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COMPARISON OF COMPONENT PROPERTIES AND ECONOMIC EFFICIENCY OF THE ARBURG PLASTIC FREEFORMING AND FUSED DEPOSITION MODELING

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Abstract

The additive manufacturing process Fused Deposition Modeling (FDM) is established in the industry for many years. A new, similar process to FDM is the Arburg Plastic Freeforming (APF). The main differences between both processes are the form of the starting material (FDM: Filaments, APF: Conventional granulate) and the material deposition during the layer formation (FDM: Melt strand, APF: fine molten droplets).

Since the two processes can be used in similar applications, the aim of this study is to compare both processes in a holistic way. Furthermore, the advantages and disadvantages of the processes are to be highlighted. The systematic comparison between a Stratasys 400mc and the Freeformer 200-3X is divided into the areas of component properties, design limitations and economic efficiency. The material ABS-M30 (Stratasys) is used in both processes. The results show comparable component properties regarding mechanical and optical properties but also differences in design limitations and cost efficiency.

Introduction

The Arburg Plastic Freeforming (APF) is a relatively new additive manufacturing process with its official market launch in 2013. With this process it is possible to manufacture three-dimensional components using standard granulates without the need of molding tools [1]. The unique technique of the material deposition in the APF process is opening a new field of possibilities and also new boundary conditions. In contrast to the widely known Fused Deposition Modeling (FDM) process the material in the APF process is not deposited as a strand but in the form of fine molten thermoplastic droplets. As the droplets in the APF process are significantly smaller than the standard strand widths in the FDM process e.g. more detailed component geometries can be realized. Both the APF and the FDM process can be used for similar applications. Until now there is no in-depth comparison of the two processes regarding the component properties, design limitations and economic efficiency.

The aim of this research is the development of an overview of the capabilities of both, the APF and FDM process. For this purpose, the same specimens for the evaluation of the different aspects will be manufactured with both processes. On both machines, the Stratasys Fortus 400mc (FDM) and the Freeformer 200-3X (APF) the material ABS-M30 will be used to assure comparability while maintaining highest filament quality.

State of the Art

The Arburg Plastic Freeforming is characterized in particular by the processing of standard plastic granulates as well as by the production of components out of very fine molten thermoplastic droplets. The associated machine system for this technology is the Freeformer from Arburg GmbH & Co KG. Its most important machine components are shown in Figure 1.

The raw material, a qualified standard thermoplastic granulate, is fed via a hopper. In the material preparation unit, the granulate is molten with a screw as in the injection molding process. The molten material is then pressed into the material reservoir. Here, a piezo actuator performs a pulsed nozzle closure using a needle to close the nozzle opening. The needle in the nozzle moves up and down, producing almost 250 droplets per second. The movement of the building platform, for the precise positioning of the discharged droplets in the x- and y-direction, is realized by two linear motors. After the completion of a layer the building platform is lowered by one-layer thickness, using a spindle drive [1, 2, 3].

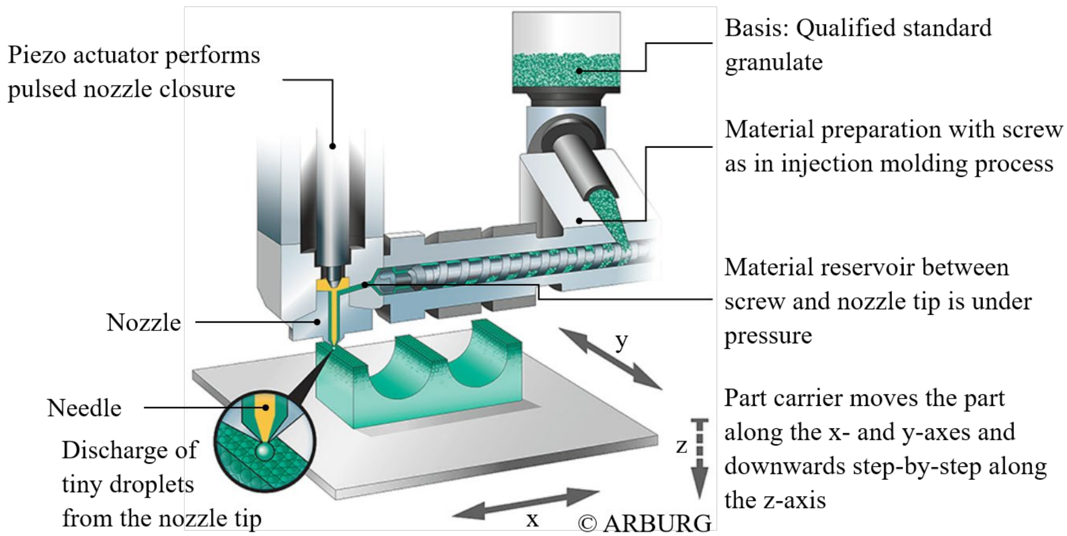

Figure 1: Schematic setup of the Freeformer [1].

The Fused Deposition Modeling process (FDM) was first commercialized in 1991 by Stratasys. As shown in Figure 2 a thermoplastic filament is fed into the heated nozzle where it is molten and pushed through the nozzle opening by the trailing filament. Through the defined movement of the FDM head in the x-y-plane the material discharged from the nozzle is deposited in a specific manner. After the completion of the current layer either the FDM head is raised or the building platform is lowered, depending on the machine, by one layer height. Afterwards the deposition process starts again until the desired component is completed [4].

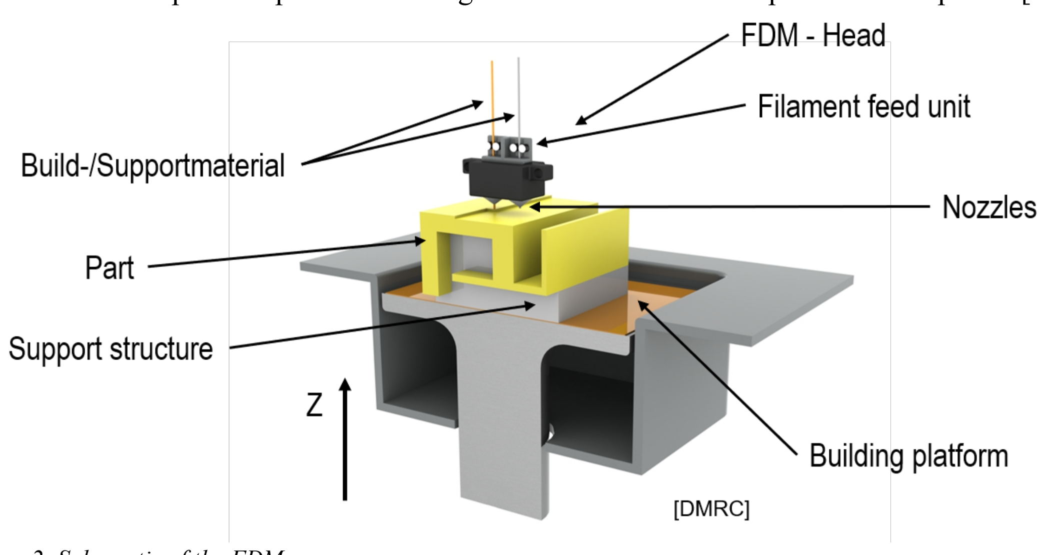

Figure 2: Schematic of the FDM process.

A first comparison of the mechanical properties resulting from the FDM and the APF process was conducted by PINTER et al. [5]. In the investigations, components manufactured in the FDM, APF and injection molding process were compared. Considered properties are the tensile strength, Youngs's modulus, elongation at break, flexural strength, flexural modulus, flexural strain, impact energy and density.

Experimental Investigations

For the investigations of the process limit for the FDM and APF process the process limits to be considered are divided into two categories. These are the resolution and the specific limits of the material extrusion. The specimen geometries for each of the categories are given in Figure 3 and are assigned to the specific aspects via the letters a-i.

The investigation of the resolution is further divided into the following aspects: minimum wall thickness (a), minimum slot width (b), minimum pin diameter (c), minimum hole diameter (d) and minimum part thickness in z-direction (e). The specimen geometries (a) - (d) are in accordance of the standard DIN ISO 52902. Specimen geometry (e) is according to an investigation carried out by ADAM [6].

The specific limits of the material extrusion are too further divided into the maximum bridging length without support (f), the maximum overhang without support (g) and the minimal angle between building platform and component without support (h). Another aspect of the specific limits of the material extrusion is the achievable length to diameter ratio in z-direction (i). The specimen geometries (f) and (g) are according to FERNANDEZ et al. [7] while (h) is according to the standard DIN ISO 52902. Finally, specimen geometry is according to ADAM.

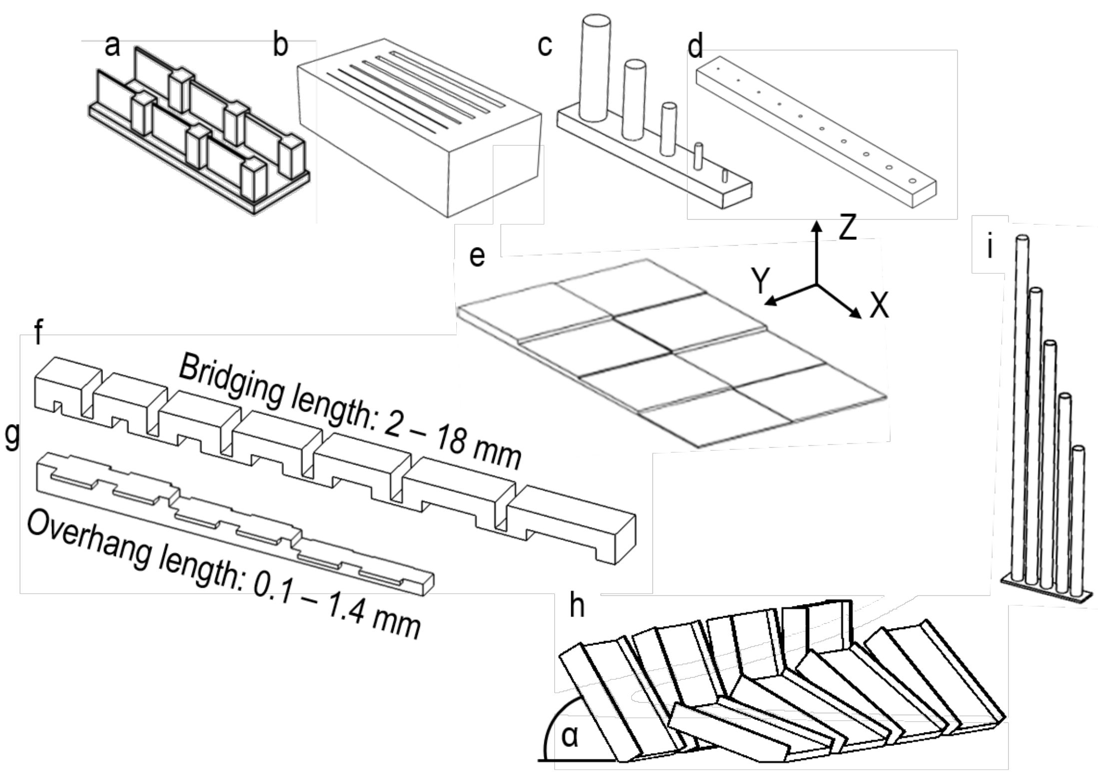

Figure 3: Display of the used specimen geometries.

All investigations are carried out with the ABS-M30 material distributed by Stratasys. This is for assuring the comparability of the specimens between the FDM and APF process while also maintaining a high filament quality. As the slice heights are preselected for different nozzle sizes in the slicing software (Insight) for the Fortus 400mc the layer height for the APF process was adapted accordingly. For a layer height of 0.1778 mm in the FDM process a corresponding layer height of 0.178 mm was set for the APF process. Other relevant process parameters are given in Table 1. Also, all specimen geometries are built with identical STL-files for both processes.

Table 1: Description of the applicable process parameters for each process.

Process	**APF**	**FDM**
Nozzle size	0.2 mm	T12
Layer height	0.178 mm	0.1778 mm
Nozzle temperature	250 °C	320 °C
Build chamber temperature	90 °C	90 °C
Shrink factor (x/y)	1.005 %	1.0055 %
Shrink factor (z)	1.006 %	1.0059 %
Contour width	-	0.3556 mm
Raster width	-	0.3556 mm
Raster angle	45° (alternating)	45° (alternating)
Self-supporting angle	> 75°	> 43°
Air gap	-	0 mm
Form factor (build/support)	1.3439	-
Discharge level (build/support)	47 %	-

The tensile test specimens are manufactured according to DIN EN ISO 527-2 Type 1B in the orientations xy, xz and z (see Figure 4 left). For the tensile test specimens orientated in z-direction in the APF process a special support structure has to be applied to stabilize the part and prevent it from oscillating with raising build height (see Figure 4 right). A soluble support material is used to avoid damaging the tensile test specimens during the removal of the support structures. The specimens manufactured with the FDM process are without a support structure.

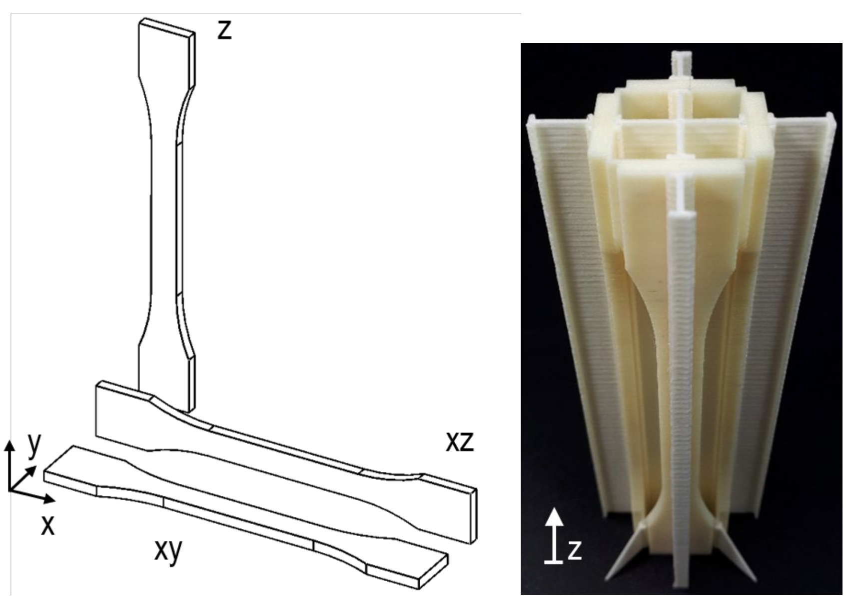

Figure 4: Orientation of the test specimens (left) and the special support structure for the z-orientation (right).

Specimens for the comparison of the impact strength are manufactured in the same orientations according to DIN EN ISO 179-2, while specimens for the flexural strength are manufactured according to DIN EN ISO 178. All specimens are tested according to the individually applicable standards.

Furthermore, specimens for the examination of geometrical properties are built with the FDM and the APF process. The specimen for the geometrical properties consists out of a variety of different design elements (Figure 5). For example, curved surfaces, holes and circles. With this specimen a direct comparison of several design elements between the two processes is possible. The densities are determined using cubes with an edge length of 20 mm. The assessment of the economic efficiency is described in the separate section "Economic Efficiency" after the evaluation of the experimental results.

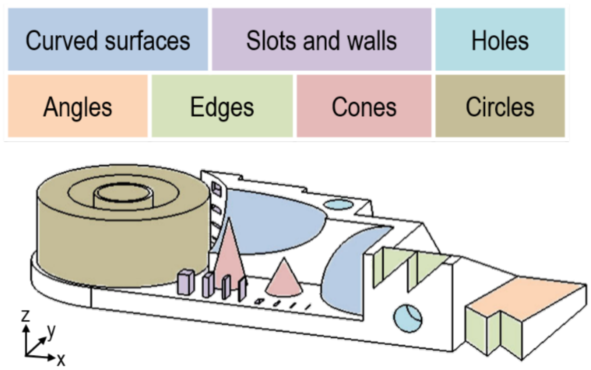

Figure 5: Specimen for the geometrical properties.

Results and Discussion

Beginning with the comparison of the achievable resolution with the FDM and APF process the results for the minimum wall thickness and minimum slot width show that in both aspects both processes deliver similar results (Figure 6). With both processes only the 0.2 mm and the 0.1 mm thick walls could not be manufactured. It is noticeable that in the FDM process only the wall with a thickness of 1 mm is being filled. All other walls are only consisting out of two contour strands. In contrast the APF process can realize a filling of all manufacturable wall thicknesses (see Figure 6 bottom). This is because the drops have a smaller width than the deposited strands in the FDM process.

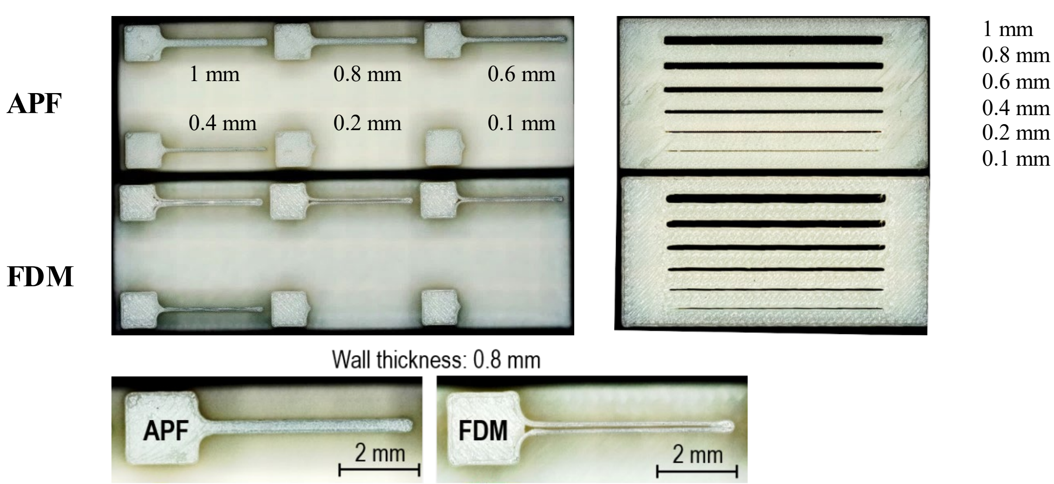

Figure 6: Comparison of the minimum wall thickness (left) with a detail view of the wall thickness of 0.8 mm (bottom) and the minimum slot width (right).

The next two aspects in the evaluation of the experimental results are the minimum pin diameter and minimum hole diameter. Here, pins with the diameters 4 mm, 3 mm, 2 mm, 1 mm and 0.5 mm were manufactured with both processes. As shown in Figure 7 (left) all pins except for the one with 0.5 mm diameter are manufacturable. Regarding the minimum hole diameter all holes could be manufactured with the APF process. Holes with a diameter of 0.7 mm, 0.6 mm and 0.5 mm could not be manufactured with the FDM process (see Figure 7 right). The reason for this is again the lower drop width in the APF process compared to the strand width in the FDM process.

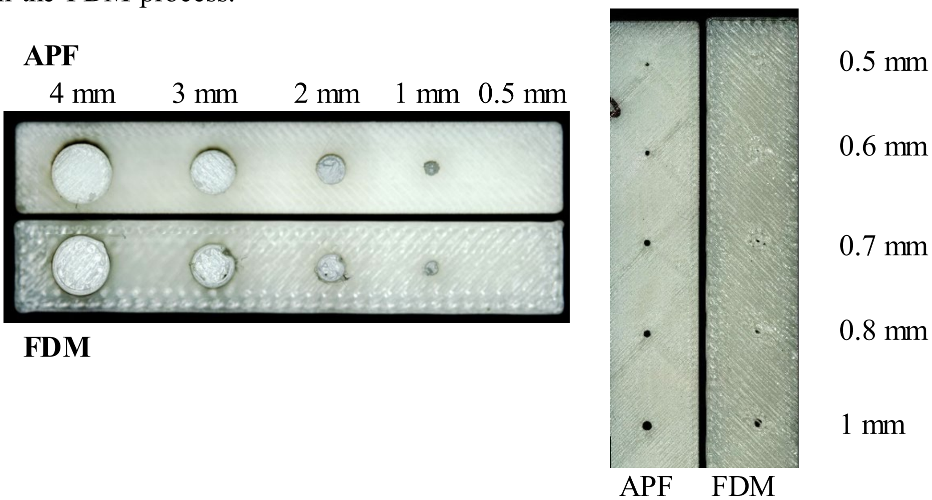

Figure 7: Comparison of the pin diameters (left) and the hole diameters (right).

The last aspect regarding the resolution of both processes is the minimum part thickness in z-direction. The results show that for the FDM process a minimum part thickness in z-direction of 0.6 mm is necessary to achieve a visually closed part surface. Using the APF process a part thickness in z-direction of 0.3 mm is sufficient to obtain a visually closed part surface.

Following, the results for the specific limits of the material extrusion are presented. The specimens for the maximum bridging length without support show better results in the FDM process. Bridging lengths of up to 10 mm are manufacturable without fatal defects in the specimens. In the APF process a length of 4 mm can be bridged without significant errors. This is because each droplet is deposited individually in the APF process and is only slightly connected to the previously deposited droplet. In contrast to that the strand deposited in the FDM process can be stretched over 10 mm without the strand sagging to a critical extend.

The specimens for the maximum overhang show no significant differences between the FDM and APF process. Overhangs of up to 0.8 mm can be manufactured with minor defects in both processes. The minimum angle between build platform and component on the other hand shows significant differences between the two processes. In the FDM process the minimum angle where parts can be manufactured without defects is 40°. With 60° the APF process needs significantly higher angles to assure a reliable process. The comparison of the maximum length to diameter ratio (LDR) shows that in the FDM process specimens with a height of 150 mm and a diameter of 5 mm can be realized resulting in an LDR of 30. In contrast to that the APF process is only capable of producing specimens with a height of 75 mm with a diameter of 5 mm resulting in an LDR of 15. This is because in the APF process the build platform is moved instead of the head in the FDM process. This causes an oscillation of the specimens at a much lower height in the APF process and leads to lower achievable LDRs. Results for the density show no relevant differences. The specimen for the geometrical properties (Figure 5) shows identical results for both processes.

The results of the determination of the mechanical properties show for most parts similar values. For the tensile strength, Young's modulus and elongation at break the values for the xy- and xz-orientation are approximately in the same range. Only the results for the z-orientation show significant differences (Figure 8). The reason for this is that probably the heat energy brought into the component by the new deposited material is higher for the FDM process as the strand has a greater volume as the droplet in the APF process. Therefore, the weld seams between the layers are not as distinct in the APF process as they are in the FDM process which leads to lower values for the z-direction.

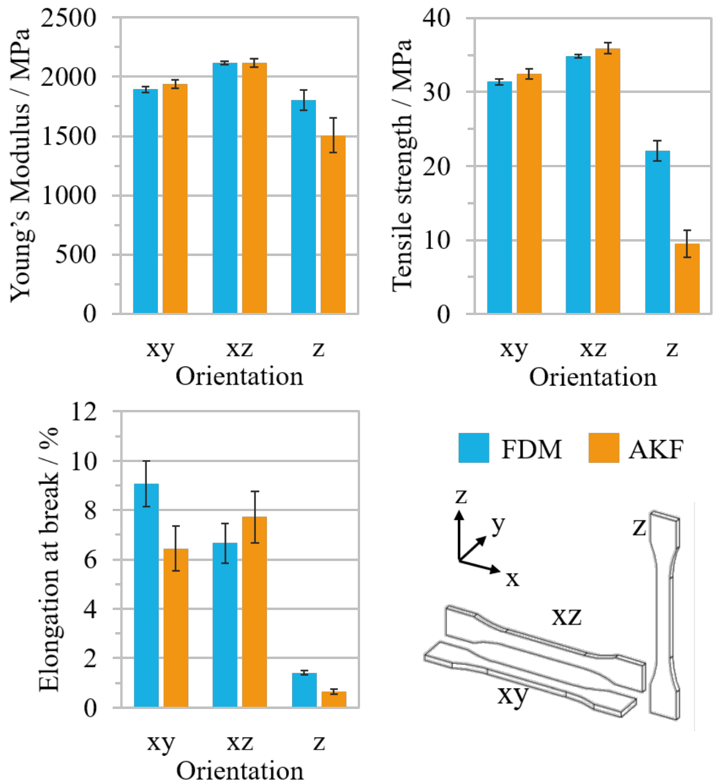

Figure 8: Results of the tensile tests.

The results for the flexural tests are shown in Figure 9. The values for the flexural strength and modulus are in the same range for both processes in all orientations. Only flexural strain shows noticeable differences between the two considered processes. Here, the APF always delivers higher values, except for the z-orientation where the values are again on a comparable level. The values of the impact strength test show slightly higher values for the APF process (Figure 10).

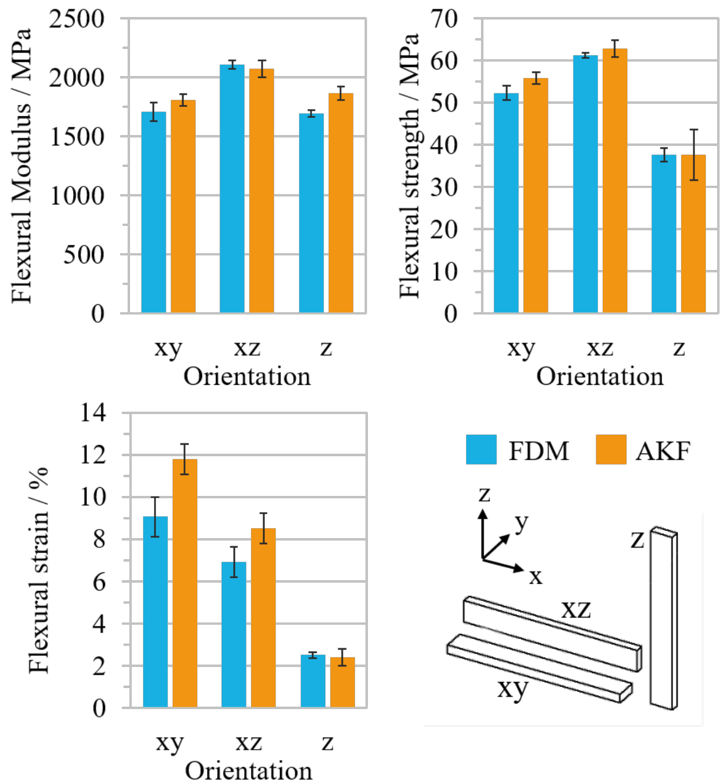

Figure 9: Results of the flexural tests.

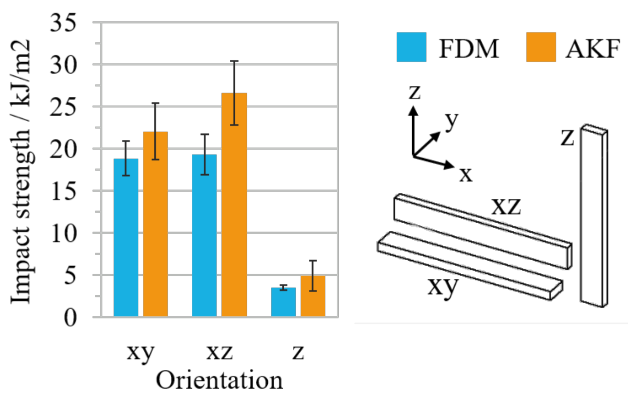

Figure 10: Results of the impact strength tests.

Economic Efficiency

For the evaluation of the economic efficiency over 60 influencing factors are considered. In this paper, in total six influencing factors with the highest impact are selected and investigated (Table 2). As standard granulates can be used in the APF process the material costs are significantly lower. As nozzles e.g. are more expensive in the APF process the costs of wear are higher compared to the FDM process. The same is observable for the depreciation as the Freeformer is more expensive that the Fortus 400mc but needs less energy. Also, the maintenance costs are lower in the APF process as they must not be performed by a service technician. The staff costs for the APF process are higher because preparing a build job requires flushing the material reservoir and calibrating the droplet size, which both take time. All in all the resulting costs per hour of build time are on the same level. But due to the overall higher build rate in the FDM process the FDM process is cheaper.

Table 2: Comparison of the most influential costs.

	APF	FDM
Material costs (ABS)	12.50 €/kg	216.26 €/kg
Wear	0.09 €/cm^3	0.01 €/cm^3
Depreciation (5 Years)	30,000.00 €/a	24,000.00 €/a
Energy	961.71 €/a	1,361.36 €/a
Maintenance	3,750.00 €/a	8,000.00 €/a
Staff costs	0,75 h/job with 60 €/h → 45 €/job	0,58 h/job with 60 €/h → 34.80 €/job

Conclusion and Outlook

The investigations show that although a different type of material deposition is used in the APF and FDM process the resulting part properties are mostly very close to each other. In the resolution aspect the APF has a slight advantage when it comes to small hole diameters or the complete filling of thin walls. On the other hand, the FDM process is capable of manufacturing lower angles between building platform and component than in the APF process. Also the bridging of gaps of up to 10 mm without support structures is possible in the FDM process. Regarding the mechanical properties the main differences can be observed in z-orientation. Here, the FDM process shows higher values compared to the APF process. The comparison of the economic efficiency shows that the FDM process is more economic efficient. Especially when switching to an open parameter FDM machine, which enables the use of cheaper materials, the advantage of the FDM process in regard to the economic efficiency is significant.

In further investigations the development to speed up the building process in the APF to catch up to the FDM process is planned. In addition to that, the economic efficiency shall be further investigated to get an even more detailed insight into the applicable costs. Finally, more process parameters shall be considered for the comparison of the mechanical properties.

Acknowledgement

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