Fiber Reinforcement Minimizes Warpage in Large Area Additive Manufacturing

Staying Grounded

In additive manufacturing the material selection plays an important role for producing dimensionally accurate parts. Akro-Plastic developed a method to quantitatively assess warpage in additive manufacturing with pellets, which shows the influence of the material composition and the process parameters in an application-oriented manner.

3D printed: Friederike Schwartz and Michael Rieck from Akro-Plastic checking the quality of a part made of a flame-retardant compound. © Akro-Plastic

Screw extrusion additive manufacturing with pelleted feedstocks (fused granulate fabrication, FGF) offers the possibility of producing large-format components in a short time. By using standard granulates, material costs are significantly reduced compared to filaments. At the same time, the range of printable materials is extended significantly, since materials with high filler contents of up to 60 wt.% or flame-retardant compounds can be processed as well. The FGF process allows for the extrusion of almost all polymers, however, producing dimensionally stable parts is not trivial. Due to the tendency to warp and the thermal boundary conditions during processing, the material range is limited. Unreinforced materials, for example, are subject to high warpage. In the case of high-temperature materials, the part size is often limited, or adapted processing machines are required. Semi-crystalline, reinforced plastics are particularly interesting for technical components, but are more difficult to process. Akro-Plastic investigated the influence of material composition on warpage in additive manufacturing (**Title figure**).

Warpage Takes Effect during the Process

In extrusion additive manufacturing, warpage occurs due to the layer-by-layer build-up and the resultant temperature

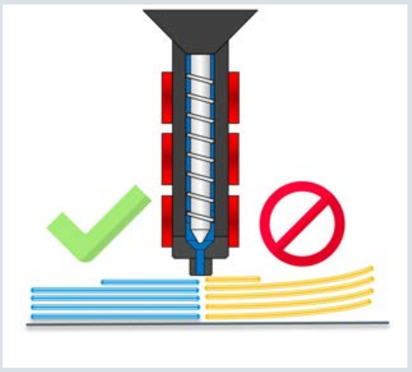

Fig. 1. Warpage can already be an issue in the build process. Source: Akro-Plastic; graphic: © Hanser

and shrinkage differences. The crystallization process of semi-crystalline thermoplastics amplifies the effects. In compounds with low or without reinforcement, the part can detach from the build plate. Severe warping can lead to a collision with the extruder and thus to a failed print or to damage of machine components. Therefore, low warpage is necessary for the defect-free build-up of a dimensionally stable part (**Fig. 1**).

Commonly, warpage is reduced in injection molding by optimizing the process parameters. However, the mold-free process, the low pressures in the process and limited temperature control strictly limit a process-controlled warpage reduction in additive manufacturing. The use of a heated bed and build chamber to minimize warpage is state of the art in filament-based printing. However, applying this kind of temperature management is not economically feasible or even possible in FGF printing, due to the machine size and temperature limitations of machine components. Nevertheless, reinforcing the compound with fibers is a practical approach to effectively reduce warpage. Glass and carbon fibers have a low or negative coefficient of thermal expansion and therefore reduce the shrinkage potential. Furthermore, the stiffness of fiber-reinforced compounds effectively counteracts stress-induced deformation of the component.

The shrinkage of thermoplastic compounds is usually determined based on manufacturing processes. In injection molding, for example, shrinkage is determined with the help of test plates by evaluating the change of dimension relative to the mold. In contrast the final dimensions in FGF are not mold-related but predefined as machine code. Taking into account the repeatability of the traversing systems and flow fluctuations during extrusion, measuring dimensional change to determine shrinkage is not viable.

Manufacturing-Oriented Quantification of Warpage

However, the process-related evaluation of warpage is possible in FGF. One way of doing this is the evaluation of corner warp. The drawback of this method is its strong dependency on print bed adhesion. The method described below allows a quantitative comparison of different materials and the determination of a warp-index (**Equation 1** see page 84) of printed test specimens using image processing.

The test specimen (**Fig. 2**), printed in the FGF-process is designed with trapezoidal test surfaces on three sides. To take different orientations in the build chamber into account, each side is scanned and evaluated separately. The surface structure with orientation and path of the layers is converted into a binary representation and digitally evaluated (**Fig. 3**). The warp-index is obtained as the deviation of the position in the z-direction of each layer in the edge areas of the test surface from the position of the respective layer in the center of the test surface. For each layer, the differences of the center line to the right edge and to the left edge are calculated as an error sum of squares and divided by the number of evaluated layers. The resulting value allows for a quantitative comparison of the warpage of differ- »

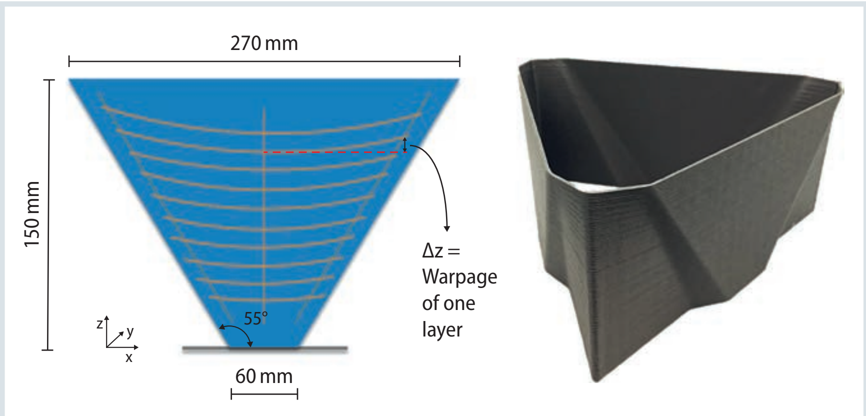

Fig. 2. Dimensions of the test specimen and method of evaluation. Source: Akro-Plastic; graphic: © Hanser

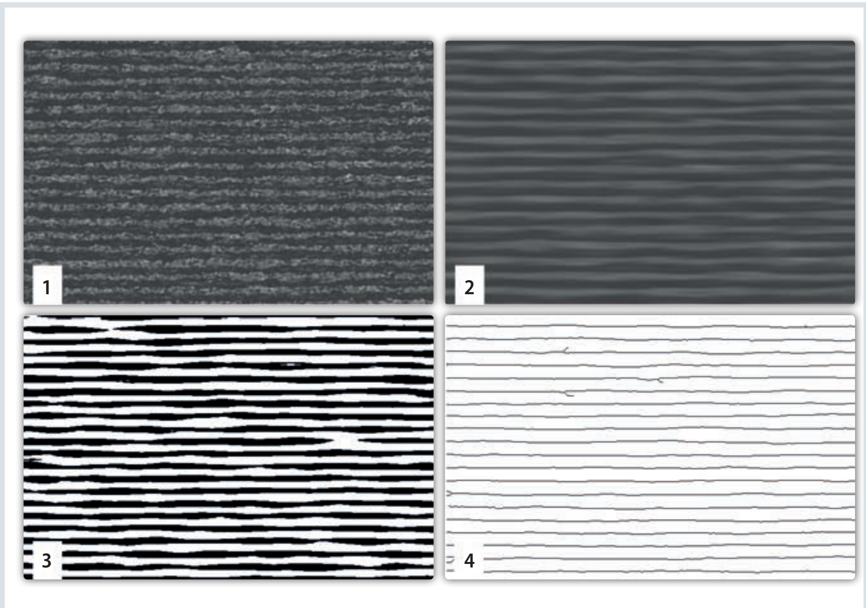

Fig. 3. Image processing for the computer-aided evaluation of warpage. © Akro-Plastic

$$warpage = \frac{\sqrt{\Sigma[(y_i(reference\ line) - y_i(centerline)) \times 1000]^2}}{n}$$

Equation 1. Determination of the warp-index. © Akro-Plastic

ent compounds within the selected process conditions.

The test specimens are printed with a nozzle diameter of 2 mm, 0.8 mm layer height and 2.5 mm layer width at a speed of 70 mm/s using a robot-guided extruder (SpaceA-1100–500-S, Yizumi Germany GmbH) without heated build plate or chamber. The influence of fiber reinforcement, glass fiber versus a recycled carbon fiber (ICF – Industrial Carbon Fiber with lower CO_2 footprint compared to glass fiber), in combination with different polymers (PP, PA6, PA11), is considered. Three test specimens are printed per material and thus nine test surfaces are examined. The test specimens show bed adhesion along the entire circumference. With the corresponding unreinforced plastics, printing the test specimen is not possible.

Carbon Fiber Reduces Warpage Effectively

The influence of the fiber material on the warpage is investigated as a function of the fiber content for PA6 (**Fig. 4**). In general, warpage is reduced with increasing fiber content. Carbon fibers in particular effectively reduce warpage, whereas the use of glass fibers has a minor effect. The warpage of PA6-CF30 is significantly decreased by half compared to PA6-GF30. Even in the case of similar fiber volume fraction for PA6-GF50 and PA6-CF40, the warpage of the GF-reinforced compound is more than twice as high. Increasing the carbon fiber content from 30 to 40 wt.% results in an additional 17 % reduction in warpage.

Apart from the fiber material and content, the matrix polymer is of importance. However, its effect on the warpage is less pronounced. This is demonstrated clearly for PP-CF30. Although it has a higher fiber volume fraction than PA11-CF20, the measured warpage of both materials is about the same while the warpage of the PP-CF30 is higher compared to the PA11-CF30 with similar fiber volume fraction (**Fig. 5**). This observation correlates, on the one hand, with increased shrinkage due to crystallization and, on the other hand, with the stiffness of the compounds. Assuming a maximum fiber content of 20 wt.% for reinforced filaments, the warpage can be reduced by up to 37 % by further increasing the fiber content to 40 wt.% and printing with pellets. From the tested materials, PA11-CF40 (Akromid Next U28 ICF 40 1 black (8238)) showed the lowest warpage while also having a low coefficient of thermal expansion and low moisture absorption leading to high dimensional accuracy in use.

Regarding the possibilities of the FGF-process, the presented test specimen is in the lower end of range in terms of dimension and strand cross section. With increasing component size and higher extrusion volume, the warping potential becomes increasingly decisive for dimensional stability. Smaller components can be manufactured with lower fiber content (< 20 wt.%), similar to filaments. For components with dimensions in the meter range, the shrinkage-induced stresses increase accordingly, so that corner warpage becomes more likely. Higher reinforced compounds

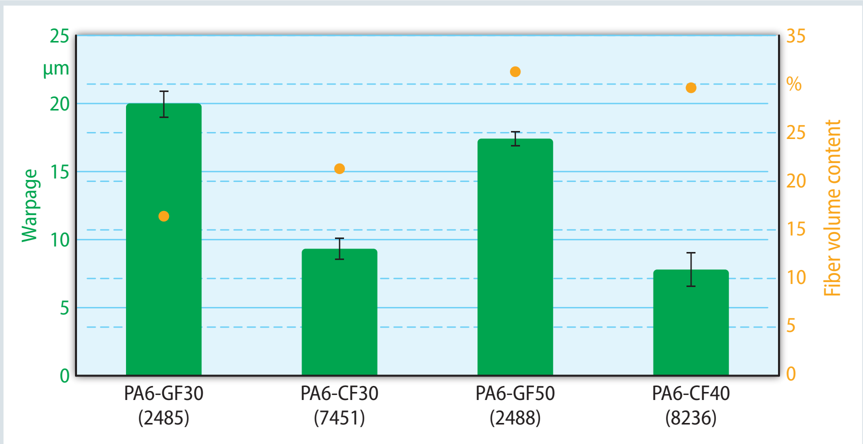

Fig. 4. Carbon fibers reduce warpage more than glass fibers. Source: Akro-Plastic; graphic: © Hanser

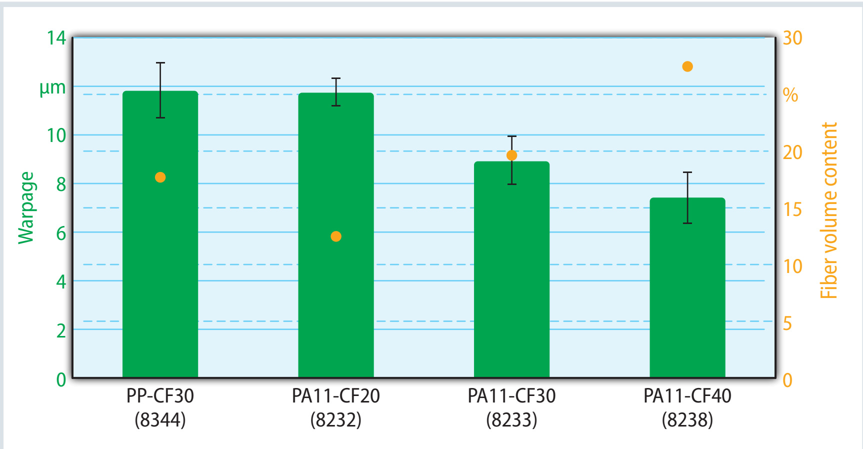

Fig. 5. The warping behavior can be optimized by the choice of polymer and fiber content.
Source: Akro-Plastic; graphic: © Hanser

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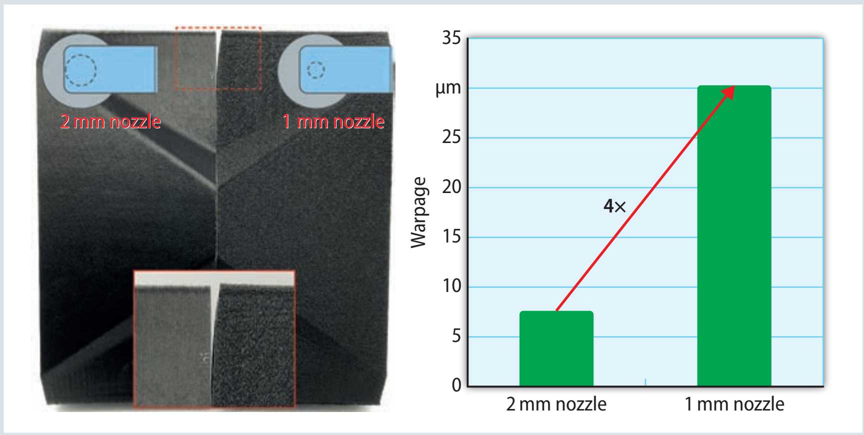

Fig. 6. Fiber orientation is crucial for warpage and can be influenced via the process.
Source: Akro-Plastic; graphic: © Hanser

(> 30 wt. %) contribute to low-warpage production of large-format parts.

Importance of Processing Parameters

To exploit the full potential of carbon fiber-reinforced plastics and produce dimensionally stable parts, optimized processes are necessary.

The fiber orientation in the deposited strand can significantly affect the warpage and the mechanical properties of the part. It is directly influenced by the relations of extruder throughput and printing velocity as well as the proportion of bead width and nozzle diameter. Fiber orientation transverse to the deposition direction results in low strand stiffness and shrinkage compensation. Using nozzles with 1 mm and 2 mm bore diameter leads to over-extrusion of 25 % and 150 %, respectively, at a constant strand width of 2.5 mm. This results in a four times higher warp-index for the 1 mm nozzle and a clearly visible detachment of the corners from the build plate of the PA6-CF30 specimen (**Fig. 6**). These findings can be transferred to larger strand geometries commonly used in tool and semi-finished product manufacturing.

Conclusion

The method presented allows the reproducible evaluation of the warpage tendency of materials for additive manufacturing with pellets. Thus, the warping behavior can be considered in the material selection. The use of carbon fibers significantly reduces the warpage of additively manufactured parts. Additionally, CF-reinforced compounds currently offer decisive advantages over GF-reinforced compounds in processing and use. These include good surface quality combined with higher productivity and mechanical properties that enable efficient lightweight construction. A good part quality is only achieved with appropriate process settings, which can also be evaluated and optimized with the method. ■