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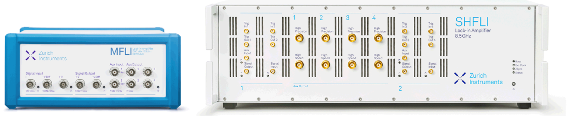

A Method to Evaluate the Process-Specific Warpage for Different Polymers in the FDM Process

Christian Schumacher[a,b,1], Volker Schöppner[a,2] and Camilla Fels[c]

[a]Kunststofftechnik Paderborn (KTP), Paderborn University, D-33102 Paderborn, Germany
[b]Direct Manufacturing Research Center (DMRC), Paderborn University, D-33102 Paderborn, Germany
[c]Paderborn University, D-33102 Paderborn, Germany
[1]christian.schumacher@dmrc.de; [2]volker.schoeppner@ktp.upb.de

Abstract. Additive manufacturing processes, like the Fused Deposition Modeling (FDM) process, do not need product-specific tools and create parts directly from the CAD data. In the FDM process, the semi-finished product, a wire of a thermoplastic polymer, is melted and forced through a nozzle. The continuous positioning of this nozzle allows the polymer to weld together strand by strand and layer by layer to produce a component. Because no mold is used in the FDM process, no holding pressure can be generated as in injection molding processes, in which the holding pressure is used to minimize the shrinkage and warpage of the part.

In the FDM process, the part is generated in an ambient pressure environment. Each strand cools down and shrinks separately. This causes residual stresses in the part that can lead to major warpage and a complete stoppage of the process. This is the main reason why the material selection in the FDM process is restricted in comparison to conventional polymer processing technologies.

In this paper, the warpage of different polymers is quantified as a criterion for evaluating the processability of polymers in the FDM process. Due to the process principle, the part properties in the FDM process are mainly influenced by the machine quality and the data processing, so that it is difficult to test a material for FDM independently of the machine and the data processing. Considering these influences, a custom-built specimen is created to test and quantify the warpage of different types of blended and reinforced polyamide 6. Considering the experimentally investigated warpage, the materials can be evaluated and the warpage can be related to the shrinkage investigated in pvT measurements.

This procedure allows the machine- and process-independent rating of the processability in terms of warpage for different materials. Alongside other criteria, this is a necessary step to develop new materials with good processability in the FDM process.

INTRODUCTION, DESCRIPTION OF THE PROBLEM AND TARGET

In the processing of plastics, shrinkage processes related to the material (e.g. stiffness or hardness of the processed plastic) and to the processing (in injection molding, due to non-stationary and inhomogeneous mold and molding temperatures in connection with flow-related orientations of microstructures and additives) lead to property anisotropies. This causes warpage of the part in the form of curvature, twisting or distortion [1; 2]. In the processing of plastics in molten form, complex thermodynamic-rheological processes take place. With semi-crystalline plastics, for example through the rearrangement of the polymer chains, crystalline areas are formed with a higher density [3]. Production machines, most of which have a molding function, are therefore usually still operated and optimized empirically [1]. The unavoidable process-related deviations of the molded part from the target geometry are taken into account in injection molding through a corresponding tolerance of the production deviations, design measures on the molding or the molding tool, or optimization of the production process [1; 4].

In the injection molding technology, a high level of warpage can cause inadequate part quality. Nevertheless, it is very rare to find a process that consequently works unreliably with the possibility of the process being stopped for the operator to intervene and carry out maintenance or cleaning of the machine. This is due among other things to the fact that the stiffness of the mold and the mold constraint prevent any significant deformation of the component during processing, i.e. before demolding.

In the FDM process, on the other hand, there is no mold constraint during processing. Warpage of partly finished areas of the component and the component itself is, despite the occurrence of shrinkage processes, suppressed due to the inherent stiffness of the areas of the component already produced (or the adhesion of the component to the build platform and its stiffness). If this is not sufficient to adequately suppress the deformation, the internal stresses brought about by shrinkage processes cause significant warpage of the part during processing. In this case, a reliable production process can no longer be guaranteed. Excessive warpage is often illustrated by areas of the component bending upwards out of the production plane [3]. In the subsequent course of the process, they usually collide with the nozzle. In addition to the danger of inadequate part quality, there is thus also the risk of a complete process failure, with the result that intervention by the operator and possibly subsequent cleaning and maintenance of the machine become necessary.

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FDM-TYPICAL WARPAGE AS A CRITERION FOR PROCESSABILITY

Process reliability in manufacturing the component geometry can no longer be guaranteed in FDM if excessive warpage occurs during the process. For this reason, the FDM-typical warpage is an important criterion for establishing the suitability of various plastics for processing in the FDM process. Another evaluation criterion can be the attainable weld strength in the FDM process (cf. [5]).

The deformation of the part depends on a number of parameters – also geometry-specific and process-specific. For this reason, the warpage cannot be measured directly on the material or be determined from material data such as the shrinkage. The shrinkage, or specific volume of a plastic (v), as a function of temperature (T) and pressure (p) can be measured under defined conditions in a pvT measurement. The shrinkages actually occurring in the process, however, are also dependent on flow-related anisotropies, e.g. molecule and fiber alignment resulting from the process, or are connected to the crystallization of the plastic, which can depend e.g. on the cooling rate [6].

It is therefore desirable to show by experiment and be able to measure the warpage actually occurring on the part as a consequence of the shrinkage occurring in the process. The specimen and the test method that have been developed in this paper set out to enable precisely this. The aim is not to evaluate the dimensional stability of certain component geometries, as shown e.g. in [7; 8]. Instead, the procedure presented here sets out to enable an evaluation and appraisal of the processability by FDM even of plastics that are prone to heavy shrinkage and warpage. Process stoppages that can occur when the geometry bends upwards are avoided through a carefully selected geometry of the specimen. Apart from that, in a complex production process such as Fused Deposition Modeling, the final product depends on many parameters. In order to be able to evaluate the effects exerted by the material in isolation, the process must be sufficiently well understood. For example, process-specific influences and production errors lead to a situation in which certain areas of the part can, for example, not be reproducibly produced on different machines (cf. [5]).

The specimen shown in FIGURE 1, left, was designed taking these findings into account. The deformation of the measuring area (cf. FIGURE 1, right) serves as the parameter for evaluating the warpage. This depends not only on the material but also on the geometry of the part and the production strategy. The geometry of the specimen has therefore been selected so that, in the measuring area, it is dependent only on a few process parameters. These process parameters can, as well as the manufacturing strategy, be unambiguously defined. Because of the special geometry of the specimen, it is also possible to work with materials with high warpage. The deformation of the measuring area occurs toward the outside and not upwards into the build plane. A collision with the nozzle can thus be avoided. The production of materials that are difficult to process is more successful than in a method presented by [10], and the results are less dependent on the machine used and the varying production influences.

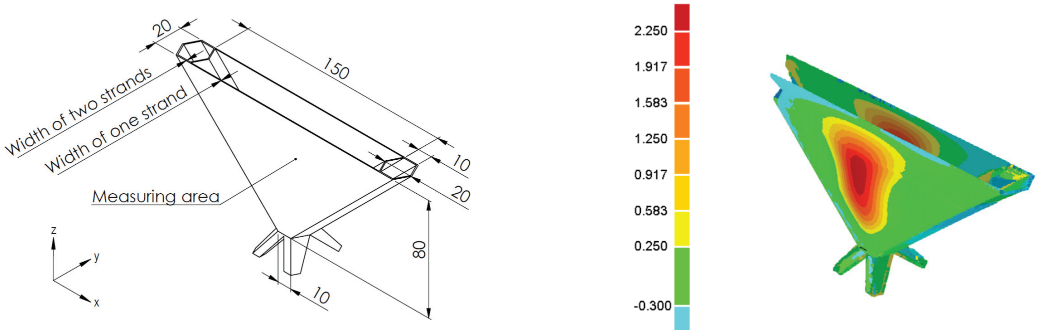


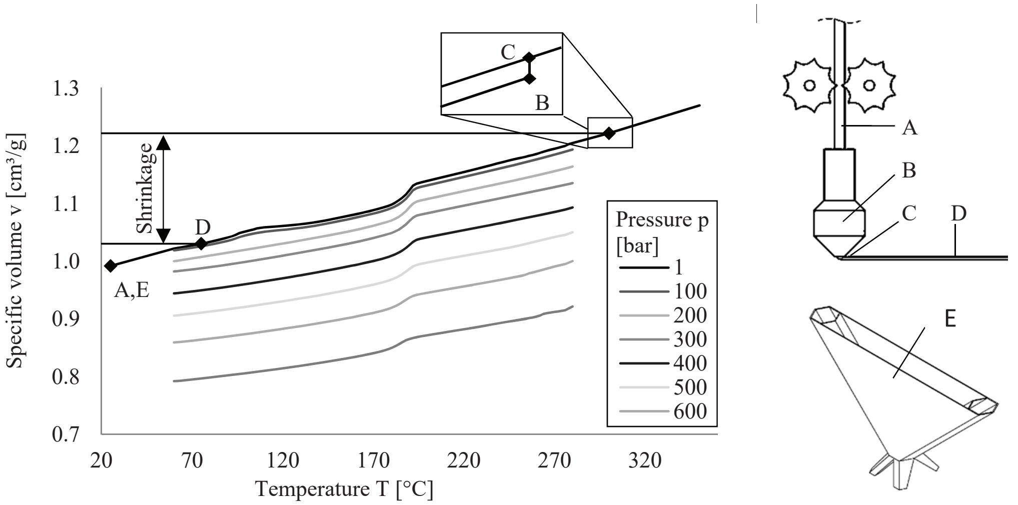
FIGURE 1. Drawing of the specimen for quantifying the warpage (left), 3D-scan of a manufactured specimen to show the deformation of the measuring area (right)

SHRINKAGE – PVT MEASUREMENT

In injection molding, when examining the total shrinkage, a distinction is made between processing shrinkage (including demolding shrinkage) and post-shrinkage [1; 6]. In FDM, too, a distinction can basically also be made between two shrinkage processes. In this publication, processing shrinkage in FDM is defined as the recurring shrinkage of the partly manufactured component or of individual component areas during the production process. The post-shrinkage is defined as the shrinkage of the finished component that occurs after removing it from the oven that is still at process temperature.

With plastic melts, the specific volume (v) changes in relation to the pressure (p) and temperature (T). This behavior can be documented with a pvT measurement and can be illustrated in a diagram (see FIGURE 2).

Knowledge of the pvT behavior of the plastic melt can be taken into account for designing the process and for estimating the processing. FIGURE 2 shows the FDM process with relevant process points (A, B, C, D, E).



A	Filament at room temperature and ambient pressure
B	Polymer melt at nozzle temperature under process pressure
C	Polymer melt at nozzle temperature and ambient pressure
D	Solidified strand at oven temperature and ambient pressure
E	Component at room temperature and ambient pressure

FIGURE 2. pvT diagram and shrinkage of an example material

FIGURE 2 shows an example of a pvT diagram. The processing shrinkage, in other words the change in specific volume when cooling from nozzle temperature to oven temperature in the FDM process, can be read as volume shrinkage. The procedure is shown in FIGURE 2. The processing shrinkages of all the examined plastic types are shown in TABLE b). All seven plastics studied in this paper have the same polymer base and were modified only through the addition of an amorphous blend component and/or through the addition of fillers.

TABLE a) Shrinkage of the investigated polymers (determined from pvT measurements, cf. FIGURE 2)

Material number	Material description	Nozzle temperature [°C]	Oven temperature [°C]	Shrinkage [%]
1	PA 6 low viscosity	300	75	17.46
2	PA 6 high viscosity	300	75	17.08
3a	PA 6 low viscosity + amorphous blend components and additives	300	25	18,81
3b		300	75	15.66
3c		300	125	13,03
3d		350	25	21,90
3e		350	75	18,86
3f		350	125	16,33
4	PA 6 high viscosity + amorphous blend components and additives	300	75	15,76
5	PA 6 low viscosity + amorphous blend components + filler type 1	300	25	14.26
6	PA 6 low viscosity + amorphous blend components + filler type 2	300	75	13.20
7	PA 6 low viscosity + amorphous blend components + filler type 3	300	75	11.55

RESULTS AND MATERIAL COMPARISON

The measurements for the warpage, i.e. the bulging of the measured surfaces (cf. FIGURE 1), are listed in TABLE a) for the seven material variants examined in this paper. The specimens of all seven materials were each produced with a nozzle temperature of 300 °C and an oven temperature of 75 °C. For material no. 3, measurements of the warpage are also listed for different processing temperature combinations. The bulging of the surfaces was measured in line with [1] after storage in a standard climate (cf. [9]).

TABLE b) FDM-typical warpage (measured bulging of a FDM specimen)

Material number (cf. TABLE a))	Nozzle temperature [°C]	Oven temperature [°C]	FDM-typical warpage (average) [mm]
1	300	75	5.6
2	300	75	4.9
3a	300	25	3.7
3b	300	75	3.0
3c	300	125	3.8
3d	350	25	4.2
3e	350	75	3.1
3f	350	125	4.0
4	300	75	1.8
5	300	75	2.5
6	300	75	0.5
7	300	75	0.1

FIGURE 3 shows the volume shrinkages (determined from pvT measurements) from TABLE a) and the FDM-typical warpages (measured bulging of a FDM specimen) from TABLE b) for the seven examined material variants at the same process temperatures. FIGURE 3 shows the volume shrinkages from TABLE a) and the FDM-typical warpages from TABLE b) for material no. 3 at various process temperature combinations.

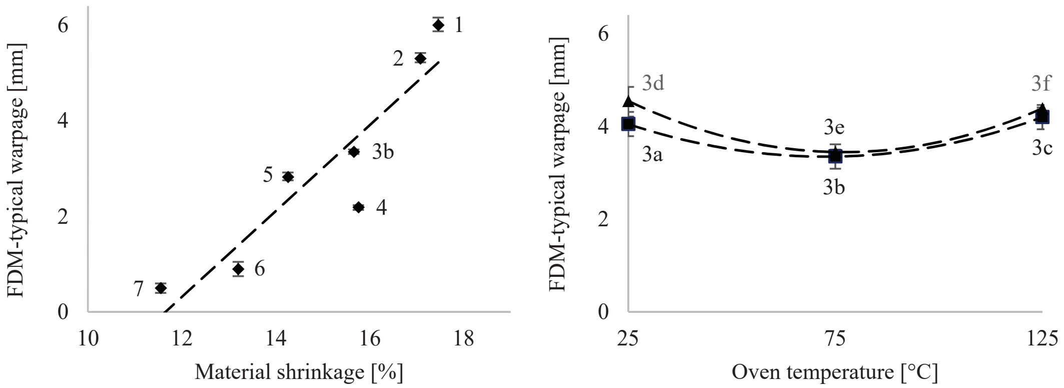


FIGURE 3. Warpage and shrinkage of different material variants at the same process temperatures (left) and the warpage of material 3 as a function of the process temperatures (right)

FIGURE 3, left, shows that the FDM-typical warpage and material shrinkage for all seven materials correlate when processed at the same process temperatures. The method presented in this paper for determining by experiment the warpage occurring in FDM thus yields plausible results. FIGURE 3, right, shows for material no. 3 that the warpage occurring in the FDM part has a minimum at an oven temperature of 75 °C. The cause of this could be e.g. temperature and cooling rate dependent crystallization processes.

SUMMARY AND OUTLOOK

In this publication, a method is presented for depicting and quantifying the warpage typically occurring in the FDM process with the aid of a specimen. The specimen can also be produced from materials with a high shrinkage tendency and high expected warpage (like the PA 6 types used here).

Different material variants were produced by adding an amorphous blend component and/or through the addition of fillers. With the help of the presented method, the FDM-typical warpage (a measured bulging of a FDM specimen) and the shrinkage (measured as the difference in specific volumes between nozzle and oven temperature in the pvT diagram) were determined for each material type. The good correlation between shrinkage and FDM-typical warpage across all material variants shows that the method presented here provides plausible measurements. In addition, tests were carried out on how shrinkage and warpage behave in relation to the processing temperatures. These studies showed that the warpage occurring on the part as a function of the process temperatures does not necessarily correlate with the material shrinkage (determined from pvT measurements).

The presented method thus enables a picture to be gained of the effect of the process temperature and other process parameters on the warpage occurring in the component. This makes it possible, for example, to identify potentially suitable processing parameters for a material or to adapt a material to the process.

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