

## PROCESS PARAMETER OPTIMIZATION TO IMPROVE THE MECHANICAL PROPERTIES OF ARBURG PLASTIC FREEFORMED COMPONENTS

A. Hirsch\*, F. Hecker\*, E. Moritzer\*

\*Direct Manufacturing Research Center (DMRC), Paderborn University, Germany and  
Kunststofftechnik Paderborn (KTP), Paderborn University, Germany

### Abstract

The Arburg Plastic Freeforming (APF) is an additive manufacturing process that allows three-dimensional, thermoplastic components to be produced in layer by layer. The components are generated by depositing fine, molten plastic droplets. One of the main advantages of the APF process is the open machine control. Thus, the process parameters can be adapted and optimized for the individual applications.

The optimization is carried out on the basis of a variation of the process parameters using a statistical design of experiments. Relevant process parameters are the layer thickness, the form factor, the raster and delta angle as well as the overlap between the contour and the filling of a layer. In addition, the nozzle and build chamber temperatures are varied. Using this procedure, the effects of the influencing parameters on the mechanical properties and the interactions between the influencing parameters are analyzed and converted into mathematical models. On the basis of the results and the models, guidelines will be developed to assist the user of APF technology in the systematic process configuration for their own applications. The material used is ABS, one of the most frequently used amorphous thermoplastics in additive manufacturing. The mechanical properties are determined on the basis of tensile tests and the characteristic values tensile strength, elongation at break and Young's modulus. The results should show the performance of the APF technology in regard to the mechanical properties.

### Introduction

With its official market launch in 2013, the Arburg Plastic Freeforming (APF) is a relatively new technology in the field of additive manufacturing. This technology enables the production of three-dimensional thermoplastic components in one process from standard plastic granulate without the use of molding tools [1]. One of the main advantages of the APF technology is the open machine control which allows the variation of almost all process parameters. Thereby the process can be individually optimized for each component, and a large number of thermoplastics in granulate form can be processed. This results in a diversity of processable materials. It is possible to process cost-efficient materials, known from injection-molding. For the process parameter optimization and the processing of new materials, the exact influences and interactions of the process parameters on the component quality must be known. These influencing variables and interactions are not yet sufficiently known, so that a material qualification or optimization of the mechanical properties for a new material is currently based on the try and error principle.

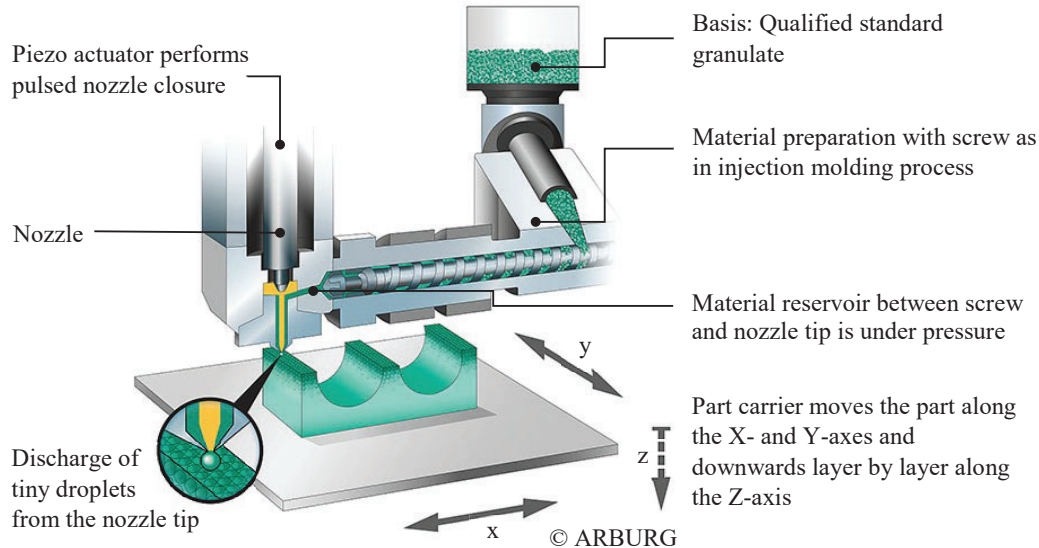
The aim of this research is the development of manufacturing guidelines for a rapid process configuration and optimization for the APF process. A detailed understanding of the process itself and the most important influencing factors should be developed. At the same time, manufacturing restrictions are to be identified during the investigations.

### 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. 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]



There are many process parameters that could influence the mechanical properties of plastic freeformed components. One of the most important process parameters with an influence on the component strength is the form factor. It is a special process parameter for the plastic freeforming. The form factor is used to vary the distance between the single droplets and between the droplet chains (Figure 2 a) [4]. Consequently, this parameter influences the porosity and filling of the components. Figure 2 b) shows the influence of the form factor on the surface quality. The left figure shows an overfilled component with an uneven surface from an overfilled specimen. The illustration on the right shows an ideal surface with the individual droplets of a not overfilled test specimen. Based on such an analysis of the surface, a simplified visual determination of the form factor is carried out. This must be done with every new material, in order to process it with the Freeformer. In addition to the form factor, there are other process parameters that could have an influence on the mechanical and visual properties of the manufactured components. These include for example the layer thickness, nozzle and build chamber temperature, overlap between raster and filling and the raster angle. [5]

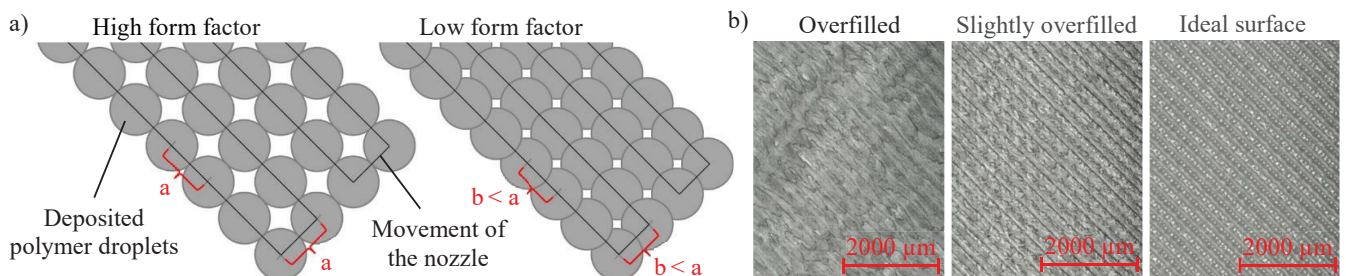


Figure 2: a) Schematic description of the process parameter form factor [4], b) Evaluation of the component surface of overfilled and non-overfilled test specimens

In principle, the APF process is similar to the Fused Deposition Modeling (FDM). The decisive difference is that the APF process generates a chain of many droplets while in the FDM process a continuous strand is deposited. The assumption suggests that the strength values of an FDM strand is higher than those of the APF droplet chain. Nevertheless, there are probably some general trends with regard to the influencing variables. In [6, 7], the influences of the filling strategy on FDM components were investigated, allowing initial conclusions

to be drawn, regarding the behavior of plastic freeformed components. In [5, 8, 9] first investigations on the resulting mechanical properties of plastic freeformed components were carried out. For example, process parameters which influence the filling strategy and the build direction were varied. In addition, comparisons of the mechanical properties of APF, FDM and injection molded components were made. Nevertheless, the literature does not provide comprehensive studies of the influencing variables and their interactions on the mechanical and visual properties, so that no summarizing manufacturing guidelines can be derived from them.

### **Experimental Investigation**

The influences of the process parameters on the mechanical properties of APF components are investigated with statistical design of experiments. Based on preliminary investigations, the production restrictions were identified and analyzed previously to the investigations in order to exclude any impact on the investigations. In the following, the basic conditions for the production of the test specimens and the execution of the design of experiments are defined. The material ABS Terluran GP35 from INEOS Styrolution is used for the production of the test specimens. Type 1B test specimens from DIN EN ISO 527-2 standard are used in the XY-direction to determine the mechanical properties (Figure 3 a). Three of these test specimens are produced together for each build job (Figure 3 b). The distance between the individual test specimens is 5 mm.

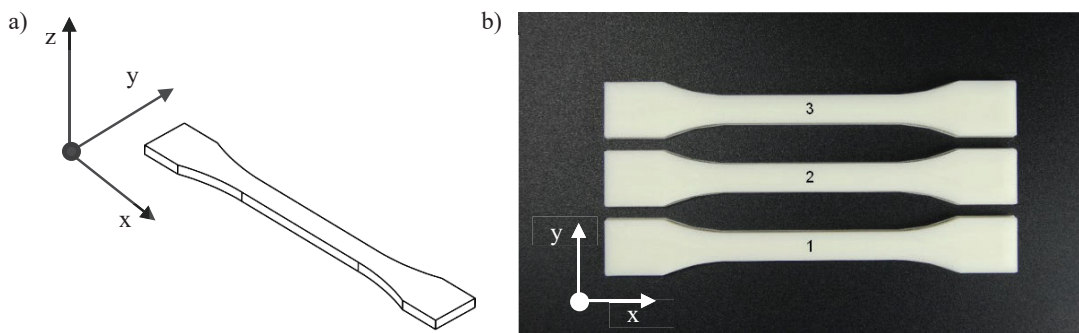


Figure 3: a) Flat orientation on the building platform, b) Positioning of the test specimens in a build job

The discharge level is an important process parameter which regulates the volume of a single droplet. This parameter must be monitored during the production of the test specimens because even a small variation in the droplet volume during the manufacturing process has an effect on the porosity of the component. For reproducible production of the test specimens, the discharge level must be within a tolerance range of  $\pm 5\%$  around the set point. The issue is that due to the smallest irregularities on the building platform, the discharge level varies widely, especially in the first component layer. The machine software does not readjust the discharge pressure in this layer, which leads to strong variations in the discharge level. This procedure was chosen by Arburg because unevenness on the building platform is compensated and at the same time the discharge level in the following layer achieves the previously calibrated value due to the constant pressure. As a result, the tolerance range of the discharge level of  $\pm 5\%$  is exceeded and the build job is aborted by the machine. The solution is to "raise" the test specimens by 0.2 mm in the Z-direction. To fill the gap, support material is used in the first two layers. The tolerance regarding the discharge level of the support material is set to  $\pm 50\%$  to prevent a termination of the build job. The test specimen is then manufactured on these correction layers without exceeding the tolerance range. After each build job the production report is checked for compliance with the tolerance range (Figure 4).

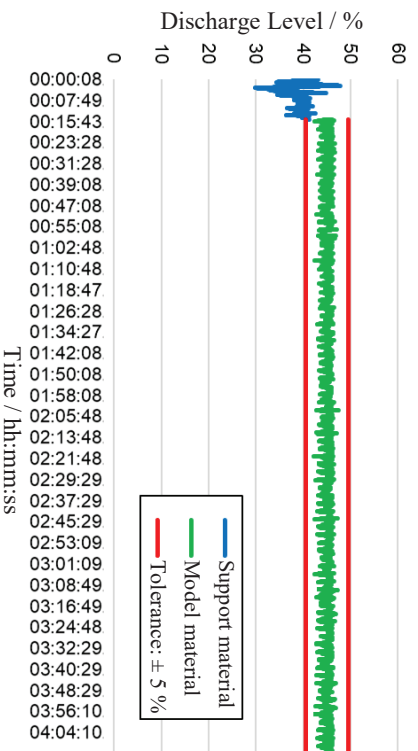


Figure 4: Production report for checking the tolerance of the discharge level

Five process parameters are analyzed with the design of experiments. These include the form factor, the nozzle and build chamber temperature, the layer thickness and the overlap between filling and contour. The Response Surface Method (RSM) is used in combination with the software Minitab. In detail, a Central Composite Design (CCD) with four continuous and one categorical factor, the layer thickness, is used. The influences of the raster angle and the delta angle are examined individually after the evaluation of the design of the experiments. The categorical factor layer thickness is fixed in the first step at 150  $\mu\text{m}$  and 200  $\mu\text{m}$ . The reason for selecting these layer thicknesses is that the layer thickness of 200  $\mu\text{m}$  is used as standard by Arburg for the nozzle diameter of 200  $\mu\text{m}$ . A layer thickness of 150  $\mu\text{m}$  is in the range of the lower limit for the material ABS Terluran GP35.

Table 1: Individual factor levels of the process parameters of the design of experiments

Parameter / Factor		Parameter / Factor Levels					
Layer thickness		150 $\mu\text{m}$		200 $\mu\text{m}$			
Nozzle temperature		230 °C	240 °C	250 °C	260 °C	270 °C	
Build chamber temp.		80 °C	(87.5 °C)	95 °C	(102.5 °C)	110 °C	
Form factor	150 $\mu\text{m}$	1.615 (- 0.05)	1.640 (- 0.025)	1.665 ( $\pm$ 0)	1.690 (+ 0.025)	1.715 (+ 0.05)	
	200 $\mu\text{m}$	1.315 (- 0.05)	1.340 (- 0.025)	1.365 ( $\pm$ 0)	1.390 (+ 0.025)	1.415 (+ 0.05)	
Overlap		40 %	50 %	60 %	70 %	80 %	

For the statistical validation two build jobs, therefore six test specimens are produced for each testing point. Due to the choice of five parameters, the design of experiments results in a total of 124 test points respectively 124 build jobs. Since this large number of build jobs cannot be realized, the number of test points is reduced to 80 with the D-optimality criterion. The D-optimality criterion is a function of the Minitab software. When this function is used, an algorithm only selects certain test points which are particularly important for the modeling process. This allows to reduce the number of test points without strongly affecting the quality the model. Table 1 provides an overview of the factor levels used in the design of experiments for the individual process parameters. The determination of the factor levels is based on experiences and preliminary investigations. One of the preliminary investigations is that a visual material qualification must be carried out for the two selected layer thicknesses. The most important aspect of this material qualification is the determination of a form factor depending on the layer thickness, the discharge level as well as the nozzle and build chamber temperature. A special characteristic of the experimental design is that the form factor is varied between -0.05 and +0.05, because the exact values of the form factors for the two different layer thicknesses are different (table 1).



## Results and Discussions

Based on the results of the investigations of the mechanical properties, mathematical regression models for the individual target values are set up with the help of Minitab. These models are used to identify and describe the main influencing parameters and interactions.

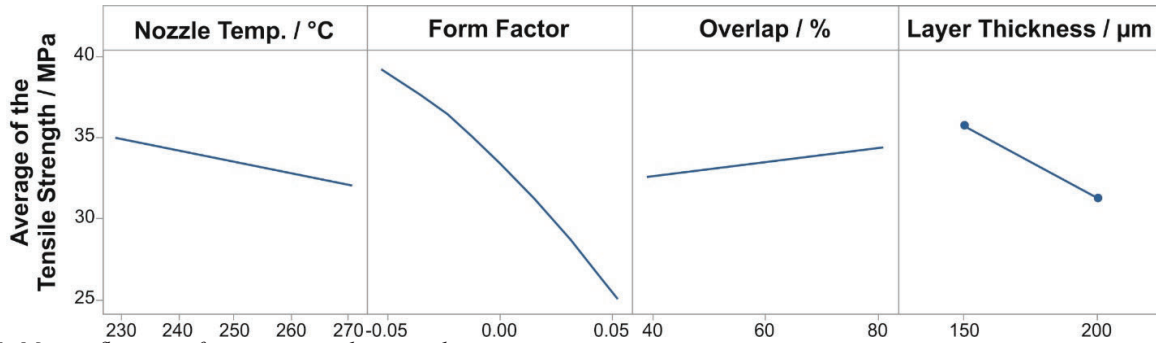


Figure 5: Main influencing factors on tensile strength

Figure 5 shows the main influencing factors on tensile strength. The most important influencing factor is the form factor. With a low form factor, a higher tensile strength is achieved due to the higher filling degree of the components. The second main influencing factor is the layer thickness. Higher tensile strength values are achieved with a lower layer thickness. The third main influencing factor is the nozzle temperature, followed by the overlap between filling and contour. The evaluation shows no remarkable interactions of the influencing parameters on the tensile strength. The main influence diagram for the Young's modulus looks very similar to that of tensile strength, so it is not discussed here further.

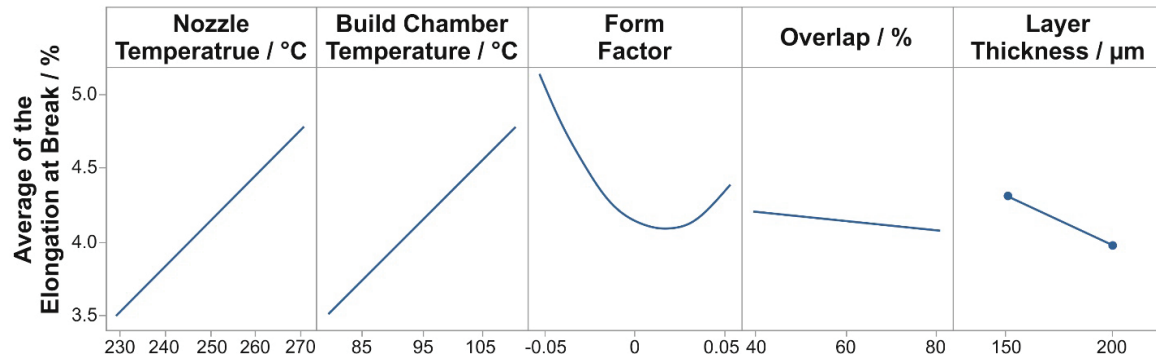


Figure 6: Main influencing factors on elongation at break

Figure 6 shows the main effects on elongation at break. The main effects are the build chamber and the nozzle temperature. Higher process temperatures result in higher elongation at break values. The third most important influencing factor is the layer thickness. With a layer thickness of 150 μm, a higher elongation at break is achieved than with 200 μm. With regard to the form factor, the model probably has some minor weaknesses in the marginal area, since an increase in elongation at break with an increase in the form factor is not to be expected. In this case, the model must be validated or, if necessary, improved by further test points.

Figure 7 summarizes the influences of the interactions on elongation at break. The most significant interactions concern the build chamber temperature, the form factor and the overlap in combination with the layer thickness. Depending on the layer thickness, the build chamber temperature has a different influence on the resulting elongation at break. With a low layer thickness (150 μm), the influence of a higher build chamber temperature is bigger than with a layer thickness of 200 μm. This means that the welding of the fine droplets of a small layer thickness is better at a high build chamber temperature. Another interaction shows diverging effects of the form factor on elongation at break depending on the layer thickness. With a small layer thickness of 150 μm, a small form factor must be used to achieve high elongation at break values. With a layer thickness of 200 μm, this influence is reversed.

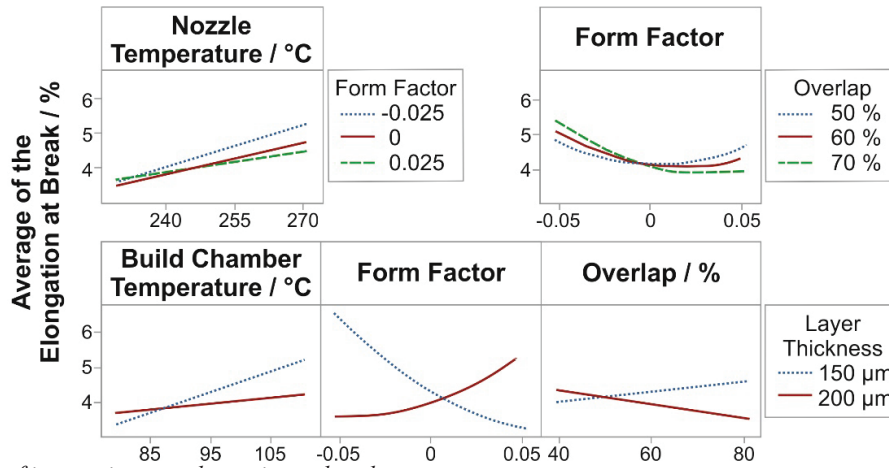


Figure 7: Influences of interactions on elongation at break

In addition to the mechanical properties, the surface roughness of the test specimens is also analyzed. The reason for these investigations was that in the preliminary period of these investigations, the components with the best strength usually had the worst surface properties due to slight overfilling. Nevertheless, the investigations have shown that the mechanical and visual properties can be optimized at the same time. The most important influencing factors are the layer thickness and the form factor. With a small layer thickness and a small form factor, the surface roughness  $R_z$  is minimized. The influences of the process temperatures and the overlap between filling and contour are significantly lower and not so significant.

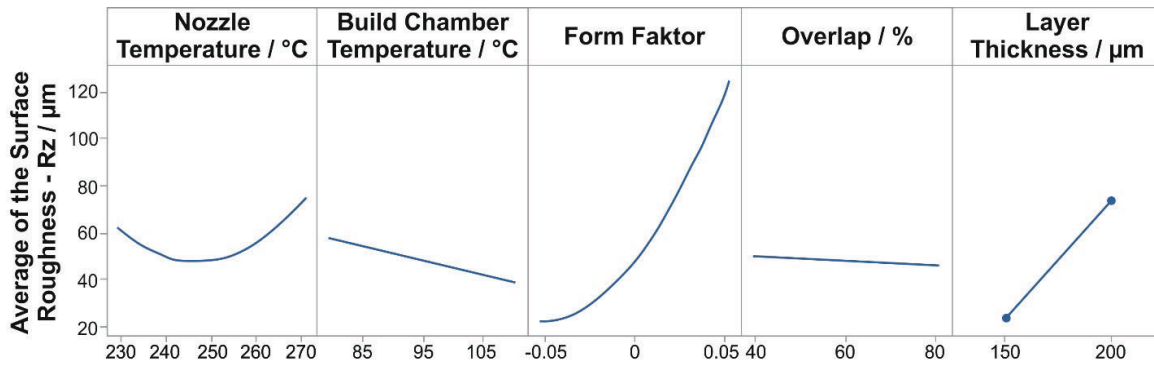


Figure 8: Main influencing factors on surface roughness

Based on the mathematical models, a parameter optimization for the maximization of the target properties tensile strength, elongation at break and Young's modulus is carried out. Table 2 summarizes the optimized process parameters with the predicted and experimentally determined mechanical properties and their deviations. The comparison between the predicted values from the mathematical model and the experimentally determined values shows that the models overestimate the influence of the process parameters. The deviations are in the range of between 10 % and 16 %. Considering that the test points are extreme values in the marginal area of the models, this deviation is acceptable.

Table 2: Optimization of tensile strength, elongation at break and Young's modulus using the mathematical models

Type of Load	$T_N$	$T_B$	F	$d_L$	$w_R$	$d_S$	Model	Exp. Investigation	Deviation
Tensile Strength / MPa	230 °C	110 °C	1.615	80 %	45°	150 μm	44.93	36.30	- 15.44 %
Elongation at Break / %	270 °C	110 °C	1.615	80 %	45°	150 μm	9.38	8.45	- 9.91 %
Youngs modulus /MPa	230 °C	110 °C	1,615	80 %	45°	150 μm	2.532	2.113	- 16,54 %

In the following, the physical mechanisms behind the experimental results will be examined in more detail. With regard to the surface quality there are two effects which will be mentioned here. The layer thickness is the most important influencing factor on the surface roughness. The reason for this is shown schematically in Figure 9 a). Between the larger droplets there are deeper notches than with a small layer thickness with small droplets.

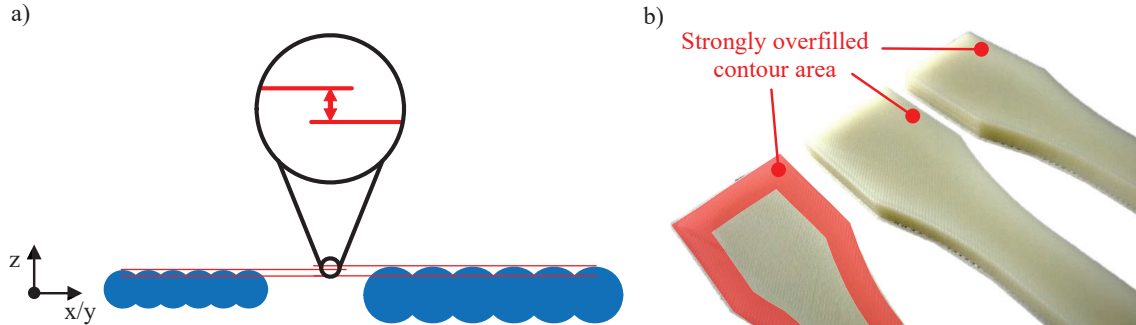


Figure 9: a) Schematic influence of the layer thickness on the surface roughness, b) Overfilling in the edge area due to high overlap between filling and contour

A further effect results from the parameter overlap between filling and contour. The models show no significant influence of this parameter on the mechanical or visual properties. Nevertheless, a strong overfilling occurs in the contour area of the specimens if the overlap is too large. This uneven surface quality must be avoided. Figure 9 b) shows this effect. The affected contour area is marked in red. In addition, the investigations have shown that combination of thin-walled components and a too high overlap between filling and contour, results in completely overfilled components. Thus, the resulting filling level of the components depends on the wall thickness. Since real components have different geometries with different wall thicknesses, overfilling of this kind must be avoided. The parameter overlap between filling and contour should be kept constant at the standard value of 50 % and should only be varied in exceptional cases.

After the evaluation of the experimental design and the subsequent modelling and optimization, the influence of the filling strategy is investigated with a variation of the raster angle. The test specimens were produced with the optimized process parameters. Figure 10 b) schematically shows the raster angles  $0^\circ$  and  $90^\circ$  on the basis of the test specimens. The green lines represent the individual filling lines. The results show that almost the same mechanical properties are achieved with all three filling strategies (Figure 10 a). Based on previous findings from the FDM research and preliminary investigations, this is a surprising result. Figure 11 shows two failure analysis for a raster angle of  $0^\circ$  and  $90^\circ$ . Although the load direction is vertical to the filling lines at a raster angle of  $90^\circ$ , a finer and more homogeneous structure can be seen in figure 11 b).

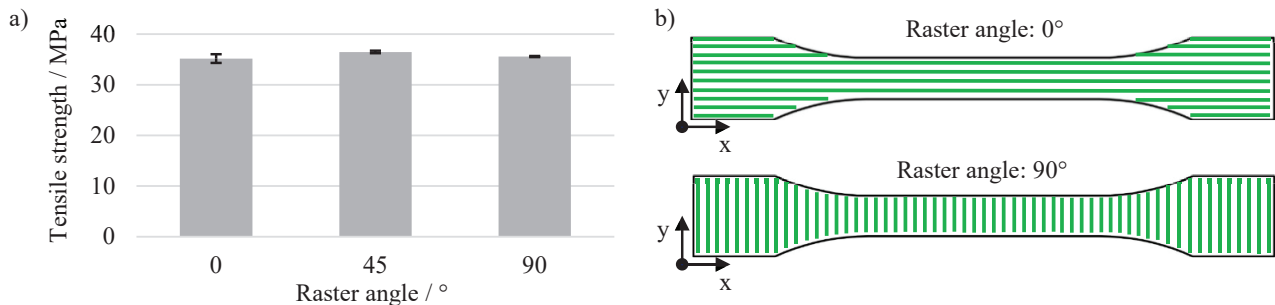


Figure 10: a) Comparison of the maximum tensile strength at different raster angles, b) Schematic illustration of the raster angles

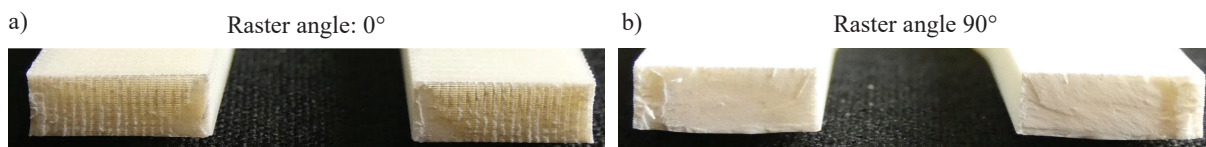
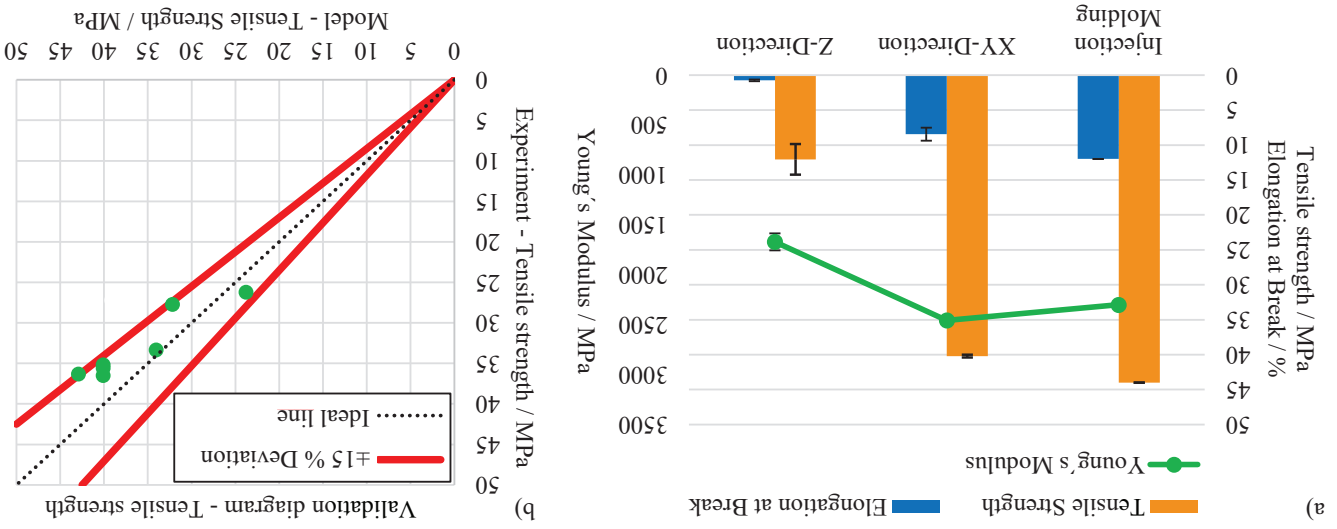


Figure 11: Failure analysis at a raster angle of a)  $0^\circ$  and b)  $90^\circ$

Figure 13: a) Comparison of the maximum values between injection moulding, APF in XY-mounting direction and APF in Z-direction, b) Comparison between simulated and experimentally determined mechanical properties



The following section provides a brief insight into the influence of the build direction on the mechanical properties. Using the optimized parameters from the design of experiments, test specimens were produced and analyzed in the Z-direction. Figure 13 a) compares the maximum values of the two build directions with the mechanical properties of injection-molded test specimens. For the XY-direction, the APF specimens are very close to the properties of injection molded specimens. 90% of the tensile strength of injection molded specimens is achieved. The Young's modulus of injection molded specimens is identical and the elongation at break reaches 70% of the maximum value of injection molded specimens. In the Z-direction, the mechanical properties are significantly lower than those of the XY-direction. The tensile strength drops to under 30 % and the elongation at break to less than 10 % of the injection molded test specimens. Further investigations are currently being carried out to determine whether the mechanical properties in the Z-direction can be further improved.

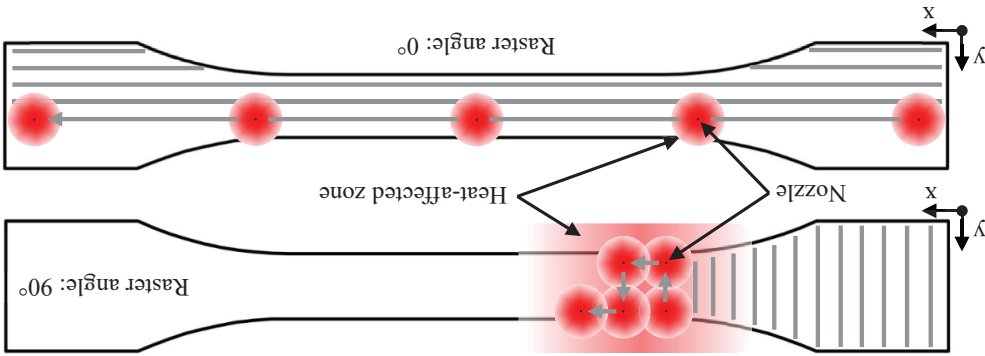


Figure 12: Schematic illustration of the heat-affected zone with a raster angle of 0° and 90°

The almost identical mechanical properties using different raster angles can be explained by the effects shown in Figure 12. Two specimens with a raster angle of 0° and 90° and the corresponding filling lines are illustrated. The difference between the two filling strategies is that the nozzle remains above certain areas of the component for different periods of time. This results in a more intensive heat-affected zone and a higher temperature for the welding process during droplet deposition at a raster angle of 90°. Therefore, a better strength is achieved at a raster angle of 0° in combination with the used test specimen geometry. The second influence of the anisotropy caused by the droplet chain. This leads to a better strength at 90° raster angle. At a raster angle of 45° there is a mixture of both effects. Overall, the effects are balanced out, resulting in the same mechanical properties for the used test specimen geometry. Since the effects are dependent on the filling lines, it must be considered that this does not apply to any component geometries.



Finally, a comparison between the simulated and experimentally determined mechanical properties is made. The deviations for tensile strength and Young's Modulus are within the tolerance range of  $\pm 15\%$ . Figure 13 b) shows an example of the validation diagram for tensile strength. All randomly selected validation test points are within the tolerance range. This means that the predicted results are almost identical to the experimental results for these parameters. The model shows significant deviations regarding elongation at break. Accordingly, there is potential for further improvement. Looking at the validation diagrams, it is noticeable that the models tend to deliver too high values and overestimate the positive influence of the process parameters.

### **Summarized Manufacturing Guidelines**

Subsequent, the results are summarized in the form of manufacturing guidelines. The most important process parameter is the form factor. This parameter should be as low as possible without overfilling the components. It must be considered that this process parameter is slightly dependent on the component wall thickness. This means that the form factor must be adjusted partially for large-area layers or very small wall thicknesses. Such an adjustment is currently not possible in the data preparation software. Further investigations are planned for this aspect. For the process parameter layer thickness, the investigations show that a low layer thickness improves the mechanical and visual properties. With regard to this process parameter the build time and the associated economic efficiency of the application must be considered, since with a lower layer thickness the build time increases drastically. At the same time, the residence time of the material has to be considered due to the low discharge level. The process parameter overlap between filling and contour has no significant influence on the mechanical properties. Since this process parameter can quickly lead to overfilling of thin-walled components or the contour area, this parameter should be set to the standard value of 50%. The nozzle temperature should be as high as possible. Nevertheless, the thermal degradation of the material must be considered. As an indicator for the thermal degradation, the color of the material in the resulting component can be observed. The guidelines for the build chamber temperature are similar. The temperature should be as high as possible. The glass transition temperature provides a first indication for this process parameter. It should be noted that in the case of a component with short layer times, the build chamber temperature should be adjusted in exceptional cases, as otherwise the deposited droplets will not cool sufficiently and the component will behave unstable. The following aspects must be observed for the filling strategy. An ideal filling is achieved with a raster angle of  $45^\circ$  in combination with a delta angle of  $90^\circ$ . It is important that the raster filling does not run parallel to long contours. Otherwise, the surface of the contour area is not exactly shaped. The investigations have shown that the heat-affected zone below the nozzle could have an influence on the resulting mechanical properties. This influence cannot be specifically taken into account due to different component geometries. This is different with the orientation of the components in the build chamber. In the Z-direction, the mechanical properties are significantly lower than in the XY-direction. This anisotropy must be considered for the component orientation.

### **Conclusion and Outlook**

The influence of the process parameters on the mechanical and visual properties of APF components were identified during the investigations. Based on the models a process parameter optimization with a maximization of the target parameters (tensile strength, Young's modulus and elongation at break) could be achieved. The model validation showed that the deviations between the predicted and the experimentally determined values for tensile strength and Young's modulus are 15 %. Only for the elongation at break, larger deviations occurred. The findings of the investigations finally result in the manufacturing guidelines for the APF process. These manufacturing guidelines in combination with a detailed understanding of the process should help the user of the APF technology to configure the process for the individual application at an early stage.

In further investigations, the applicability of the model and the developed guidelines to other materials will be examined. The tendencies of the influencing variables will probably be similar. Nevertheless, the question is whether it is possible to adapt the model using a material-dependent factor. This could enable the early predictability of the resulting mechanical properties of plastic freeformed components. In addition, further investigations are to be carried out regarding the mechanical properties in the Z-direction. The results underline clear weaknesses in this build direction, which limits the maximum load of the components. A specific process parameter optimization, aimed at improving the mechanical properties of the Z-direction, is planned.

### **Acknowledgement**

The presented results were obtained in the context of the research project MO 685/19-1 “Investigation and modeling of design and manufacturing guidelines for the plastic freeforming by use of ABS considering the process-specific material degradation” sponsored by the Deutsche Forschungsgemeinschaft (DFG). We would like to thank the DFG for its support. In addition, we thank the company Arburg GmbH & Co KG for their cooperation.

### **References**

- [1] H. Gaub: “Customization of mass-produced parts by combining injection molding and additive manufacturing with Industry 4.0 technologies”, Reinforced Plastics, Volume 60, Number 6, 2016.
- [2] M. Neff, O. Kessling: “Geschichtete Funktionsteile im industriellen Maßstab“, Kunststoffe, Nr. 08/2014, pp. 64-67, 2014.
- [3] O. Keßling: “AKF - Neues industrielles additives Verfahren“, RTEjournal - Forum für Rapid Technologie, vol. 2015, accessible online: <https://www.rtejournal.de/ausgabe11/3963>, retrieved on 28.08.2019.
- [4] K. Günther, F. Sonntag, E. Moritzer, A. Hirsch, U. Klotzbach, A. F. Lasagni: “Universal Micromachining Platform and Basic Technologies for the Manufacture and Marking of Microphysiological Systems”, Micromachines, 8, 246, 2017.
- [5] A. Klope: “Tröpfchen im Millisekundentakt“, Kunststoffe 11/2018, Carl Hanser Verlag, München, 2018.
- [6] A. Klope: “Untersuchung der Werkstoff-, Prozess- und Bauteileigenschaften beim Fused Deposition Modeling Verfahren“, Ph.D. Thesis, Paderborn University, 2016.
- [7] S. H. Ahn, M. Montero, D. Odell, S. Roundy, P. K. Wright: “Anisotropic material properties of fused deposition modeling ABS”, Rapid Prototyping Journal, Volume 8, Number 4, 2002.
- [8] P. Pinter, S. Baumann, C. Lohr, A. Heuer, L. Englert, K. A. Weidenmann: “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”, Solid Freeform Fabrication 2018, Proceedings of the 29th Annual International, 2018.
- [9] F. Kaut, V. Cepus, W. Grellmann, R. Lach: “Structure–property relationship of additive manufactured thermoplastic polymers processed with ARBURG Freeformer Technology”, Rapid.Tech – Fachkongress, Forum AM Science, pp. 217-235, 2018.