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Processing Short Fiber-reinforced Polymers in the Fused Deposition Modeling Process

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Abstract

By adding fibers to a polymer matrix, a reinforcement of the material can be achieved. Short fiber-reinforced polymers can easily be processed by the Fused Deposition Modeling (FDM) process without major modifications to the processing machine. For instance, short fiber-reinforced filaments can be processed to produce short fiber-reinforced components in the FDM process. In many other additive manufacturing processes this is not possible at this low cost. The choice of the matrix material, fiber type, fiber length and fiber orientation have a major influence on the properties of the produced component. In this paper, short fiber-reinforced filaments are processed by the FDM process. The processing properties and the resulting part properties are investigated with regard to fiber-specific influences. Additionally, the effects of different strand geometries and thus changed flow fields on the fiber orientation and mechanical part properties are investigated.

Introduction

The addition of reinforcing materials can significantly influence the processing and material properties of polymers. In the case of fibers as reinforcing materials, not only the type and content, but also the fiber orientation have a significant influence. When using short fiber-reinforced thermoplastics, a process-specific and flow-related alignment of the short fibers is expected, depending on the process (e.g. investigated in [MG82] or [GW93] for the injection molding process). With conventional processing methods like the injection molding process, a short fiber reinforcement can be realized by the processing of short fiber-reinforced granules.

In the FDM process, the semi-finished product is a filament of a thermoplastic polymer. This is melted and forced through a nozzle. The continuous positioning of the nozzle allows the polymer to weld together strand by strand and layer by layer to produce a component. The energy for the welding of the individual strands largely results from the thermal energy of the deposited polymer melt and, if present, from a heated chamber (cf. [YHG+97]). Due to this process principle, the processing of short fiber-reinforced polymers can be realized with little effort by the processing of short fiber-reinforced filaments as semi-finished products. A process-specific fiber orientation because of the characteristic strand deposition principle can be expected and has been shown in [TKV+14]. Also the processing of continuous fiber-reinforced materials by FDM is possible with the aid of special machines as shown in [DBM+17] or [vKT+16].

In this paper, the influences of filled and short fiber-reinforced filaments on the processing properties and attainable mechanical part properties in the FDM process are investigated. For this purpose, different materials based on polyamide 6 (PA 6) are investigated. The fiber length and fiber orientation are measured in the semi-finished product (filament) and in the FDM part. The mechanical properties of the parts are tested for different PA 6-based materials reinforced with different filler and fiber types. Additionally, some processing parameters are varied to produce different strand geometries and different flow fields during the strand deposition. The effects on the fiber orientation and the mechanical properties are investigated. The materials used in this project were provided by the company ALBIS PLASTIC GmbH. The project is conducted in cooperation with the company ALBIS PLASTIC GmbH under the NRW "Fortschrittskolleg Lightweight – Efficient – Mobile" (FK LEM).

Experimental approach and test methods

The FDM process can be understood as a constantly repeating welding process. To produce strong components, it is necessary that the strands deposited and welded together in the FDM process form a sufficiently strong connection [Cru89]. The weld strength is therefore an important criterion for comparing the suitability of different materials for processing. In addition to the material, however, the attainable weld strength depends on many effects (cf. [SRB+08]). One reason for this is that, in the FDM process, certain influencing factors occur that affect the production result and the mechanical properties of the part. Such factors can cause fiber-like structures that should be considered (cf. [BG03]) or porosity in the parts. If only a material-related comparison is made, it is necessary to use a test method and a test specimen that allow the manufacturing and testing of a representative weld that can be reproducibly produced in the FDM process [SSG17].

Taking into account a design suitable for FDM manufacturing, e.g. with adequate part stiffness, the structures shown in Fig. 1 are designed and produced in the FDM process. Tensile test specimens of Type 1B according to [DIN EN ISO 527-3] are subsequently cut from defined parts of the structure to avoid significant influencing factors (cf. Figure 1 and [SSG17]). The tensile tests are carried out on specimens produced in the z-direction (cf. Figure 1 right) to identify the weld seam strength and, in the x-direction, to identify the strand strength (Figure 1 left). The tests are carried out on a tensile testing machine according to the specifications in [DIN EN ISO 527-3].

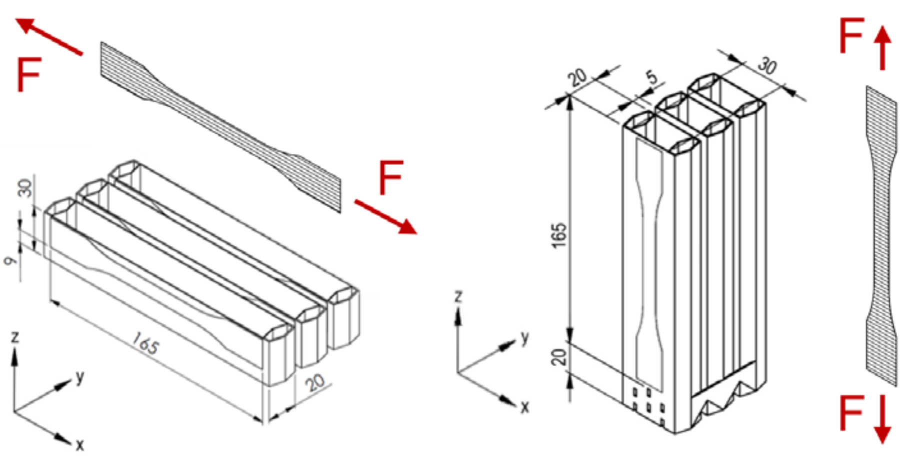


Fig. 1: Tensile bar in the x-direction (left) and z-direction (right)

To enable a proper material comparison in terms of weld seam strength, additional data need to be collected. For this purpose, a microsection (cf. Figure 2) of every specimen that was produced in the z-direction is prepared and the geometries of the strands as well as the resulting weld seam widths are measured optically. The weld width factor (1) is defined and can be used to calculate the actual area of the weld seam when only the width of the strand is measured. Similar approaches to consider the special weld geometries in the FDM process are taken into account by defining a wetting factor e.g. in [CK17]. Another important factor to describe the strand geometry of FDM strands is the w/h-ratio (2) – also known as the aspect ratio. Usually the layer height (the height of a strand) is kept constant and locked to a strand width.

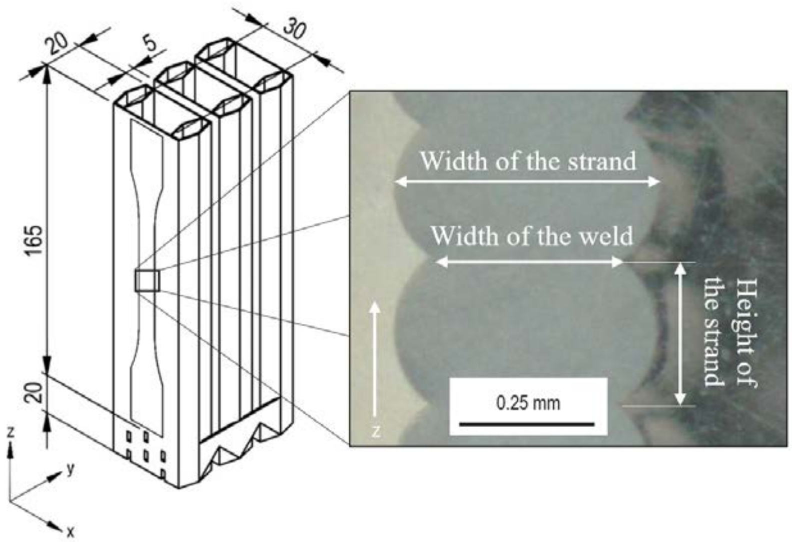


Fig. 2: Tensile bar in the z-direction

$$\text{Weld width factor} = \frac{\text{Width of the weld}}{\text{Width of the strand}} \quad (1)$$

$$\text{w/h} - \text{ratio (aspect ratio)} = \frac{\text{Width of the strand}}{\text{Height of the strand}} \quad (2)$$

Because filled and fiber-reinforced materials are processed during these investigations, additional measurements to identify fiber-related properties are conducted. Computer tomography (CT) analysis is used to measure the fiber orientation. For this purpose a Phoenix nanotom s CT and the VG Studio Max software are used.

Experimental investigations

In this publication, the weld seam strengths of four polymers based on polyamide 6 (PA 6) are tested. Three of the polymers are filled with different fillers with different fiber characteristics. The strength of the fiber characteristics increases from filler type 1 to 3. The fourth polymer is the unreinforced PA 6-based matrix material.

Weld seam strength influenced by fiber reinforcement

Firstly, the attainable weld seam strength (z-direction) is determined for all four materials according to the method described above. The parts are manufactured with a w/h-ratio of 2/1 (cf. Figure 2 and equation (2)), which represents a standard w/h-ratio that is used frequently by many machine manufacturers. The results, shown in Figure 3, therefore already include the weld width factor determined in the microsection. The specified strength values therefore refer to the actual surface area of the weld. Notch factors are not taken into account. In addition, the strand strengths (x-direction, cf. Figure 1 left) of the three filled materials are determined. It is not possible to determine the strand strength (x-direction) of the unfilled (unreinforced) material because the specimens cannot be produced due to excessive material shrinkage and warpage during the production process. The fact that the addition of fillers (or fibers), among other things, reduces the warpage occurring in the FDM has already been shown in [SSF18].

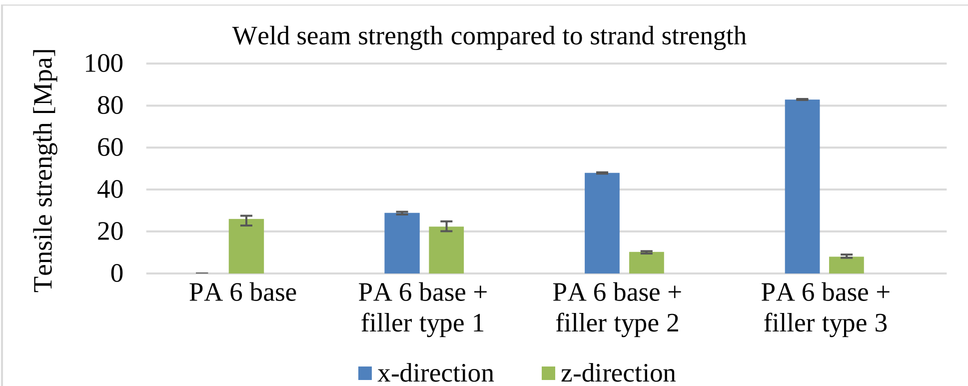


Fig. 3: Tensile tests (w/h-ratio = 2/1)

Figure 3 shows that the weld seam strength of the filled (reinforced) materials is significantly lower than the strand strength (also investigated for different materials e.g. in [ZLZ+01]). This effect increases with a higher fiber character and fiber strength of the filler. The reason for this is the expected fiber orientation in the direction of the FDM strands and orthogonally to the direction of the stress due to the principle of the process. In addition to the effect that the fibers do not form a welding joint, the fibers constitute defects due to their orientation and weaken the welding joint. The fiber orientation is shown in the following chapter.

Fiber orientation for a standard w/h-ratio of 2/1

For short fiber-reinforced parts, the fiber orientation has a significant influence on the mechanical properties. When processing short fiber-reinforced materials in the FDM process, it can be assumed that the fibers would orient themselves along the strand deposition due to the process principle and the flow conditions. This has also been shown in [TKV+14]. To verify this assumption in these investigations, the FDM component in Figure 2, which was manufactured with a w/h-ratio of 2/1, is examined in the CT (cf. Figure 4, right). The material with filler type 2 is investigated because the fibers used in this material can easily be detected with the help of CT measurements due to a sufficient difference in density. In addition, it is shown that the fibers are already aligned in the semi-finished product used by the extrusion manufacturing process (cf.

Figure 4 left). The fiber orientation in the FDM strands (in the FDM part) and in the semi-finished product, the filaments, are shown in Table 2.

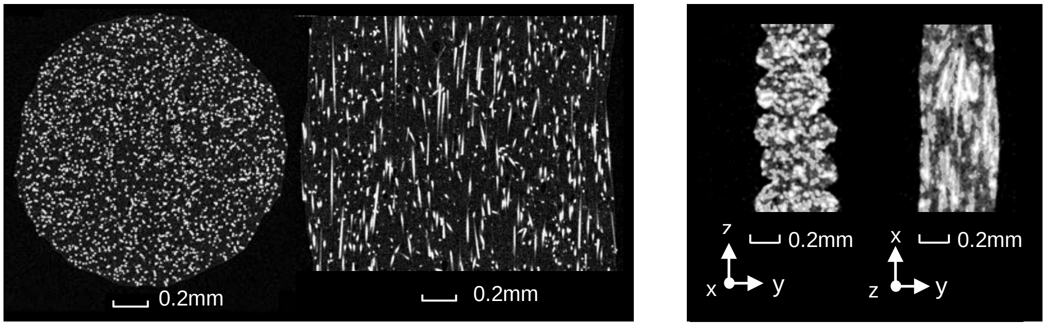


Fig. 4: Fiber orientation in the filament (left) and in the FDM part / strands (right)

Table 1: Fiber orientation (filler type 2)for a w/h-ratio of 2/1

Sample	x-direction (filament-direction)	y-direction (across 1)	z-direction (across 2)
Filament	75%	13%	12%
FDM part	77%	12%	11%

Changing the w/h ratio to influence the flow field and fiber orientation

One possible approach to influence the fiber orientation in the FDM process is to change the flow conditions of the melt. A simple approach for this is to change the w/h-ratio (cf. figure 2 and equation 2). Simulations in [Bel02] also show that the nozzle smoothes the strands deposited in the FDM process, which is why larger w/h-ratios are also possible with a constant layer height. With the use of a constant layer height the strand widths are varied for the following investigations. The FDM components shown in figure 1 are manufactured with w/h-ratios of 5/4 and 4/1 in addition to the already manufactured components with a w/h-ratio of 2/1. At w/h-ratios above 4/1, however, process abortions occur due to the increased material swelling next to the nozzle in the layer above. W/h-ratios of less than 5/4 cannot be produced due to excessive stretching of the deposited strands and insufficient layer adhesion. Figure 5 shows cross sections and CT measurements for the parts that were manufactured with w/h-ratios of 5/4, 2/1 and 4/1.

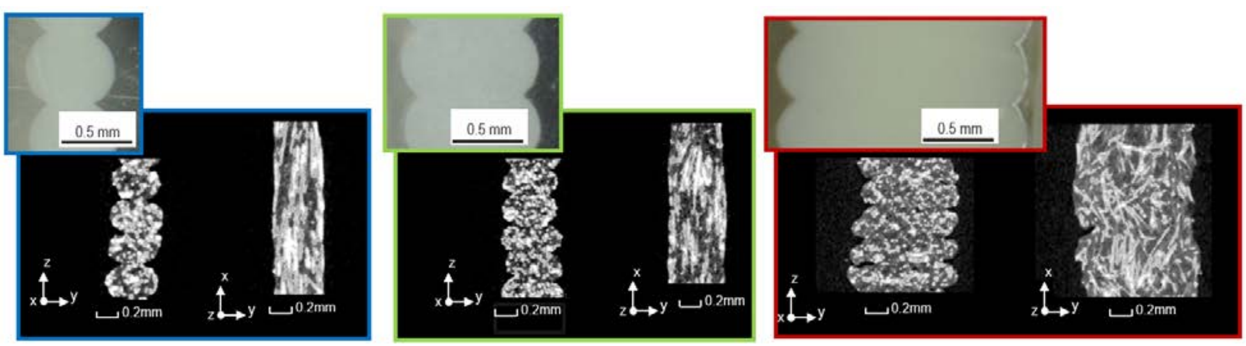
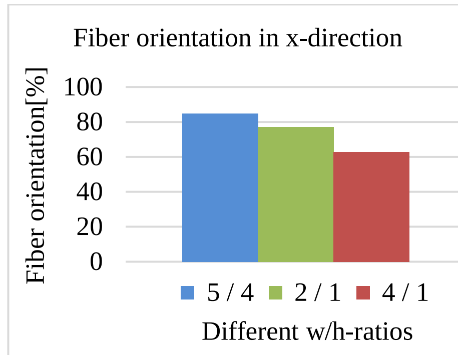


Fig. 5: Fiber orientation for different w/h-ratios (left: 5/4, middle 2/1, right: 4/1)

Table 2 shows the fiber orientation for the different w/h-ratios. The x-direction is the direction of the FDM strand. The measurements show that the fiber orientation in the x-direction (in the direction of the FDM strand) decreases for higher w/h-ratios. The fiber orientation can thus be influenced by varying the w/h-ratio.

Table 2: Fiber orientation (filler type 2) for different w/h-ratios

w/h-ratio	x-direction	y-direction	z-direction
5 / 4	85%	7%	8%
2 / 1	77%	12%	11%
4 / 1	63%	23%	14%



To determine the weld seam strength, the manufactured specimens with the w/h-ratios of 5/4 and 4/1 are tested in the same tensile test setup as the specimen with the 2/1-ratio. The results for the weld seam strength shown in Figure 6 (left) already include the weld width factors. Figure 6 (right) shows that the weld width factors increase with increasing w/h-ratios. Although more fibers are oriented in the direction of the force with increasing w/h-ratio (cf. Table 2, z-direction) the tensile strength decreases for lower as well as higher w/h-ratios than 2/1. Because the w/h-ratio has a huge influence on the weld seam strength as shown in [Klo16] and also in Figure 6 for the non-reinforced PA 6 base material, the influence of the fiber orientation cannot be identified separately. In [Klo16] the weld seam strength increases for a higher w/h-ratio and the tested material. However, a different material was tested with a maximum w/h-ratio of 2.8/1 and no weld width factor (or similar) was taken into account.

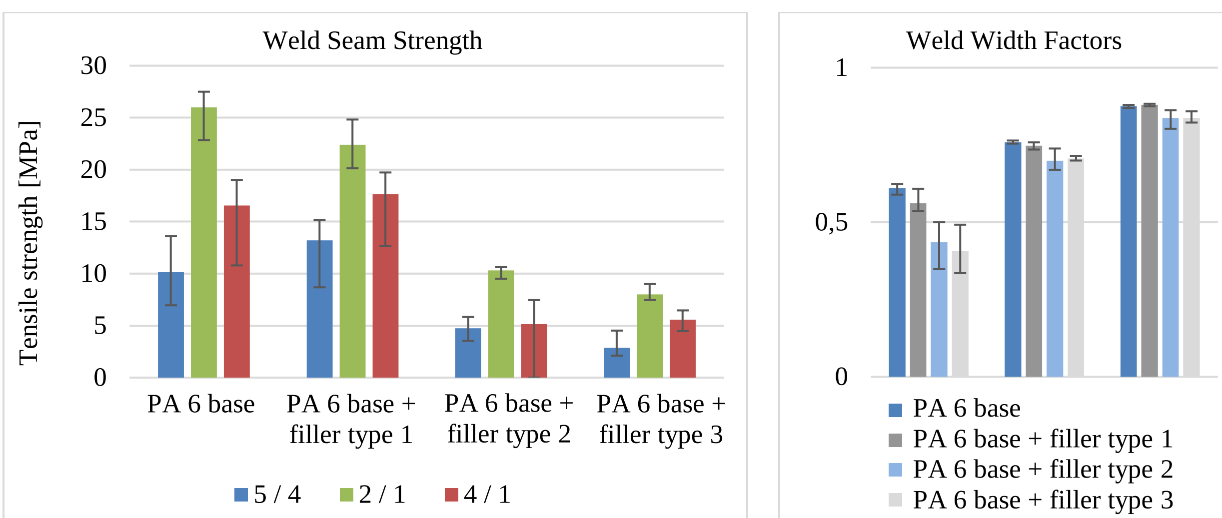


Fig. 6: Weld seam strength for different w/h-ratios

Nozzle erosion due to the processing of abrasive materials

During these investigations, erosion of the FDM nozzle is observed. It turns out that the processing of filled and fiber-reinforced materials increases the wear of the nozzle regarding the diameter. This effect should be taken into account, because different nozzle diameters can affect the production results including the mechanical properties of the components.

In addition to the change in the nozzle diameter as shown in Figure 7, the edges of the nozzle become worn and rounded, especially when using higher w/h-ratios. This is because the nozzle smoothes the abrasive material at higher w/h-ratios.

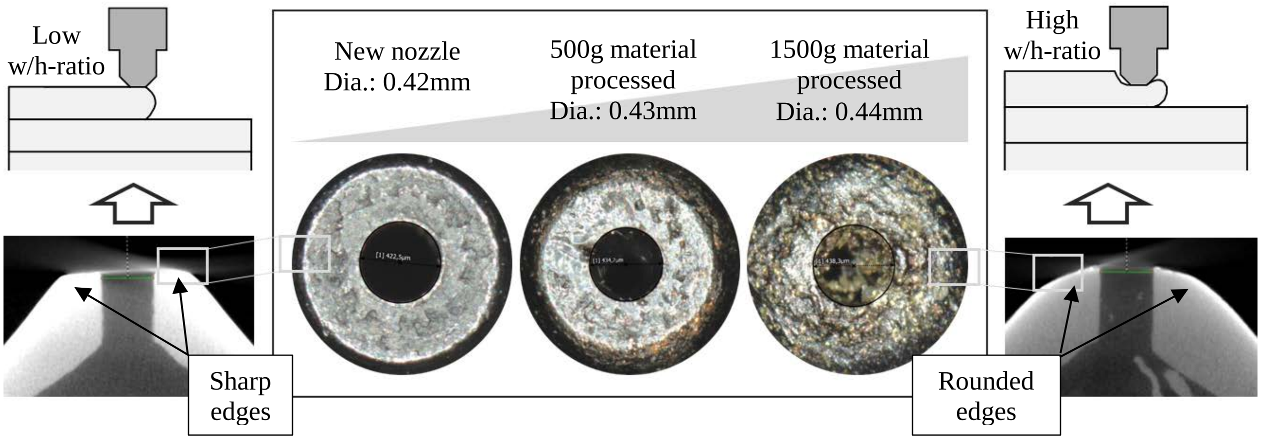


Fig. 7: Nozzle erosion for different w/h-ratios due to the processing of filled materials

Summary and Outlook

The investigations show that it is possible to process short fiber-reinforced filaments by the FDM process to produce short fiber-reinforced components, but that high erosion of the nozzle occurs. As expected, the process-specific fiber orientation occurs mainly in the direction of the deposited FDM strands. This effect decreases the weld seam strength due to fibers that act as notches and the overall reduced area for the weld due to the filler materials (e.g. fibers) that do not act as part of the weld.

The investigations show that fewer fibers are oriented in the direction of the FDM strands when the w/h-ratio is increased. But although more short fibers are orientated in the direction of the force when using higher w/h-ratios, the overall weld seam strength cannot be increased through the use of different w/h-ratios than the standard w/h-ratio of 2/1 for the investigated materials. Also the non-reinforced PA 6 base material achieves the highest weld seam strengths with a standard w/h-ratio of 2/1.

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