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Analysis of the dimensional accuracy of a fiber composite material manufactured by fused filament fabrication

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Abstract

Additive manufacturing is used in many areas of production, due to the increasing technological development of manufacturing processes. The technology provides a high degree of freedom concerning the design and manufacturing of complex and detailed structures. The level of dimensional accuracy is essential to ensure that inserts can be embedded with the correct tolerances and joints maintain their degree of freedom. This dimensional accuracy is related to the system and material. Therefore, it has to be assessed individually in advance. To demonstrate this, a test geometry was designed and manufactured from a fiber composite material, Onyx, using Fused Filament Fabrication. The sample geometry is based on the guideline for testing AM systems "Geometric capability assessment of additive manufacturing systems" ISO/ASTM 52902:2019 and includes several geometric aspects, including linear tolerance, roundness, wall thicknesses and diameters. For a precise assessment of the geometry in all sectional layers, the samples were measured with a CT scanner and compared with the CAD model. The results show, that there are deviations of $\Delta d = \pm 72$ µm in the X / Y direction and the warping effect that often occurs with polyamide-based materials. Precisely fitting components can be manufactured on the basis of the measured deviations by adapting the CAD model in advance.

Keywords: Fused filament fabrication, additive manufacturing (AM), 3D printing, dimensional accuracy, Design, Onyx

1. Introduction

Additive manufacturing (AM) is used in various areas, including aerospace, medical and the automotive industry. AM offers many advantages, such as the production of lighter objects with optimized use of materials and a decreased the number of assembly steps. This leads to shorter lead times and reduces costs. Due to the layer-by-layer build-up process, components can also be realized with a high degree of design freedom along with complex and filigree structures. The resolution of the component therefore depends on the selected manufacturing process and material. There are already several publications that describe the influence of printing parameters on surface quality and dimensional accuracy [1, 2]. In order to apply the components with high precision and maintain tolerances, it is necessary to record any influence on the dimensions in a standardised procedure.

2. Limitations of the Fused Filament Fabrication process

Due to its low costs, simple and safe handling and the wide range of materials that can be used Fused Filament Fabrication (FFF) is widely used technology. In the process, a line of melted material is deposited layer by layer. The nozzle movement is realized by a plotter with separate linear axis control in the X, Y and Z directions. The resolution and physical properties of the components can be modified by process parameters such as printing speed v_x, layer height s, infill density ρ_i, extrusion temperature T_x, screen width w and infill structure [2]. The nozzle diameter determines the smallest possible geometry or the representation of corners. A smaller nozzle diameter d_n can therefore increase the resolution in the X / Y direction. Due to its influence on the resolution in z direction surface quality is affected by layer thickness s. Depending on the material, warping, a slight shrinking during cooling can occur. This causes a deformation of the part which leads to detachment from the build platform. Another major influence is the extrusion temperature T_x and extrusion flow F_x, which can affect the surface quality as well as the appearance of voids.

3. Experimental setup

For dimensionally accurate components, it is important to know the geometric resolution of the AM system. For this purpose, a resolution test body was designed based on the standard "Geometric capability assessment of additive manufacturing systems" ISO/ASTM 52902:2019 [3]. These test geometries cover the geometric performance in linear axis Δd_{lin}, roundness ΔD_C, wall thicknesses Δd_w, gap dimensions Δd_g and planarity Δw, as shown in figure 1.

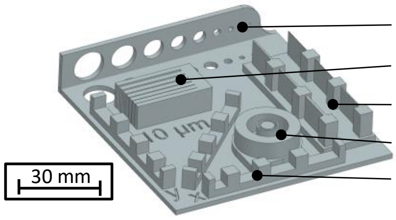

Figure 1. Test geometry for geometric capability of AM systems

On the linear test body, dimensional accuracy Δd_{lin} is measured between the peaks. These show distances between $2.5 \text{ mm} \leq d_{lin} \leq 12.5 \text{ mm}$ and are arranged with different orientations. The circular test body is used to measure the roundness ΔD_C of the cylindrical surfaces and consists of three concentric rings with diameters in the range of $5.0\ mm \leq D_c \leq 23.5\ mm$. The resolution test walls provide information on the finest detail to be produced and the walls measurements are between $0.1 \leq d_w \leq 1.0\ mm$. The resolution gaps from $0.1\ mm \leq d_g \leq 1.0\ mm$ are in contrast to this. The resolution holes show the smallest possible cylindrical features and include diameters between $0.5\ mm \leq D_H \leq 12.0\ mm$. For an analysis of the layered structure, the resolution holes are positioned flat and upright on the base plate. The test geometry was designed in the CAD software NX from Siemens Digital Industries Software, Plano, USA an. An Onyx Pro FFF-printer and carbon short-fiber-reinforced polyamide (PA 6), both by Markforged Inc., Waltham, United States, is used for the evaluation of the geometric performance. The Metrontom 800 computer-tomograph by Carl Zeiss IMT GmbH, Oberkochen, Germany, was used for the following measurement of the samples [4]. The evaluation is then carried out using Zeiss Calypso software by Carl Zeiss IQS Deutschland GmbH, Oberkochen, Germany. The Zeiss Calypso software can be used to measure geometries and program inspection plans to compare the sample with the original CAD file [5].

4. Geometric measurements

The printed samples shows warping of $\Delta w = 587\ \mu m\ (\pm 175\ \mu m)$. Specific structures, such as resolution gaps with a range of $0.1\ mm \leq d_g \leq 0.2\ mm$, resolution holes with a range of $0.05\ mm \leq D_H \leq 0.10\ mm$, and resolution wall with a range of $0.1\ mm \leq d_w \leq 0.2\ mm$, are neither visible nor measurable. This can be clearly seen in the CT image shown in figure 2. The edges of the sample are curved upwards, which is why the blue plane is only visible in the center. Such warping could be prevented by a brim or a heated build platform and build chamber.

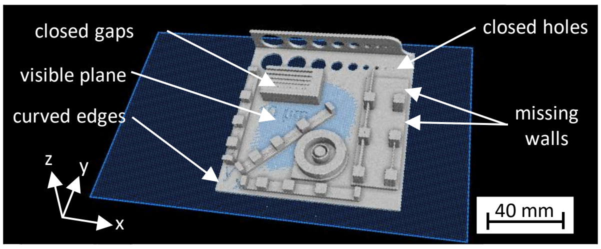

Figure 2. CT Image of the sample showing warping

Figure 3 shows the measurements of the deviations, which are shown as absolute values for better comparability. The measurements show average deviations of $\Delta d_{lin} = 65\ \mu m\ (\pm 40\ \mu m)$ on the linear test body. It can also be seen in figure 3 that different results are achieved in the X and Y directions. This is also represented by the deviations in the roundness ΔD_C of the circular test body of $\Delta D_C = 121\ \mu m\ (\pm 105\ \mu m)$. These deviations occur due to slightly oval cylindrical surfaces. It can therefore be seen that the axes of the AM system have a different resolution. In addition, the resolution holes also show these deviations from $\Delta D_{Hx/y} = 63\ \mu m\ (\pm 127\ \mu m)$ in the dimensional accuracy. The deviations of the resolution holes placed upright in the Z-direction show a higher deviation of $\Delta D_{Hz} = 123\ \mu m\ (\pm 93\ \mu m)$ due to the layer structure and bridging. The ability to outline the resolution walls depends on the nozzle diameter $D_n = 0.4\ mm$ and therefore only the resolution walls bigger than $d_w \geq 0.4\ mm$ are visible. The resolution gaps show the smallest deviations from $\Delta d_g = 19\ \mu m\ (\pm 40\ \mu m)$.

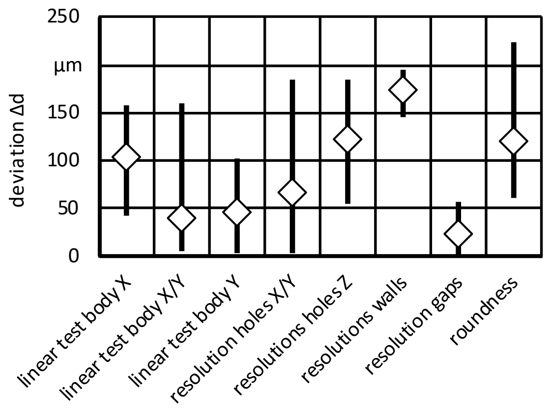

Figure 3. Measured Deviation in the geometry

A closer look at the individual results reveals that inner contours have a general deviation of $\Delta d_{In} = -65\ \mu m$ and outer contours a deviation of $\Delta d_{out} = 49\ \mu m$. The higher deviation for inner contours results from the fact that contours such as a circle are traced several times by the nozzle, while an outer contour such as an outer corner is only traced once. Internal structures as holes must therefore be designed larger and external structures smaller. This results from the material line deposited in the FFF-process, which must be wider than intended and is over-extruded.

5. Conclusion and outlook

An overall deviation of $\Delta d = 72\ \mu m\ (\pm 54\ \mu m)$ in the X/Y direction can be seen from the test bodies. This complies with the accuracy of $\Delta a = 160\ \mu m$ in the plane given by the manufacturer [6]. Nevertheless, there is a clear trend towards over-extrusion, which is why this must be taken into account when creating designs and the required tolerances. These deviations are different for each material and AM system and must be tested individually in order to obtain precise components. As an alternative, the existing slicer systems could also be optimized to prevent these accuracy issues through extrusion adjustments.

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