Solid Freeform Fabrication 2023: Proceedings of the 34th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

DETERMINATION AND COMPENSATION OF THE SHRINKAGE BEHAVIOR OF CYLINDRICAL ELEMENTS IN THE FDM PROCESS

T. Koers[1,2]*, B. Magyar[1,2]

[1] Chair of Design and Drive Technology (KAt), Paderborn University, Germany
[2] Direct Manufacturing Research Center (DMRC), Paderborn University, Germany
* Corresponding author: thorsten.koers@upb.de

Abstract

Fused Deposition Modeling (FDM) is an additive manufacturing process to produce complex thermoplastic geometries layer by layer. The filament is melted in a nozzle, iteratively deposited, and then cools down. Due to the solidification process, the deposited filament strands deviate from their intended position due to shrinkage, resulting in significant geometric deviations in the final part. In terms of dimensional accuracy, there is a need for optimization, especially for local curved geometries in relation to the global part with higher nominal dimensions. The aim of this study is to investigate the size and shape deviations for cylindrical FDM elements and to compensate the expected deformations by using an in-house software with adaptive scaling factors in the x-y plane. Previous studies mainly focus on simple, non-curved objects, this study also considers the influence of curvature and global as well as local deviations on the final part.

Introduction

Additive manufacturing (AM) is characterized by its layer-by-layer buildup and requires no tooling. Without the use of a tool, there are almost no restrictions on the design of a part, such as for complex geometries that could not be manufactured in conventional processes. The basis for each AM part is its CAD model, from which the layers are separated and then recombined during manufacturing.

Fused Deposition Modeling (FDM) is a widely used plastics extrusion process in AM for the production of prototypes, tools and final products. In this process, the layers of a part are deposited one after the other by a melted thermoplastic filament strand. The continuous strand is pulled by motors into a nozzle head, where it is melted and then deposited in a defined position onto the underlying part. The newly deposited layer and the layer underneath bond by means of thermal fusion, cool down and strengthen. The layers are now permanently joined. The problem is that the deposited strands deviate from their defined deposition position because of solidification. Depending on the part geometry the shrinkage occurs in the x/y/z direction with significant inhomogeneity. This results in a significant influence on the dimensional and shape accuracy of the part, which is usually required by high and constant quality in the final application [1].

These geometric deviations of FDM parts have often been investigated in studies. Mostly, for simplification purposes, non-complex standard elements are used, which can be divided into curved and non-curved [2]. Mainly, the studies of geometrical deviations in FDM involve non-curved parts such as cuboids. The results show that the outer length has a significant influence on the dimensional deviations. The higher the nominal dimension, the higher the deviation. For curved elements, investigations on cylinders and bores can be found. The results regarding dimensional accuracy show that inner dimensions are undersized and outer dimensions are oversized. Analog to the non-curved elements, it is shown that the deviations increase with increasing nominal diameter [3-5]. A countermeasure is offered by scaling factors, which are applied to the CAD model by the supplier or the software in the pre-process to compensate the deviation from the nominal geometry in the manufacturing process. Here, too, increased dimensional deviations occur with increasing nominal length. The reason for this is a constant scaling factor, which is independent of the nominal dimension. Particularly for higher nominal dimensions above 50 mm, there is a need for optimization regarding the geometric accuracy. Also, no local scaling is possible to adapt for structures with complex geometries [6-10]. KNOOP [6] has developed scaling factors adapted to the expected deviation based on experimental investigations. The necessity of a simulative approach is pointed out since the experimental parameter development is expensive. In addition, the adapted scaling factors for linear elements are not applicable to curved elements, since here an analog scaling factor would further amplify existing undersize [6]. For cylindrical parts there have been investigations that developed a method to compensate the shrinkage of holes in FDM parts using adapted internal infill structures [11-12]. The combination of curved and non-curved parts has been neglected in studies to this point. Furthermore, the correlation between global and local deviations is missing. Using the scaling factors, only simple parts are considered globally. Complex parts with local variations are not considered. But dimensional deviations occur especially in parts that are predestined for AM due to their complex geometry.

The aim of this study is to determine and then compensate the shrinkage of cylindrical parts in the FDM process by applying optimized scaling factors in the x-y build direction. For this purpose, a self-developed software with adapted scaling factors is investigated on cylindrical test specimens and iteratively optimized. A nominal dimension-dependent scaling is set to generate locally instead of globally targeted adaptations for a complex part for validation.

Experimental set-up

This chapter describes the experimental investigations carried out to examine the geometrical accuracy of simple curved FDM parts. Therefore, a Stratasys Fortus 400mc is used, which is available at the research center. The machine enables processing of high-temperature plastics such as ULTEM^{TM} 9085 resin due to its heated build chamber. The material under investigation is ABS-M30, which is chosen because it is an inexpensive standard material for the Stratasys machine used and a typical application plastic that serves for comparability with other studies. The process parameters used for the ABS-M30 material are listed in Table 1. The process parameters are taken from the material file of the Stratasys Insight software and are kept constant for all test specimen and scalings used in this study [6, 13-15].

Table 1: Used process parameters for manufacturing (ABS-M30, Stratasys Fortus 400mc)

Nozzle diameter (T16) / mm	0.4064	**Air gap / mm**	0
Nozzle temperature / °C	315	**Raster angle / °**	45
Build chamber temperature / °C	95	**Minimum layer time / s**	9
Layer height / mm	0.2540	**Print speed (contour) / m/s**	0,018 - 0,038
Extrusion width / mm	0.5080	**Print speed (infill) / m/s**	0,028 - 0,102

The test specimens are defined as solid cylinders with an increasing nominal diameter in increments from 15 to 65 mm. The cylinders are aligned in the z-direction with a constant height of 50 mm. The measuring procedure is carried out with a Nikon Altera 8.7.6 coordinate measuring machine as well as an outside micrometer [16]. The coordinate measuring system is used for tactile measurement with a measuring head diameter of 2 mm and a layered measuring strategy (5 measuring rows, 10 mm intervals). The measuring points defined for the outside micrometer are the lowest, middle, and uppermost planes in the x- and y-directions (see Figure 1). The z-direction of the cylinders is not considered in this study. The testing plan includes the number 3 per build job.

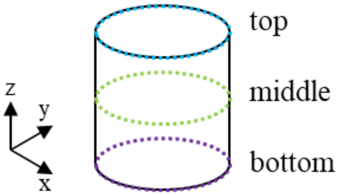

Figure 1: Measuring points in x- and y-direction of the outside micrometer

Four different scalings of the cylinders are considered in this study. Unscaled test specimens with the scaling factor ($SF_{x,y}$) equal to one are used as a basis. Standard scaled test specimens with $SF_{x,y} = 1.0059$, which are defined by Stratasys, are used as a second reference. Subsequently, an in-house developed software with self-adapted scaling factors is applied to unscaled cylinders in the pre-process before slicing. The method and functionality of this software were presented by HECKER at the Polcom 2022 in Bucharest [17]. It is based on the theory that raster lines shrink primarily in the direction of their nominal length. By adjusting the individual raster lines the software targets to compensate the shrinkage behavior in each layer. In this study, the scaling of the variants "Adaptive Scaling V2.4" and "Adaptive Scaling V3.2" are examined for one build job each. The main distinction between these two variants is that the iteration "Adaptive Scaling V3.2" is compensating the curvature of the specimens and "Adaptive Scaling V2.4" is not. Finally, the variants "unscaled" and "Adaptive Scaling V3.2" are compared with each other using a demonstrator in the form of a bracket (see Figure 2). The bracket has a complex geometry which can only be manufactured with AM. It contains 20 individual non-curved and curved shapes with various length dimensions and outer diameters. These individual geometries are measured to check the global as well as local geometric deviations.

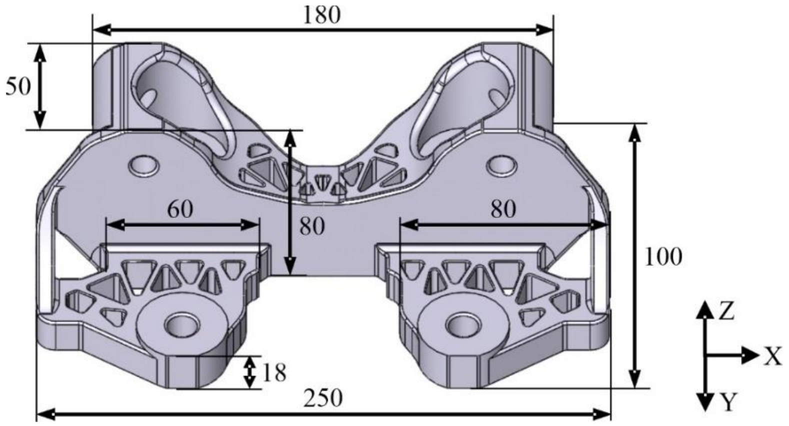

Figure 2: CAD-Model of the demonstrator

Results

The influence of the investigated scaling factors on the dimensional deviations as a function of the nominal diameter is analyzed in Figure 3 a). The dotted lines represent a trend line and the indicator bars the minimum and maximum deviations of the measured values. For the unscaled test specimens, strong dimensional deviations can be seen. The continuously increasing undersize with increasing nominal dimension confirms the previously described hypotheses as well as the statements of KNOOP [6]. With increasing nominal size, an increasing scattering of the measured values can be seen, which are from the nominal diameter of 35 mm above the standard deviation. Considering the shape accuracy of the unscaled cylinders, the so-called clover effect can be observed (see Figure 5a). A shape deviation occurs in each position at 45° to the x- or y-axis. At this position, the deposited raster lines have the highest length and accordingly the highest tensile force. This results in the strongest shrinkage in the strand direction, which influences the layer contour. The raster alignment alternates layer wise with 90°, so the deformation occurs rotation-symmetrically at four positions over the entire cylinder geometry. This shape determines the characterization of the clover. In comparison, the standard scaled test specimens exhibit an improvement in the measured values. A nearly constant negative dimensional deviation as the nominal diameter increases can be observed. Above the nominal dimension of 35 mm an increased measured value scatter above the standard deviation occurs. Compared to the unscaled test specimens there is an analog occurrence of the clover effect.

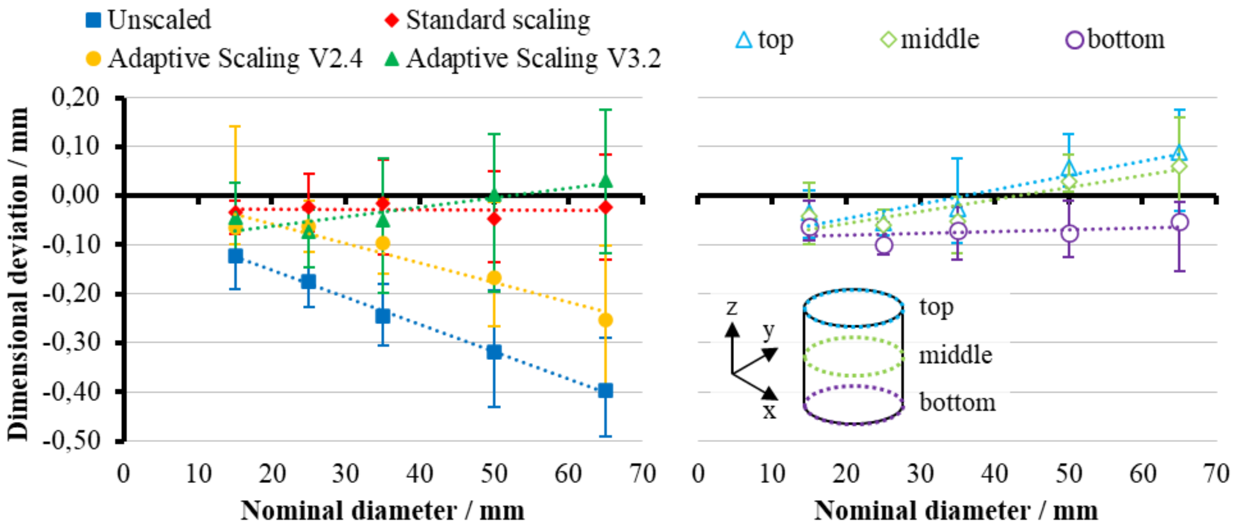

Figure 3: Influence on the resulting dimensional deviations of cylinders due to a) the different scaling factors including all measuring points (left diagram); b) the measuring height in z-direction for scaling factor "Adaptive Scaling V3.2" (right diagram)

The graph of the measured values "Adaptive Scaling V2.4" shows the results of the test specimens with the in-house developed scaling factors. Here, continuously increasing negative dimensional deviations are obtained with increasing nominal diameter. Compared to the unscaled test specimens, a reduction of the deviations can be achieved. At 15 mm diameter, the difference is 0.10 mm and increases continuously up to 0.16 mm at 65 mm. The dimensional accuracy of the standard scaling cannot be achieved. Therefore, newly adapted scaling factors "Adaptive Scaling V3.2" are elaborated by HECKER in an iteration process. The iteration achieves a nearly analog result to the standard scaling for the nominal diameter 15 mm. The dimensional deviation then increases with increasing nominal diameter up to 0.03 mm at 65 mm. Measurement value outliers are present to an increased extent. The cause of the inconsistent measured values within the standard deviation can be seen in Figure 3b. There, the dimensional deviations from "Adaptive Scaling V3.2" are shown as a function of the nominal diameter for the three measuring points top, middle, and bottom. It can be seen here that the test specimens have a conical curvature along the z-direction. The deviation of the diameter at the lower section of the cylinder is almost the same as the values for the standard scaling. The measured values increase for nominal dimensions above 25 mm for the measuring plane in the middle as well as at the top. In contrast, an enhancement of the clover effect is visible in particular for the high nominal dimensions (see Figure 5b).

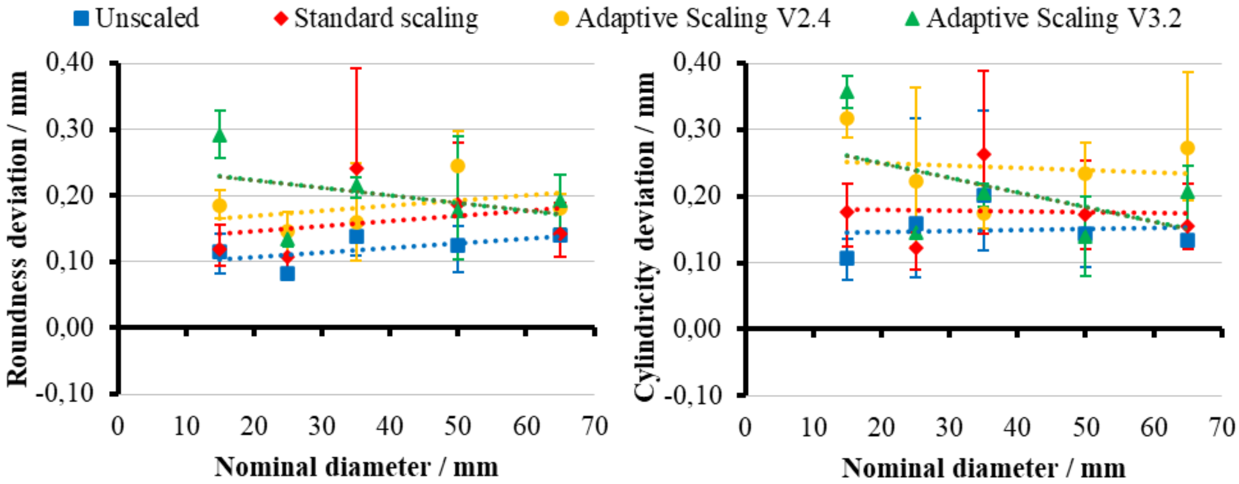

Figure 4: Influence on the resulting a) roundness deviations (left diagram) and b) cylindricity deviations (right diagram) of cylinders due to the different scaling factors

In terms of shape accuracy, almost parallel results can be seen for the scaling variants "Unscaled", "Standard scaling" and "Adaptive Scaling V2.4". "Adaptive Scaling V3.2" shows contrasting measured values. Figure 4 presents these graphically with a) for roundness deviation and b) for cylindricity. The unscaled test specimens show an increasing roundness deviation of 0.1 mm to 0.14 mm with increasing nominal diameter. The values for "Standard scaling" and "Adaptive scaling V2.4" run parallel with a difference of an additional 0.5 mm respectively 0.7 mm deviation. "Adaptive Scaling V3.2" has a high roundness deviation of 0.29 mm for the smallest diameter and decreases to 0.19 mm for diameters up to 65 mm (see Figure 4a). The same is observed for the cylindricity deviation. "Unscaled", "Standard scaling" and "Adaptive scaling V2.4" show parallel deviation trends, while "Adaptive scaling V3.2" shows a high deviation for the smallest diameter and decreases with increasing nominal diameter (see Figure 4b). The high measured value scatter for all scaling variants is remarkable for the shape accuracy.

Figure 5: Visible roundness deviation in x-y direction for a) "Standard scaling", d = 15 cm (left) and b) "Adaptive Scaling V3.2", d = 35 cm (right)

The factors "Adaptive Scaling V3.2" applied to the demonstrator bracket for validation achieve the expected dimensional deviations for the existing curved geometries according to the preliminary investigations. An overall low measured value scatter is also identifiable, which leads to constant dimensional values. This is also shown in particular by the measured length dimensions for non-curved geometries of the bracket in both the x- and y-directions. Local as well as global dimensions were considered in the non-curved measurement. In comparison, the measured dimensional deviations of the unscaled brackets increase with increasing nominal dimension from local to global. The average value of the dimensional deviations across the entire part is -0.43 mm for the unscaled demonstrator (standard deviation: 0.25 mm) and -0.37 mm for the adaptive scaled demonstrator V3.2 (standard deviation: 0.18 mm). Considering the standard deviation, there is no significant improvement in the dimensional accuracy. It must be noted that both non-curved and curved geometries are included in these average values over different measurement heights in the z-direction. While "Adaptive Scaling V3.2" achieves constant measured values along the entire z-height for non-curved geometries [17], this accuracy is not achieved for curved geometries, as previously investigated using the cylindrical test specimens. This can be seen in the measured value scatter of "Adaptive Scaling V3.2" on the curved geometries of the demonstrator bracket.

Conclusion

The aim of this study was to investigate the size and shape deviations for cylindrical FDM elements and to compensate the expected deformations with optimized scaling factors in the x-y plane. For this purpose, cylindrical test specimens were investigated with adapted scaling factors of an in-house developed software. It has been shown that the considered approach to compensate the shrinkage per layer in the direction of the raster lines provides improved dimensional accuracy compared to unscaled specimens. The dimensional deviations for standard scaled test specimens were not achieved but were approximated by an iteration process. The adapted scaling factors achieve constant dimensional values in the strand direction. In the z-direction the dimensional deviations are locally low. Due to the formation of a conical shape of the cylindrical surfaces an increased measured value scatter results globally. A further iteration of the scaling factors is necessary for a constant dimensional value over the complete z-height. Furthermore, the circle approximation has to be modified so that the clover effect of the contour can be reduced. The validation on the bracket confirmed the results on the simple cylindrical test specimen and also for a complex part with varied geometry characteristics.

The presented approach enables an improvement of quality and consistency of dimensional accuracy in the FDM process. In further investigations, it is necessary to optimize the software so that the dimensional deviations are further reduced. The range of deviations should remain constant in order to further guarantee constant dimensional accuracy. In addition, the possibility of transferring the shrinkage behavior between different materials on the basis of specific material parameters should be examined in further analyses. This would significantly reduce the future experimental effort for modeling the shrinkage behavior of further materials. These open issues can be addressed in further investigations.

Acknowledgements

The presented results were obtained in the context of the research project ZI 723/12-1 "Simulation of the shrinkage behavior in Fused Deposition Modeling" sponsored by the German Research Society (DFG). We would like to thank the DFG for its support.

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