Mechanical Properties of Additively Manufactured Polymer Samples using a Piezo Controlled Injection Molding Unit and Fused Filament Fabrication compared with a Conventional Injection Molding Process

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Abstract

In polymer additive manufacturing (AM), many processes have been developed and optimized in order to achieve decent mechanical properties in recent years. Nonetheless, it is hardly possible to reach the reference properties given by the injection molding process using the same base material.
Within this contribution, a process using a piezo controlled injection molding unit was compared with a common fused filament fabrication (FFF) process and the injection molding process. The novel AM process using an injection molding unit can theoretically process any thermoplastic granulate. In order to compare these three mentioned processes, a filament for the FFF was extruded using the same ABS granulate as for the method based on the piezo controlled injection molding unit and the conventional injection molding process.
Results show that quasi-static mechanical properties depend more on the achievable density than on the manufacturing process itself while dynamic tests offer room for optimizations.

Keywords: APF, FFF, Impact Properties, Computed Tomography

Introduction

Additively manufactured polymer components provide a big advantage in prototyping since there is no need for an expensive injection molding tool. In recent years, 3D-printers became popular because of the low price resulting from ongoing developments and a high number of producers. For thermoplastic materials, the most common method is fused filament fabrication (FFF). Throughout this contribution, the FFF process is carried out using an Ultimaker 2+ printer. Commercial FFF-printers are affordable for end-users, but the filament is relatively expensive compared to the bulk material in form of plastic pellets. Additive manufacturing with a piezo controlled injection molding unit as used in "ARBURG plastic freeforming" (APF) enables to process those pellets directly using an integrated injection molding set (Gaub 2016). Thus, the ARBURG freefomer, which is utilized within this contribution, enables to print every thermoplastic material available in pellet form which does not include filler materials. Both processes, the freeformer and the FFF, build parts slice by slice on a build plate. Thus, the interface between those layers is obviously weaker than in-plane because the material does not mix across those interfaces (N. Turner et al. 2014). Concepts for improving the strength of those interfaces are introduced in (Sun et al. 2008). Additionally, Polymer molecules are mostly aligned to the printing-path, which results in a higher strength in printing track direction (Es-Said et al. 2000). To eliminate those process-related interfaces, both processes are compared with reference components produced by injection molding using the same material.
Quasi-static mechanical properties of FFF acrylonitrile butadiene styrene (ABS) samples and injection molding have already been compared by (Tymrak et al. 2014). Dawoud et al. (2016) compared the fused deposition molding (FDM) method by Stratasys, which works similar to the FFF method, with the injection molding process. Also different orientations of the infill and impact tests were taken into account. Another contribution of (Ahn et al. 2002) compared the FFF process with injection molding using tensile and compression tests. More investigations on the layup orientation can be found in (Es-Said et al. 2000) and (Ziemian et al. 2012). Investigations on pores and dimensions of additively manufactured components by computed tomography have already been carried out by (Thompson et al. 2016).
In this contribution, the novel APF method is compared to the FFF method and injection molding. Furthermore, in addition to quasi-static tests, impact tests are investigated. In order to determine the stiffness, the ultimate tensile strength and the impact energy of the manufactured components, mechanical properties are examined by

the tensile-test, the 3-point-bending-test and the impact test. Concerning material savings and lightweight design, the density of each sample is measured to illustrate the dependency of the investigated material properties and the actually used amount of material. Investigations on the inner structure of the additively manufactured components are performed using computed tomography.

Manufacturing Processes

FFF is the most common additive manufacturing process for polymers. The filament is molten in front of a nozzle and extruded onto the build plate or the layer below, respectively. The principle of this process is illustrated in Figure 1 on the left hand side. It shows the build plate, which can be moved in x, y and z-direction. A coil contains the filament, which is carried through a plastic tube by an electrical drive, which controls the speed of the filament and therefore the material flow. This drive is not regulated with respect to the filament diameter in most FFF systems and thus, the material flow can vary if the diameter is not constant. The build plate is mostly made of glass and can be heated up to increase the adhesion to the printing material. Usually, a coupling agent is applied to the plate to promote this interface strength.
Another method for additive manufacturing is “ARBURG plastic freeforming” (APF). The ARBURG freeformer is a commercial but open system with respect to the G-code and process parameters. It is also available with two integrated injection sets to print multi-material components. The feedstock consists of ordinary polymer pellets which are molten within the injection set (Figure 1 right). At the end of this set, there is a nozzle to maintain the pressure of the polymer and to control the material flow. This piezo actuated nozzle can be triggered with a frequency between 60 and 200 Hz to release small droplets of polymer. The system prints onto a plastic build plate which is connected to the machine table by vacuum. This ensures a good connection of the components to the plate. The entire build chamber can be heated up to improve the interface between the printed tracks. Both introduced AM-methods are compared to the conventional injection molding process using the same ABS material.

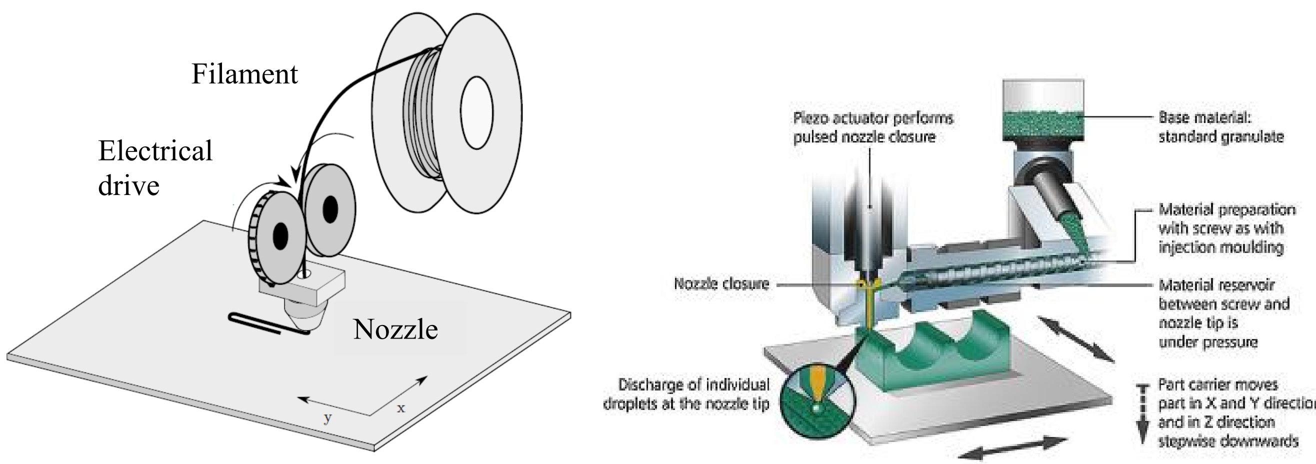

Figure 1 left: Principle of the FFF process, right: Principle of ARBURG freeformer (Gaub 2016).

Material and Methods

The material used throughout this contribution is an ABS material from BASF (Terluran GP 35), which was dried at a temperature of 80 °C for 4 h prior to the following processing. The filament for the FFF was extruded using the same basis material on a Haake Rheocord 90 single-screw extruder with a die diameter of 3.5 mm (Figure 2 upper right). Subsequently, it was cooled in a water quench (Figure 2 below). Despite the die diameter of 3.5 mm, the diameter of the filament is primary influenced by the controlled outfeed behind the die and the water quench. The outfeed velocity was set to 5.1 m/min resulting in an average filament diameter of 2.85 mm. The extruder was operated at a speed of 50 rpm with constant temperature of 150 °C at the nozzle and in all of the three temperature zones. The pressure at the nozzle was 140 bar. Finally, the filament was rolled on a coil. In order to ensure same conditions for all methods, the pellets for injection molding and APF were shredded from this extruded filament.

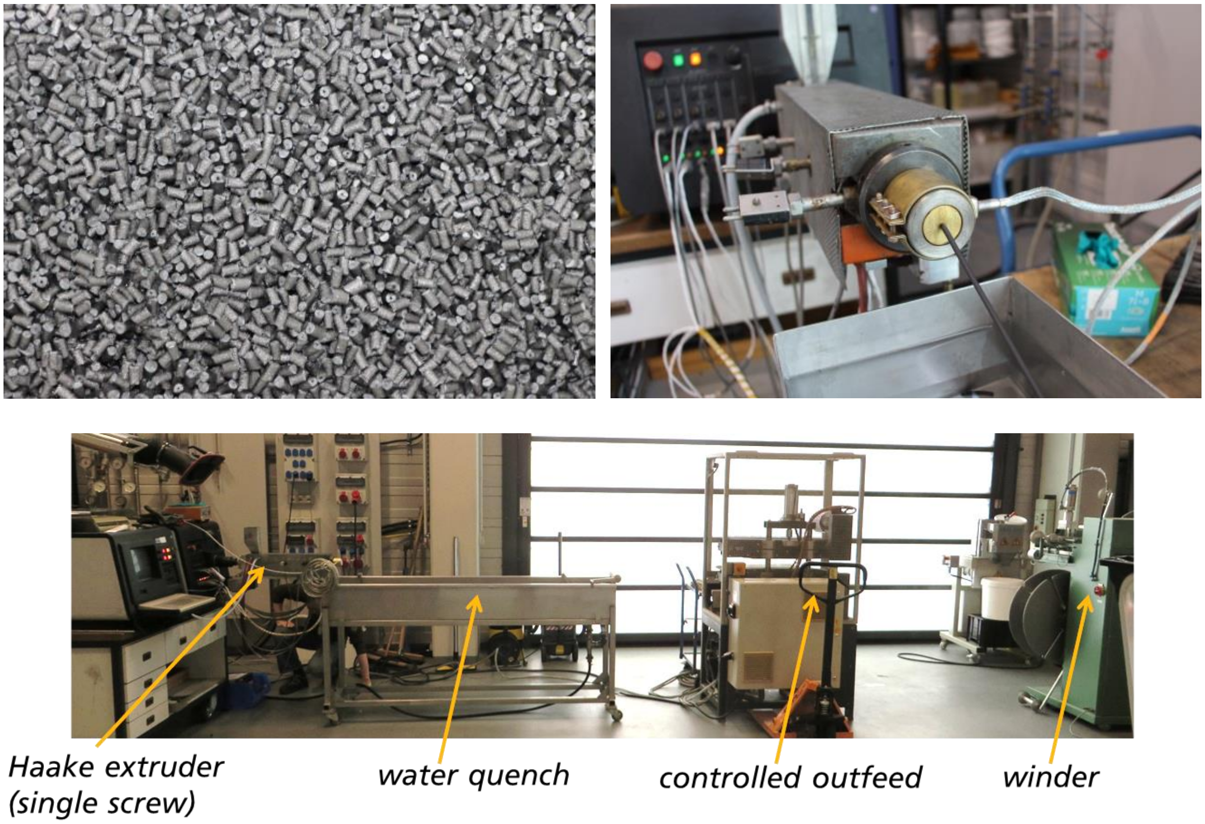

Figure 2 upper left: Polymer granulate, upper right: Die of the single-screw extruder including an extruded filament. Below: Filament extrusion line

Samples for mechanical tests were designed uniformly for the tensile test, the three-point-bending test and the impact test. Figure 3 illustrates the geometry of the samples and the printing path for additive manufacturing. One contour track, also called the perimeter, and an infill in +/-45° direction was used for FFF. Since the track width of the APF process was only half of the track width using Ultimaker 2+, two contour tracks are used to receive comparable parts. More detailed parameters for the AM processes are listed in Table 1.

Table 1: Process parameters of additively manufactured samples

	ARBURG freeformer	Ultimaker 2+
Nozzle diameter	0.2 mm	0.4 mm
Layer height	0.2 mm	0.2 mm
Track width	0.21 mm	0.45 mm
Nozzle temperature	230 °C	230 °C
Temperature build plate / chamber	80 °C	80 °C
Coupling agent	Not necessary (plastic build plate)	Hairspray

Injection molded parts were manufactured on an ENGEL 120t injection molding machine. To equalize the process parameters to the additive manufacturing processes, temperatures were chosen similarly. The nozzle temperature was set to 230 °C and the mold temperature was 80 °C for all produced specimens. The maximum injection pressure was 870 bar and the dwell pressure was 450 bar and has been kept for 10 seconds. The cooling duration was 25 s. Mold dimensions resemble the multipurpose test dog bone specimen described in DIN EN ISO 3167. For injection molded parts, the sample geometry for the mechanical tests was cut from those standard specimens

with the dimensions of 10 x 80 x 4 mm³ (Figure 3). Each mechanical test was carried out on 10 samples of each manufacturing process under laboratory conditions at 22 °C. Samples have been stored under same conditions for at least 24 h before testing. Figure 5 shows a sample produced by the ARBURG freeformer.
Tensile tests were performed on a 200 kN universal testing machine by Zwick (left: Tensile test with Zwick multiXtens extensometer. Middle: 3-point-bending test with linear inductive extensometer below the sample. Right: Impact test machine.Figure 4 left), which provides an automatic tactile extensometer (Zwick multiXtens). Tensile tests were carried out with respect to DIN EN ISO 527-1 using a traverse speed of 2 mm/min. Young's modulus was determined by a regression between 0.05% and 0.25% strain and the specimen length between the clamps was 48 mm.

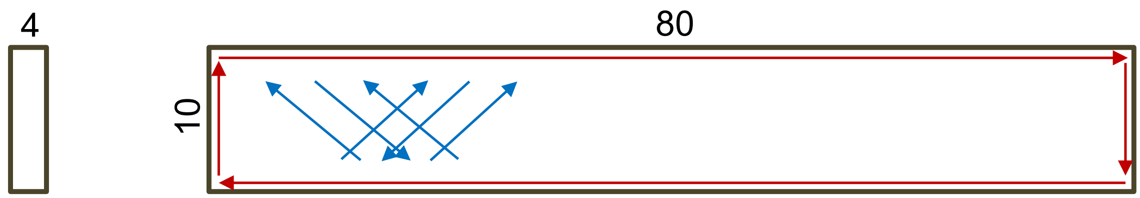

Figure 3: Specimen geometry for mechanical tests.

3-point bending tests were carried out on a Zwick universal testing machine with a maximum load of 2.5 kN (Figure 4 middle). Parameters were chosen regarding DIN EN ISO 178:2013-09 (Method A) with a bearing diameter of 10 mm. Testing speed was 2 mm/min at a span length of 64 mm and the Young's modulus was evaluated by regression between 0.05% and 0.25% strain. The smooth side of the samples, which was printed on the build plate, was facing down during testing. For measuring the displacement, a linear inductive extensometer was used at the center of the specimen.
For investigations on the impact behavior, a Zwick impact test machine (HIT5.5P) was utilized. The specimens were tested with respect to DIN EN ISO 179-1 using geometry type 1 without a notch. The smooth side of the sample was always on the upside. The impact energy was 5 J.

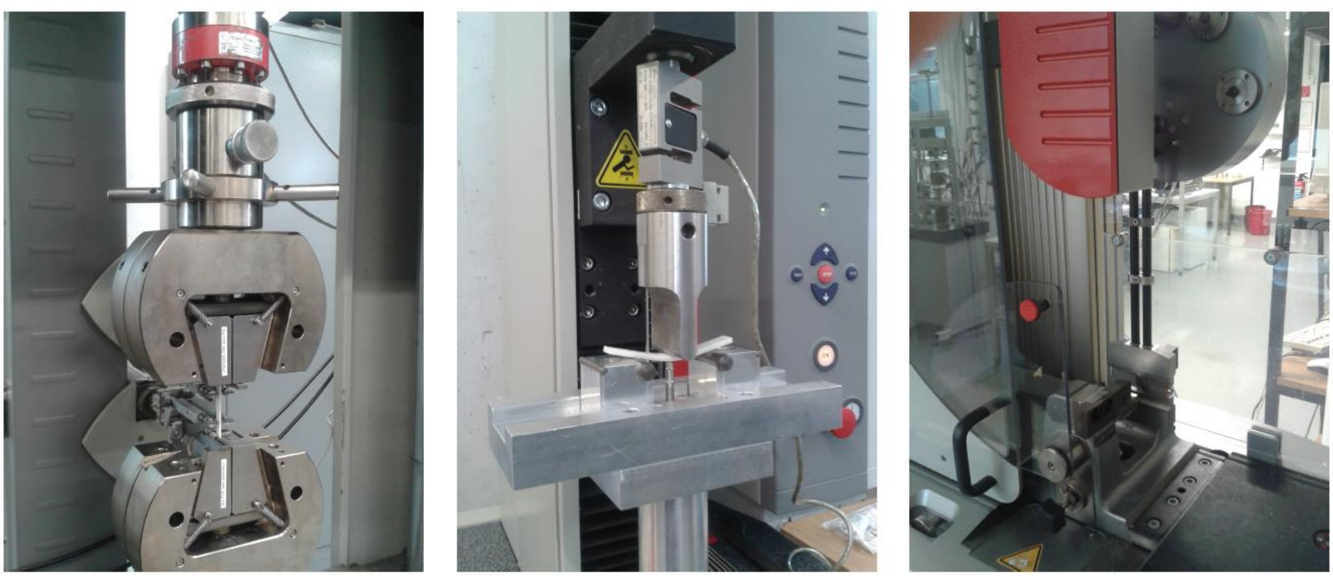

Figure 4 left: Tensile test with Zwick multiXtens extensometer. Middle: 3-point-bending test with linear inductive extensometer below the sample. Right: Impact test machine.

Figure 5: ABS sample produced by ARBURG freeformer

µCT-Investigations

µCT-Scans were performed using an YXLON Precision CT-scanner at an acceleration voltage of 100 kV and a tube current of 0.02 mA resulting in a power of 2 W. The resolution of the scans is 7.7 µm. Figure 6 illustrates a slice of the reconstructed images produced by injection molding (a), the ARBURG freeformer (b) and the Ultimaker 2+ (c). The injection molded sample does not show any visible pores at this resolution. Within the freeformer sample, there are some pores on the left and right edge of the sample. The Ultimaker sample shows periodically occurring pores all over the sample while the density on the bottom of the sample seems to be higher.

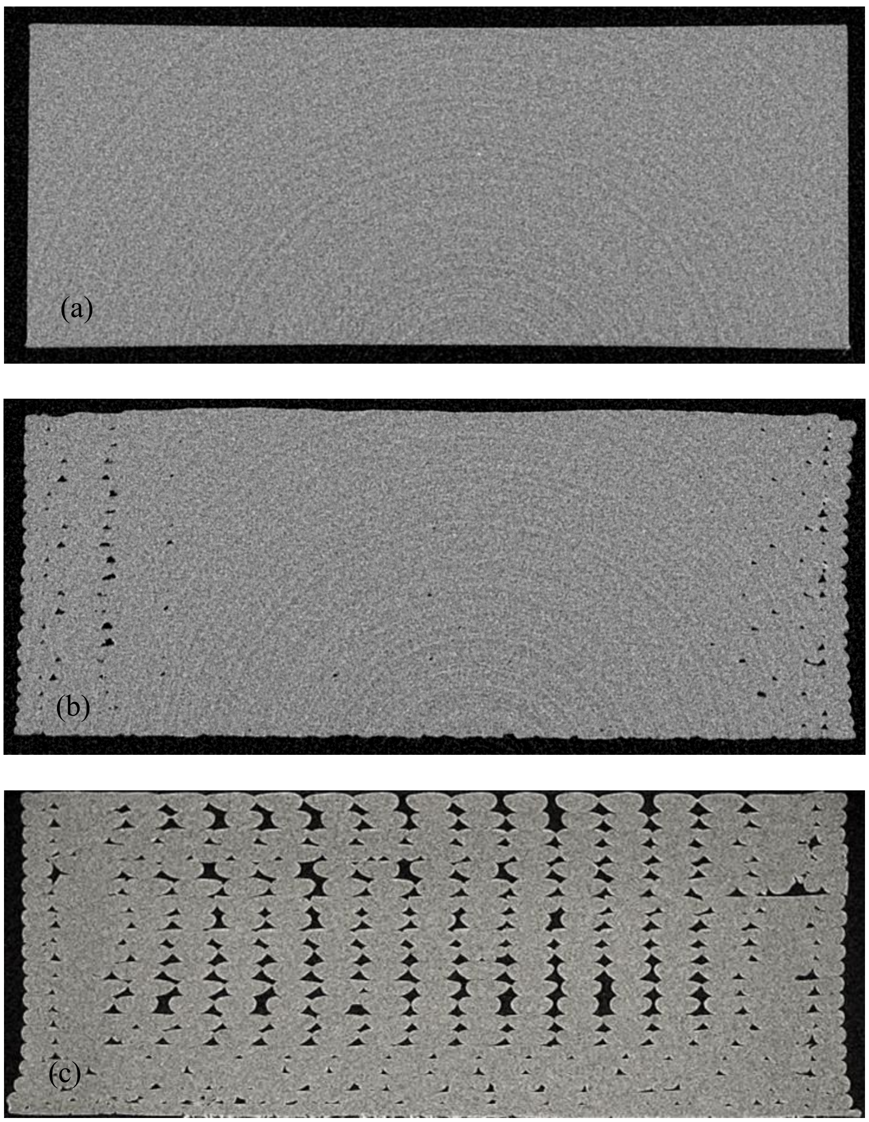

Figure 6: µCT-scans of samples manufactured by injection molding (a), freeformer (b) and Ultimaker 2+ (c).

Results

Tensile Tests show a clear correlation between Young's modulus and density of the samples. The weight of each specimen was measured using the AE240 fine scale by Mettler. Since some the AM-samples have a lower density than water, the principle of Archimedes cannot be applied and the dimensions were measured by an outside micrometer. In Figure 7, all investigated samples are depicted over the density. Independent of the manufacturing method, Young's modulus decreases with the density of the specimen. The same behavior can be observed with respect to the ultimate strength of the samples.

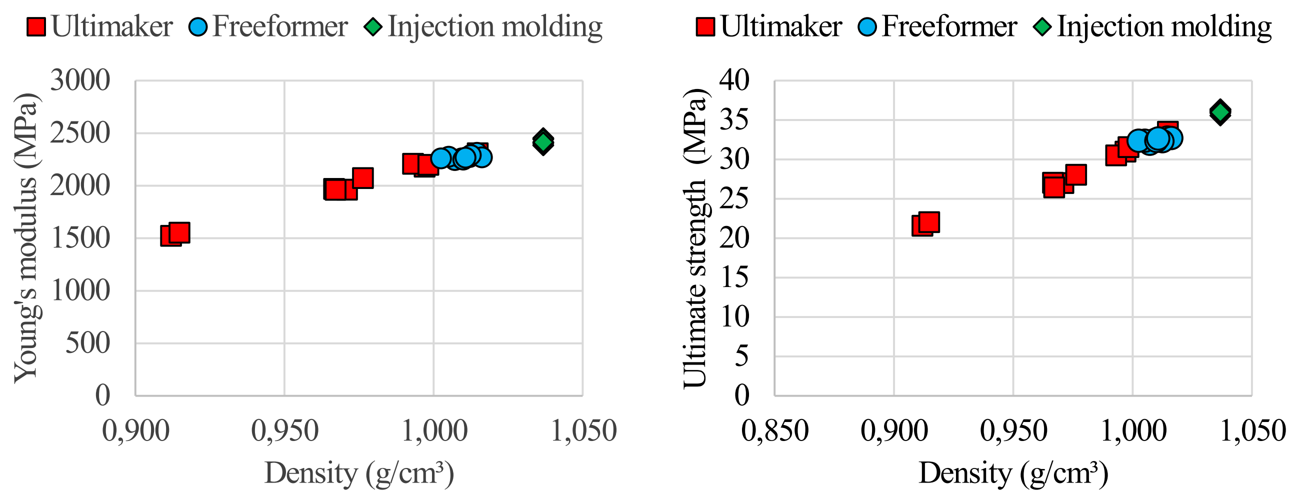

Figure 7: Results of tensile tests. Left: Young's modulus over density. Right: Ultimate strength over density.

Flexural moduli from bending tests decrease with density similar to the results of the Young's modulus from tensile testing (Figure 8). Considering a linear least squares fit of the Ultimaker data, all specimen manufactured by freeformer and injection molding are below this fit. The Coefficient of determination R^2 of this fit is 0.975.

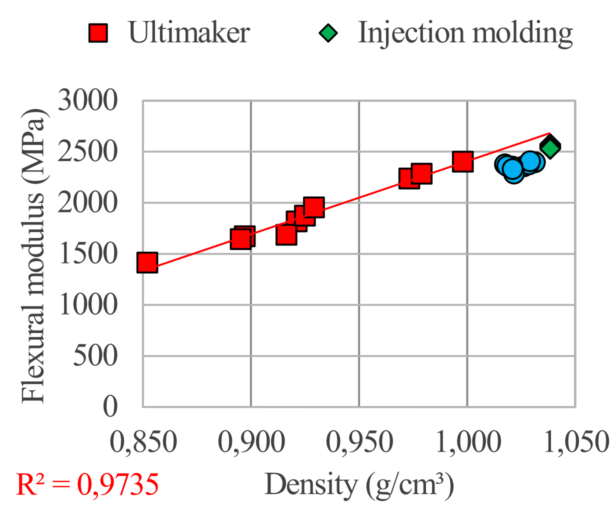

Figure 8: Flexural modulus over density resulting from 3-point bending tests.

Impact tests led to results depicted in Figure 9. Samples produced by injection molding scatter widely in impact energy, but are almost constant in density. All of the additively manufactured show a low scatter in impact energy around 20 kJ/m² while the density varies between 0.89 and 1.02 g/cm³ for the Ultimaker 2+ and between 1.00 and 1.01 g/cm³ for the freeformer.

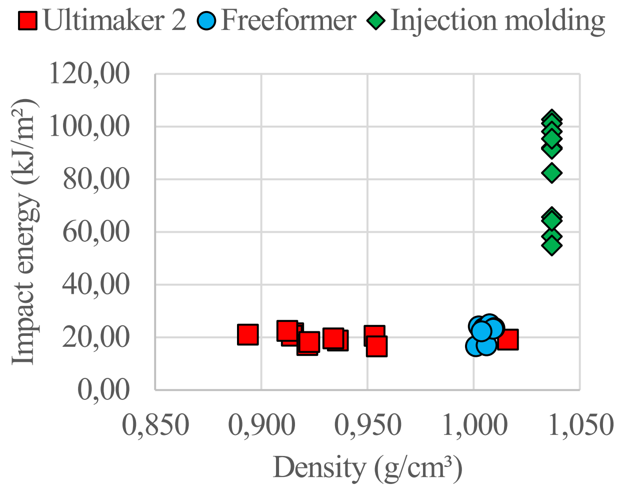

Figure 9: Impact energy over density resulting from impact tests.

Discussion

Mechanical properties regarding tensile tests led to Young's moduli and ultimate strength which are clearly related to the density of the specimens. Generally, common models predicting these mechanical properties of porous media cannot be applied as they are based on isotropic and equally distributed porosity (Gibson und Ashby 1999; Kováčik 1999; Wang 1984). Pores within the materials at hand show a high anisotropy and are mostly aligned in printing path direction. Moreover, the porosity over thickness of the sample is not uniform but periodic with respect to the layer height. Nevertheless, there seems to be an existent relation between tensile properties and density in the investigated range between 0.91 and 1.04 g/cm³ where the latter value is the density of the bulk ABS material. Samples manufactured by freeformer and injection molding do not scatter very much. Fluctuations in density using the Ultimaker 2+ may be the resulting effect from the in-house produced filament, which showed absolute deviations of 2.85 ± 0.1 mm in diameter on 20 randomly chosen points over the entire filament. Because of the missing regulation of material flow using this process, the material flow will decrease with the filament diameter and vice versa. Figure 10 shows a microscopic image of the surface of the Ultimaker 2+ sample. It is noticeable that the lower layers are not connected due to problems in material flow. Those huge gaps may also be a result from a discontinuous movement of the filament which can occur if the filament gets stuck for a short time. In tensile testing, all of the data points are on one line and thus the relation can be assumed to be linear within this region, but not for lower densities. On basis of this assumption, all of the investigated methods lead to the same properties in dependence on the density. Taking this circumstance into account, the ultimate strength is in good correspondence with the results in (Dawoud et al. 2016).
In 3-point-bending tests, the flexural modulus shows a linear connection to the density. A similar relation as for the Young's modulus can be found between flexural modulus and density. However, samples produced by freeformer seem to end in slightly lower values. Since this effect is not visible in the results of the tensile tests, a possible reason could be the significant (approximately 20x) lower strain rates in 3-point-bending and a difference in orientation of the molecules. Molecules in specimens manufactured by FFF are highly aligned to the printing direction due to the extrusion process. In APF, the material flow is expected to be less laminar due to the piezo controlled nozzle closure (Figure 1) and the discharge of droplets. The difference in alignment of the molecules can cause a difference in viscoelastic behavior (Brinson und Brinson 2008) and thus decrease the measured stiffness at low strain rates because the less aligned molecules will be stretched in loading direction. Despite the

lower stiffness at low strain rates, less oriented molecules can constitute a huge advantage in impact behavior, if there are no disturbing interfaces within the material.
Impact energies depend mainly on the presence of defects within the material. Since the injection molded parts are very dense throughout all samples, the impact energy is much higher than for additively manufactured samples. But also the scatter is high because a small imperfection within the material causes a significant drop of the energy that can be absorbed by the component. Additively manufactured samples have only minor variations on the impact energy. This results from the large amount of process-induced interfaces which appear between each layer and also between the tracks within the layer. Since the polymer does not mix with the solid material which is already printed, the adhesion between the tracks is low compared to the cohesion of the tangled polymer chains within a single filament. All of the freeformer and the Ultimaker 2+ samples absorb the same energy because it depends more on this interface strength than on the density of the sample. Investigations by (Dawoud et al. 2016) on ABS material and the same sample geometry led to higher impact energies using the same layup orientations and FFF. The impact strength of the injection molded parts result in a similar mean value. Dawoud used a nozzle diameter of 1 mm and a layer height of 0.5 mm in FFF leading to much less interfaces within the material and thus to higher impact strengths of around 40 kJ/m².

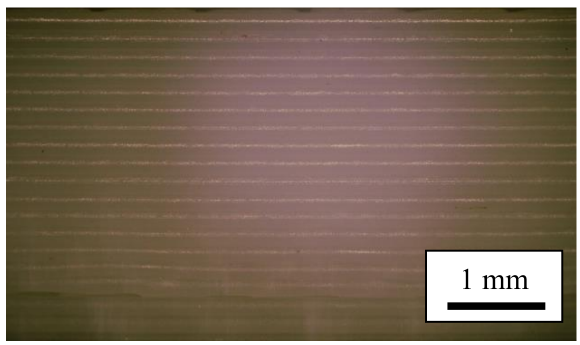

Figure 10: Light microscopic image of the Ultimaker 2+ three-point bending sample with lowest density.

Results from CT-scans showed significant differences in the microstructure of both AM-methods. The porosity of the samples produced by Ultimaker 2+ is periodic in most parts of the cross-section in Figure 6. The material is denser at the bottom which was connected to the warm build plate because of the lower viscosity of the material. Thus, the tracks can join together easily in order to reduce the free surface, which is the driving mechanism to reduce the porosity. Since the sample gets colder on layers with higher distance to the build plate, the pores between the tracks get larger. Sun et al. modeled this effect considering the temperature of the build plate and the heat conductivity and the specific heat of the polymer using a sintering model by (Pokluda et al. 1997). Due to the heated build chamber, the investigated freeformer sample does not show a dependency of porosity with respect to the position of the layer. It is very dense throughout the sample except for the interface between infill and perimeter. An active regulation of the material flow in those regions could possibly enable for an even higher density of the samples. Since the density of injection molded samples is equal to the bulk ABS material, there are no pores at all within those samples.

Conclusion

Results of the investigations performed within this contribution show that the quasi-static mechanical properties of additively manufactured parts depend more on the feasible density than on the process itself. In our investigations, the ARBURG freeformer led to a much better consistency in density than the Ultimaker 2+, since the material flow in FFF is not regulated and dependents directly on the diameter of the filament. Impact energies of the AM-samples are almost constant because the interface strength between the layers and the tracks is low compared to the cohesion within each track. Investigations on CT-scans did not directly lead to a better understanding of the macroscopic mechanical properties of the material, but can be used to optimize samples with respect to the porosity in future applications.

Acknowledgements

The authors like to thank Patrick Weiss from the Fraunhofer ICT for valuable discussions and his support in filament extrusion. Moreover, the support of ARBURG is gratefully acknowledged.

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