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INVESTIGATION AND MODELING OF THE RESIDENCE TIME DEPENDENT MATERIAL DEGRADATION IN THE ARBURG PLASTIC FREEFORMING

F. Hecker*, A. Hirsch*, 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 with which three-dimensional, thermoplastic components can be produced layer by layer. One disadvantage of the APF is the long residence time of the molten material in the plasticizing unit compared to conventional injection moulding. The dosing volume is emptied very slowly due to only discharging fine plastic droplets. As a result, long residence times can be expected, which can lead to thermal degradation of the material.

The aim of this study was to develop a model for calculating the residence time of the material in the APF. The residence time of the material in the thermally critical dosing volume is predicted using software developed in-house. The accuracy of the model could be verified by experimental investigations. Finally, the thermal degradation of the material was investigated by analyzing the correlation to the mechanical properties of tensile strength specimens.

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 using the Freeformer machine system [1]. The unique technique of the material deposition in the APF process is opening a new field of possibilities and also new boundary conditions. E.g. the residence time of the material inside the thermally critical dosing volume. This is because the dosing volume is emptied slowly by discharging only fine droplets. In the meantime the material remaining in the dosing volume is exposed to high temperatures. For materials which react sensitively to the residence time a precise estimation of the expectable residence times is advantageous.

The aim of this research is the development of a software to calculate the residence time of the material in a previously defined thermally critical volume. In the software, relevant process parameters which have an influence on the build speed and therefore on the residence time are taken into account. The software itself mimics the build process. For this the build process was analyzed. For example, the acceleration and deceleration of the building platform and thereby the changes in the deposition frequency of the droplets are analyzed. This is critical for a precise virtual reproduction of the build process. Further influences were considered but will not be presented in detail in this paper.

After completion of the software, it is validated by calculating the build time and the number of deposited droplets and comparing the results to the values obtained by physically building the component. Finally, tensile test specimens are manufactured with the material ABS-M30. The residence time is varied by altering the percentage of support material used in the job. With these tensile test specimens an influence of the different residence times on the mechanical properties are evaluated.

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].

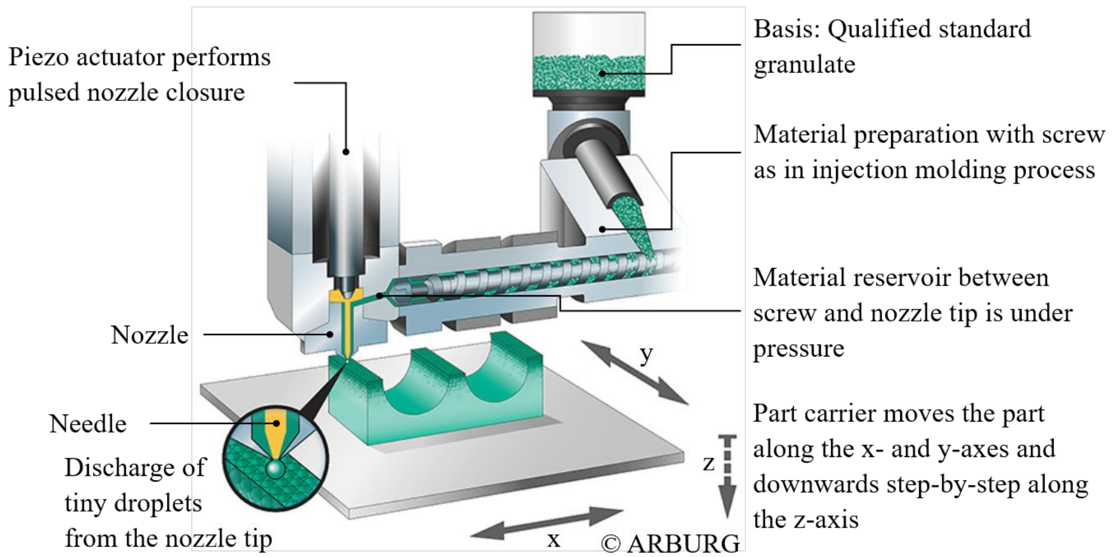

Figure 1: Schematic setup of the Freeformer [1].

Process parameters in the APF process influence the build time and therefore the residence time. One of the most influential process parameters is the form factor. The form factor is a dimensionless value which specifies the distance between the droplets in layer plane [4]. Another process parameter with a significant impact on the build time is the discharge level. The discharge level specifies the size of each droplet [5]. The discharge level is adapted to a specific layer height for each material. Therefore, it is not freely selectable and cannot be used to directly influence the residence time. The influence of the discharge level therein justified that small droplets are deposited at the same speed as large droplets. So, the influence of the discharge level on the residence time is significant as it, together with other boundary conditions, determines how fast the material travels through the thermally critical volume. Other influencing process parameters are the overlap, which indicates to what extend the contour lines are overlapped by the components filling [6]. Other processes specific parameters considered in the software are the metering stroke and the melt cushion known from injection molding.

Following the other process parameters which are know from the Fused Deposition Modeling (FDM) process for example and which are also considered in the software are named. These are the infill, the raster angle, the raster sequence angle and the number of contour lines.

The software is developed using "Python 3.8" and the "Tk GUI" toolkit for the implementation of the graphical user interface (GUI).

Experimental Investigations

The calculations conducted by the software (**Rio** – **R**esidence T**i**me Pr**o**gram) base on the input process parameters and build files. The build files are generated with the slicer provided by the manufacturer. The *.cli-files (common layer interface) provide the contours of the parts separated by layers. Support structures are output by the slicer in separate *.cli-files. The process parameters, the *.cli-files of all structures in the build job are entered into the GUI. The build order in which the parts are built in each layer are entered to allow a precise virtual reproduction of the build job. Up to ten components of each, build and support material, can be entered (see Figure 2).

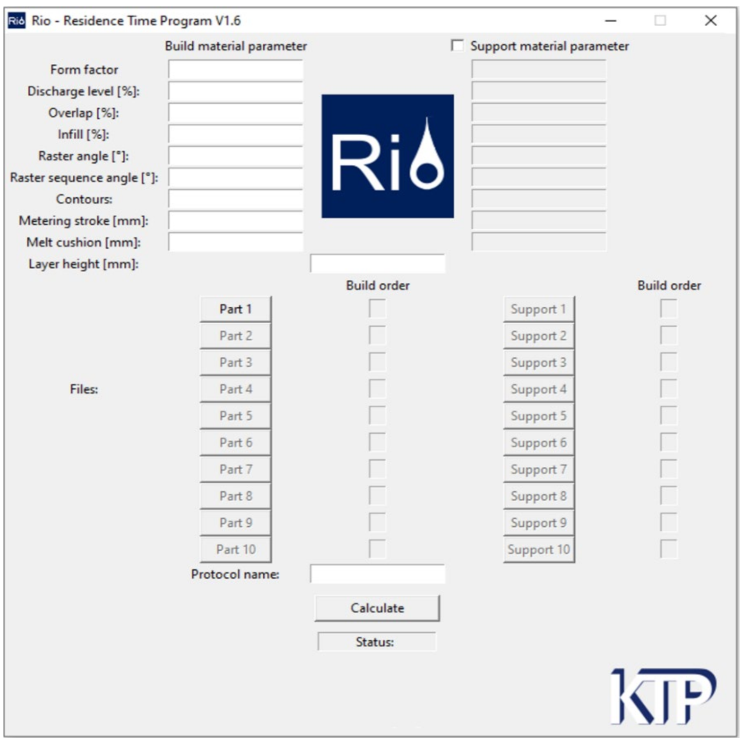

Figure 2: Screenshot of the GUI for the software.

First the software determines the raster and contour lines which will be deposited for each component depending on the entered process parameters. All data is stored in lists sorted by component. These lists are further divided into the data for each layer with the distinct layer number. In these lists the information of each raster and contour line with the number of droplets and the deposition speed are stored. In theory this enables the software to track the residence time of each drop that is deposited. In the calculation of the residence time each layer with each component represented in the layer and each layer is virtually pushed through the thermally critical volume. The residence time of the beginning and the end of the raster line deposited from the thermally critical volume is logged and the thermally critical volume is filled with fresh material. For this the thermally critical volume is divided into sections. Each deposited raster line creates a new section of the same size at the entry into the thermally critical volume. The time it took the current raster line at the exit of the thermally critical volume to be deposited is added to all sections. If a section is interrupted during the deposition by e.g. a metering process a new section is generated. The process of the section generation is shown in Figure 3.

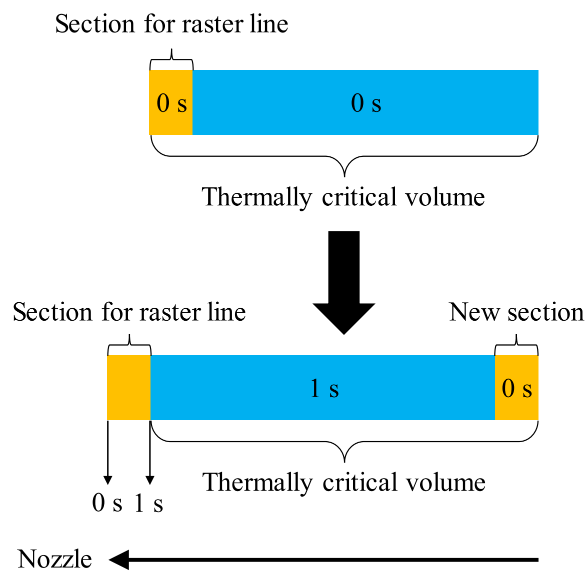

Figure 3: Depiction of the section generation in the thermally critical volume by the software.

The thermally critical volume is stored in the software as a constant volume in form of droplets. The number of droplets contained in the volume is calculated depending on the input discharge level. It is based on the definition that the volume which is enclosed by the machine part that are heated to the nozzle temperature is the thermally critical volume. This includes the volume inside the nozzle and the part of the material reservoir which is enclosed by the part in which the nozzle is fixed in the machine, the nozzle holder. Here, the small channel through which the molten thermoplastic is fed into the nozzle and the area of the nozzle holder which has direct contact to the melt 2.8 mm towards the screw is included (see Figure 4).

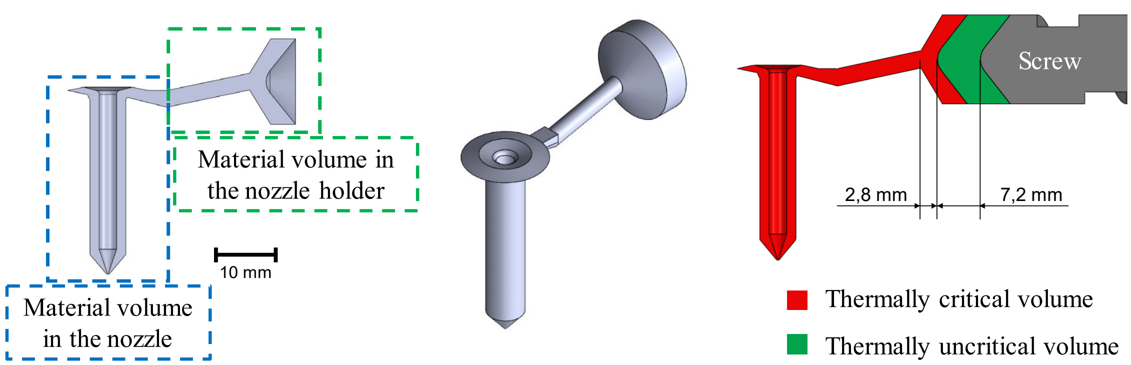

Figure 4: Definition of the thermally critical volume in the Software with an exemplary metering stroke of 10 mm.

To show the capabilities of the software to consider round corners, cut out areas in layers and disruptions of the part in z-direction a demonstrator is designed (see Figure 5). All the described geometrical conditions are represented in the demonstrator's design. To be able to validate the software for different sized components the demonstrator is scaled in three sizes with the scaling factors 1 / 1.5 / 3. In addition, the form factor is modified in three steps for each demonstrator size to vary the drop count. The validation is conducted by comparing the calculated build time and drop count to those obtained from the production log.

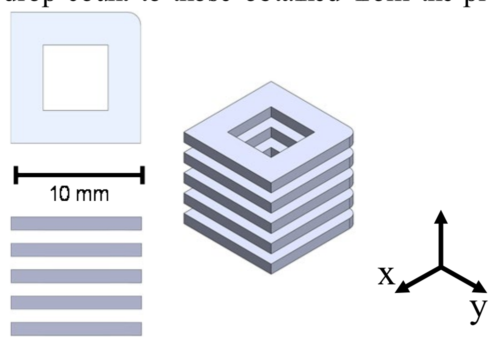

Figure 5: Demonstrator part used for the validation of the software.

The influence of the residence time on the mechanical properties is investigated by manufacturing tensile test specimens. The residence time is varied by adjusting the percentage of support material used in the buffer part. The buffer parts geometry is a tensile test specimen. The size is kept constant for all build jobs to eliminate influences of e.g. different layer times. As shown in Figure 4, parts of the buffer part are substituted by support material to increase the residence time. For this, the buffer parts consist out of 0.002 % / 50 % / 100 % support material depending from the desired qualitative increase of the residence time. To achieve this, the gaps in the 50 % and 0.002 % buffer parts shown in Figure 6 are filled with support material. For each configuration three tensile test specimens are built. The average residence time for the 0.002 % / 50 % / 100 % specimens are 643 s / 772 s / 968 s according to the calculations.

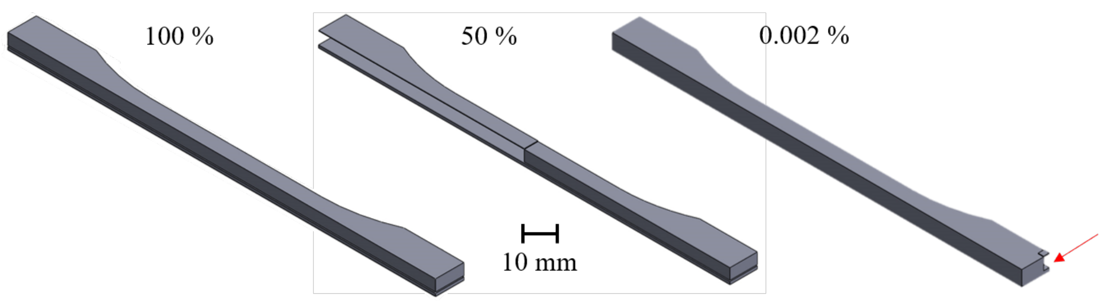

Figure 6: Visualization of the buffer parts as a cross section of the 100 % / 50 % / 0.002 % support material share in the buffer part.

The tensile test specimens which are built from model material next to the buffer parts are then tested according to DIN EN ISO 527-2. Here, the tensile strength, Young's modulus and elongation at break are measured for each specimen.

Results and Discussion

The validation of the software shows, that the building process is well replicated. As shown in Table 1 the deviation of the drop count is, except for one result, inside of a ± 5 % range from the optimum. The maximum deviation is 5.26 % for the demonstrator scaled with x1 and built with a form factor of 1.2463, which equals 4,102 droplets in that specific case. On the other side the minimal deviation is 2.89 % for the demonstrator scaled with x1.5 and built with a form factor of 1.2334.

Table 1: Deviations of the drop count.

Scaling	Form Factor	Deviation drop count [%]	Deviation drop count
x1	**1.2334**	4.14%	3253
x1	**1.2463**	5.26%	4102
x1	**1.2554**	3.81%	2918
x1.5	**1.2334**	2.89%	6594
x1.5	**1.2463**	3.81%	8641
x1.5	**1.2554**	3.47%	7791
x3	**1.2334**	3.11%	48977
x3	**1.2463**	3.05%	47783
x3	**1.2554**	3.90%	60637

Table 2 shows the results for the build time. Here the maximum deviation is -6.47 % for the demonstrator scaled with x1 and built with a form factor of 1.2554. The absolute deviation in that case are 62 seconds. The smallest deviation is shown by the demonstrator scaled with x3 and built with a form factor of 1.2554. Here, the deviation is -0.14 % which equals 16 seconds with a total build time of three hours and twelve minutes.

Table 2: Deviations of the build time.

Scaling	Form factor	Deviation build time [%]	Deviation build time [s]
x1	**1.2334**	-4.40%	-43
x1	**1.2463**	-5.05%	-49
x1	**1.2554**	-6.47%	-62
x1.5	**1.2334**	-1.39%	-32
x1.5	**1.2463**	-1.92%	-44
x1.5	**1.2554**	-2.50%	-57
x3	**1.2334**	-0.25%	-29
x3	**1.2463**	-0.23%	-27
x3	**1.2554**	-0.14%	-16

The results from the software can be plotted. A plot for the build job of three tensile test specimens with each two layers support material at the bottom is shown in Figure 7. As the software only logs the data for the model material the time jumps by the amount of the duration of the deposition of the support material at the beginning. Once no more support material is deposited and all sections in the thermally critical volume which were affected by that are pushed out of the nozzle, the residence time droplets back down and keeps on the same level for the rest of the build job.

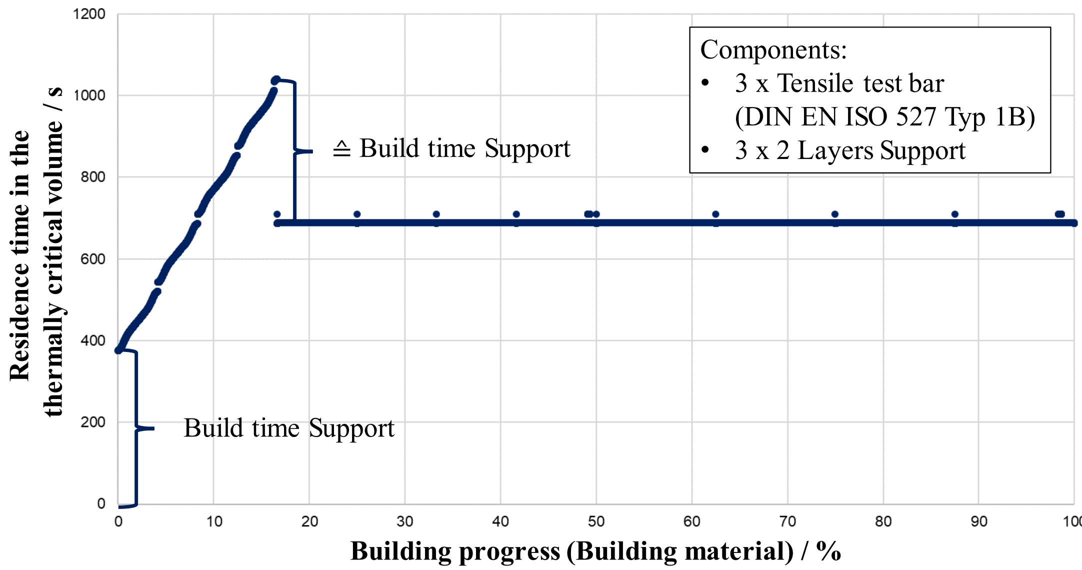

Figure 7: Plot of the data calculated by the software.

Figure 8 shows the results of the tensile test for the specimens with the different residence times. The average values show an overall decrease of all considered mechanical properties. As it is shown in the diagram for the tensile strength the average value of the specimens with the residence time of 772 s (50 %) is higher than of those with a residence time of 643 s (0.002 %). For both, the Young's modulus and the elongation at break a decline of the average values is observed. But taking the standard deviation into account, no definite statement can be made as the standard deviation overlap.

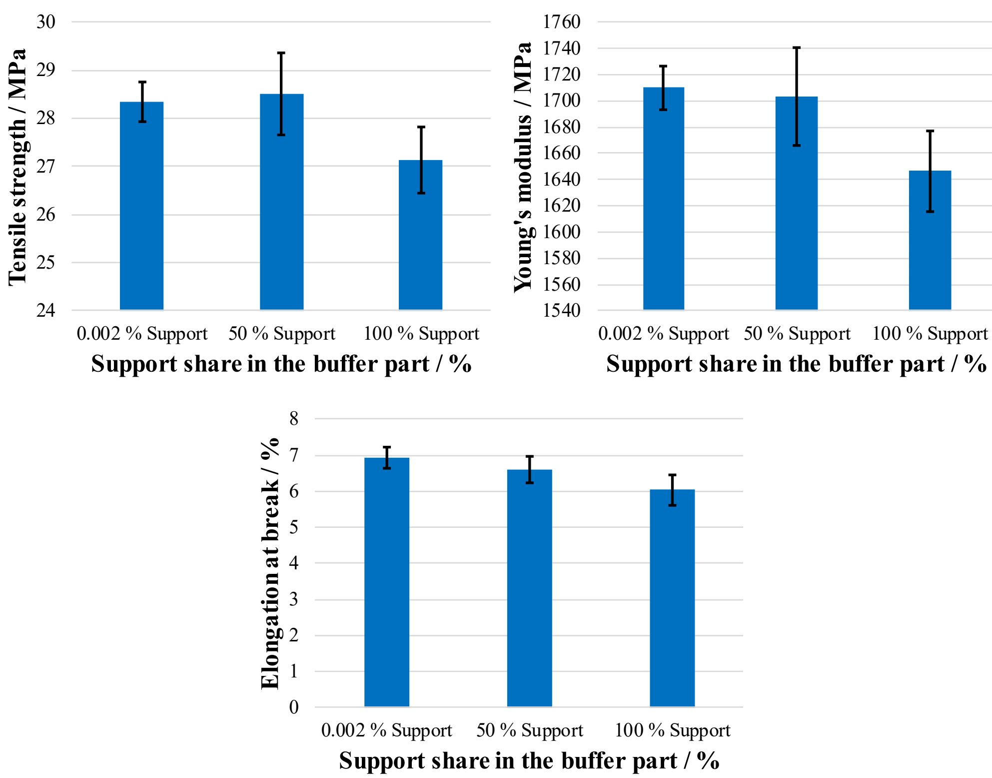

Figure 8: Results of the tensile tests for different residence times.

Conclusion and Outlook

The validation of the software shows, that the calculations are precise enough to be able to estimate the average residence time of the material in the thermally critical volume of the APF process. For the influence of the residence time on the mechanical properties no definite statement can be made. It is likely that the material ABS-M30 has a great resistance against thermal degradation and therefore does not show a decline of the mechanical properties with increasing residence time.

Based on the results of this research it will be investigated how the results of the software can be further improved. Also, the manufacturing of the tensile test specimens with different residence times will be conducted using a more critical material regarding the residence time.

Acknowledgement

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