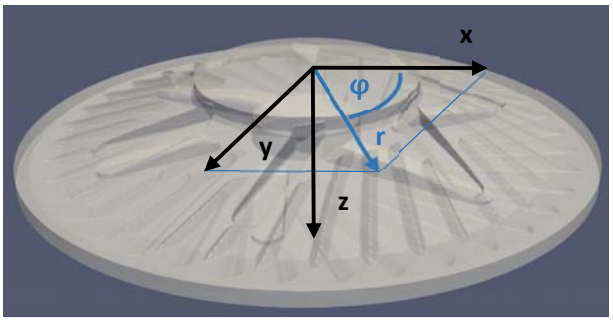

FIGURE 2. Cylindrical coordinate system for the disc geometry

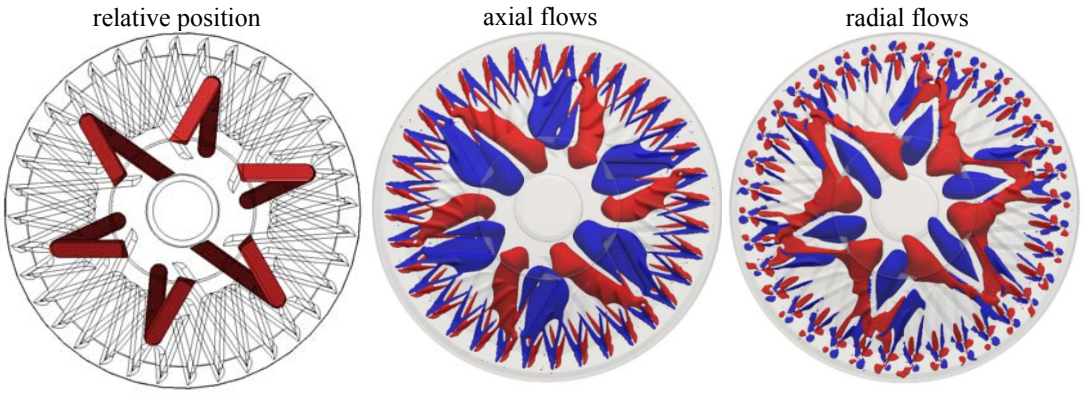

FIGURE 3. Material flows in the fluid domain expressed by isoline surfaces

With the help of the isolines the mixing currents become visible. Figure 3 shows the occurring radial and axial flows for one disk position which cause mixing. The currents are caused in particular by the eccentric arrangement of the bars, whereby during the rotation of the disc, a material accumulation occurs in front of the bars. The pressure increase in front of the bars results in an inwards-directed material flow as well as an overflow over the bars. Behind the bar an inflow of material takes place due to the pressure difference in front of and behind the bar. These flow effects in the radial and axial direction occur periodically. The grooves on the disk surface also cause a radial as well as an axial flow. This can be seen especially in the outer regions of the fluid domain, which is characterized by a narrow gap due to conicity of the discs.

Due to the periodically change of the radial and axial flow components a shifting of fluid elements, which then experience a changed shear flow situation, occurs. In this way, fluid elements are radially and axially distributed and can be thinned and superimposed by the shear flow at new position.

In order to make a quantitative statement about the mixing effect of the machine, the qualitative consideration of the flows and their effect interpretation on the mixing effect is not sufficient. To determine the mixing effect, a particle tracking of massless particles is performed. For this purpose, four addition areas (spheres of 3 mm radius) are defined within the fluid volume at which particles are continuously added during the rotation. Due to the inhomogeneous addition of particles, the mixing effect of the process can be determined afterwards. Per angular position, 50 particles are added into the fluid volume per addition area. For a complete revolution a total amount of 14,400 particles is added.

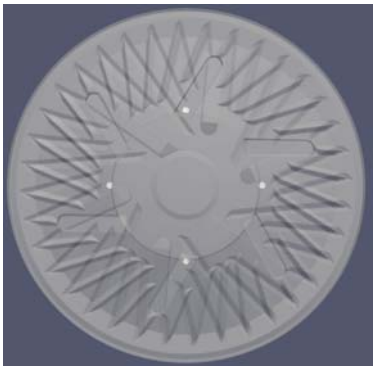

FIGURE 4. Positions of particle adding

The particle movement within the fluid volume is defined by the respective velocity field. Since the simulation is a transient velocity field, interpolation takes place between the flow fields of the discrete angular positions to determine the position caused by changes in the velocity field.

The distribution of the particles within the fluid domain after 7 seconds of operation is shown in Figure 5. Within the fluid domain, the particles are distributed from the addition area inside towards the feeding area, and outward toward the material outlet. This behavior results from the radial flows in inward and outward direction (Figure 2). Additionally a particle distribution along the circumference is visible, which is caused by tangentially acting flows as a consequence of the rotation of the disc.

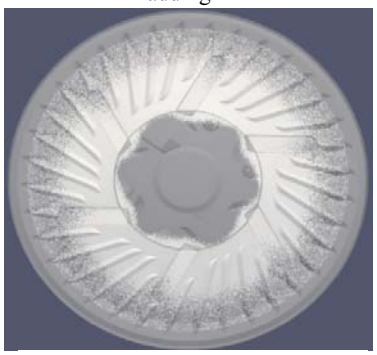

FIGURE 5. Particle distribution after 7 seconds process time (5040 angle steps)

For the qualitative determination of the mixing quality, the fluid domain is first divided into elements of equal area. The gap between the discs is used to calculate the volumes for these elements. In the following, the number of

particles x_p in the individual volumes V_i is determined and a particle concentration x_i per volume element is calculated with eq. 2.The consideration of the mixing effect takes place zone by zone. A zone indicates the area between two radial lines over the entire circumference. Since the radial resolution includes 30 radial lines, 30 zones with 120 cells each are distinguished. For the zones, the mean concentration value and the standard deviation is calculated with eq.3 and eq. 4

$$x_i = \frac{x_p}{V_i} \tag{2}$$

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{4}$$

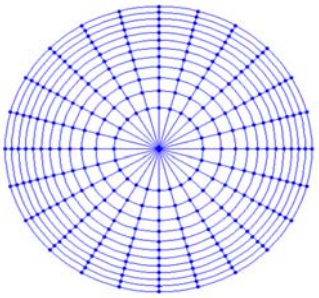

FIGURE 6. Segmentation of the fluid domain in equal areas

Since particles are continuously added into the system and accordingly different numbers of particles are present at different time steps, the standard deviation and the mean are normalized to the number of particles in the system. By using the normalized mean value $\bar{x}_n$ and the normalized standard deviation σ_n the comparability of different time steps is given. The normalized standard deviation and the normalized mean value are two quantities with which no direct statement can be made about the homogeneous distribution of the particles. In order to describe the distribution of the particles, we use the variance ν, which represents a quotient of these quantities.

$$\nu = \frac{\sigma_n}{\bar{x}_n} \tag{5}$$

The variance of the particle concentration (y-axis) per radial zone (x-axis) for the process is shown in figure 7. The lower the variance in the radial zones, the better the mixing effect in these areas. By considering the variances for the different time steps, it becomes clear that no significant change occurs after 720 time steps in the outer radial zones. This means that after this time, a steady state value of the mixture is reached. With a variance of 0.4, a very homogeneous mixture is achieved here. In the inner radial zones, a large variance can be seen, which is due to the uneven distribution of the addition areas.

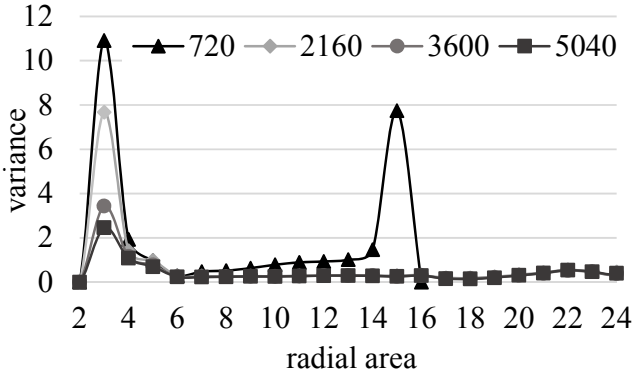

FIGURE 7. Variance of particle concertation for radial zones with increasing time steps

EXPERIMENTALS

The theoretical analysis shows that in terms of homogenization the process is very well suited for compounding. In addition to the homogenization, however, the resulting fiber length in the material is a value that must be taken into account in the compounding. In order to determine which material properties are achieved in the process, dry blends made of glass fibers (ChopVantage HP3270, 4.5 mm) and polypropylene (Lyondellbasell Moplen HP500N) are compounded. Different fiber contents of 20% (GF20), 30% (GF30), and 40% (GF40) are used for the compounding.

First of all, machine parameters for an optimized processing window are determined. Parameters which can be varied are the gap between the discs and the disc temperature. It is found that a disk temperature of 28 °C contributes to a high quality of the material. Higher temperatures lead to a lower viscosity, which causes sticking of the material after it leaves the disk. An optimal disc spacing is between 1.2-1.8 mm. If larger gaps are selected only a part of the fibers is incorporated into the matrix.

Compounds are produced with the aforementioned machine parameters. By determining the fiber content of the material and the respective standard deviations of the individual samples, the inhomogeneity of the material is

analyzed. Furthermore, a determination of the fiber length in the produced material takes place to analyze the fiber breakage during the process.

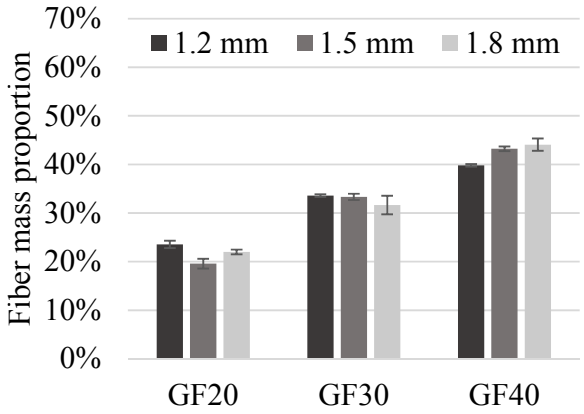

FIGURE 8. Fiber mass proportion for produced materials

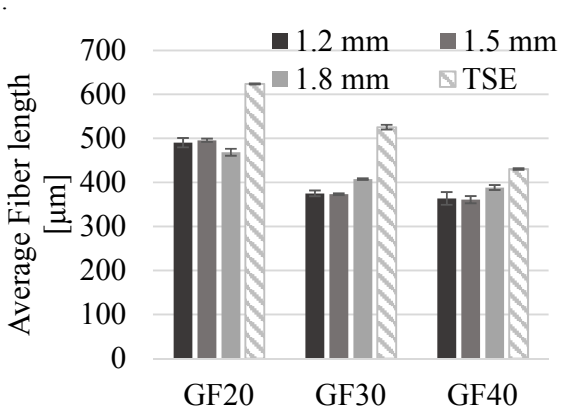

FIGURE 9. Average fiber length for produced materials

The measurement of the fiber content in the samples (figure 8) shows that the target fiber mass proportions (20%, 30%, 40%) are almost reached. The occurring deviations from the target value result from the manual production of the dry blends. For the different distances between the disks, fiber contents are nearly equal, which shows that the fibers are completely incorporated into the matrix. The small standard deviations of the individual samples for the experimental points make clear that there is a homogeneous material. This supports the statement of the particle simulations.

The average fiber length for the different disc distances and materials is shown in figure 9. It becomes obvious that the disc spacing has no significant influence on the fiber length. Only the fiber content affects the resulting fiber length. To obtain a comparison for compounding in the twin-screw extruder (TSE), fiber lengths for granules produced in this process are also shown in the diagram. The comparison of the fiber lengths shows that a shorter fiber length reduction takes place in the twin-screw process. This is a result of the different addition mechanisms of the fibers and the different shear conditions.

PROSPECTS

During the processing of the dry blends a very good homogeneity is achieved. However, compared to the compounding with the twin screw machine there is a strong fiber length reduction during the process. By changing the rotational speed of the machine this length reduction shall be prevented. In future, this machine shall be used for processing recycled carbon fibers. Here the good mixing propertied shall lead to a break up of the fiber bundles and the fiber fabric.

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