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Keywords
Material extrusion, injection molding, mechanical characterization, computed tomography, additive manufacturing

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Reaching the described benefits, the use of a material extrusion-based AM technique, often called fused deposition modeling (FDM™) or fused filament fabrication (FFF) can be applied. These material extrusion-based AM techniques are among the most widely used AM methods [2]. The low initial costs, the large selection of materials, and the possibility of a tool-free manufacturing process are a number of benefits. Hence, the rapid prototyping approach, which means generating prototypes using AM techniques, has changed to a rapid manufacturing concept. Due to the development of processes, machines, and materials, the direct manufacturing of serial parts is possible.

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The design of highly stressed serial parts via AM requires a mechanical characterization of additively manufactured materials and the corresponding process-induced defects. However, there is no standard, guideline, or restriction for a consistent determination of the material characteristics of additively manufactured polymers [3-5]. Therefore, several researchers had concerns about the mechanical characterization of additively manufactured parts [6-14].

Torrado and Roberson [6] investigated various parameter settings of additively manufactured polymers and the resulting differences in failure modes. Due to missing standardization, a fundamental analysis of varied specimen geometries was done as well. Thereby, the influence of the specimen geometry on mechanical properties was shown. Sood et al. [7] considered the effect of layer thickness, manufacturing orientation, raster angle, raster width, and air gap on the mechanical properties by using ANOVA. The experiments resulted in optimized process parameters and highlighted complex manufacturing mechanisms depending on parameter settings. Ning et al. [8] observed the effect of adding carbon fibers reinforcing the raw polymer. For this, the fiber content and length of discontinuous fibers including the corresponding impact on tensile and flexural strength were analyzed. Tekinalp et al. [9] investigated various fiber weight contents of tensile specimens and the influence on the mechanical properties. A comparison between additively manufactured specimens and compression molded specimens shows a high fiber orientation of FDM™ specimens with a focus on manufacturing. Dawoud et al. [10] analyzed the effect of manufacturing technique on the raw polymer. The comparative investigation dealt with polymer manufactured via FDM™ and injection molding (IM). The results show a general trend towards a higher tensile, flexural, and impact strength of IM specimens due to higher compaction and optimized crystalline structure compared to AM specimens. The literature review shows experiments with parameter studies identifying interactions between manufacturing parameters, basic studies on possibilities of material reinforcement, and opportunities for suitable reference specimens. Due to a lack of standardization for the characterization of mechanical properties, it is difficult to compare the results. The majority of these publications used a quasi-static experimental setup to characterize additively manufactured polymers.

However, characterizing the overall mechanical behavior includes cyclic investigations as well. Ziemian et al. [11] optimized the mesostructure of additively manufactured acrylonitrile butadiene styrene (ABS) under quasi-static and cyclic tension-tension loading. The cyclic tests were executed at low frequency and constant stress levels resulting in long test durations. Lee and Huang [12] characterized the fatigue properties of various manufacturing orientations of ABS under cyclic loading. The tests were performed at an even lower frequency and a maximum of 10,000 cycles per test. Afrose et al. [13] had noticed that there is limited information on the fatigue properties of additively manufactured parts. Moore and Williams [14] supported this theory and summarized that the fatigue properties of AM parts are essential for using the technology as a manufacturing process. Once again, the literature presents a wide range of experimental setups with varied evaluation approaches and a lack of standardization. For the even more sensitive cyclic investigations, this results in even more challenges for comparability. The frequency dependent influence of creep is just one example.

The aim of this study is a systematic approach for the characterization of additively manufactured material and the corresponding process-induced defects under tensile loading. Therefore, destructive and non-destructive testing methods are combined to enable an improved resource-efficient approach for material characterization.

### Material and Manufacturing

The mechanical characterization of process-induced defects is done by using single-batch material. Therefore, a short carbon fiber-reinforced polyamide (SCFRP) (CarbonX™ Nylon, 3DXTECH, USA) with approx. 12.5 wt.% fiber content, 7 μm fiber diameter, and a fiber length distribution between 150 and 400 μm after fabrication to filament is used. The material is delivered on vacuumed spools 2.85 mm in diameter. Prior to manufacturing, the material is dried in an oven at 50 °C for 4 hours (FP 115, Binder, Germany). Before being processed in the injection molding (IM) system, the filament was crushed in approx. 4 mm granulate to ensure a single-batch material.

An IM system (320C, Arburg, Germany) is used for the manufacturing of the reference specimens. The shape of the tooling is designed for the production of three specimens per cycle and is shown in Figure 1 during a mold flow analysis. Multiple mold gates in the first and second specimen form predetermined breaking regions. The third specimen is homogenously filled through a single mold gate and is used for mechanical investigations. Table 1 summarizes selected manufacturing parameters of the IM system.

For the production of additively manufactured specimens, an FFF system (Ultimaker 2+ Extended, Ultimaker BV, Netherlands) was used. Figure 2 shows the manufacturing orientations. The standard terminology which defines the orientation of FFF specimens in the build volume corresponds to ASTM F 2791-13. The XY (short: 0°) and YX (short: 90°) specimens were generated flat on the build platform; the specified angle indicates the manufacturing orientation in relation to the loading direction; the ZX (short: Z) specimens were produced upright. The specimens were generated directly on the build platform out of glass, which was cleaned with ace-

![Figure 1: Mold flow analysis of IM tooling with corresponding flow fronts and flow behavior during injection [15]](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>CarbonX™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dosage volume</td>
<td>cm³</td>
<td>7</td>
</tr>
<tr>
<td>Screw temperature</td>
<td>°C</td>
<td>270</td>
</tr>
<tr>
<td>Injection flow</td>
<td>cm³ × s⁻¹</td>
<td>35</td>
</tr>
<tr>
<td>Residual cooling time</td>
<td>s</td>
<td>8</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>MPa</td>
<td>100</td>
</tr>
<tr>
<td>Back pressure</td>
<td>MPa</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 1: Selected manufacturing parameters for the IM system
tone in a pre-process. Each 90° and 0° specimen was manufactured separately in a specific print job; the Z specimens were fabricated in a batch of 5 specimens per print job. Simplify3D was used for slicing the 3D volume, selected parameters are given in Table 2.

### Experimental Setup

#### Quasi-static tests.

The quasi-static tensile tests were carried out on a universal testing system (Zwick, 1464, Fmax = ±50 kN) according to DIN 527-1. The tactile extensometer MultiXtens (Zwick, Germany) measured the strain of the entire tests. Determining Young’s modulus in a range between 0.05 to 0.25 %, a displacement speed of 1 mm × min⁻¹ was applied. After that, the displacement speed was switched to 50 mm × min⁻¹ to determine tensile strength. Preload was defined at +10 N, stop criterion was set to a 50 % drop in force. Acoustic emissions were monitored by high frequency impulse measurement (HFIM) (Optimizer4D, Qass, Germany). All specimens for quasi-static tensile tests were stored under standard atmosphere according to DIN 527-1 at 23 °C and 50 % humidity for 24 hours (KMF 240, Binder, Germany) and tested immediately after removing. For each variation, a number of sample n = 5 was tested.

#### Cyclic tests.

Constant amplitude tests were performed on a servo-hydraulic testing system (Instron, 8872, Fmax = ±10 kN) under sinusoidal tension-tension loading with a stress ratio R = 0.1 and a frequency of f = 5 Hz under room temperature. Via digital image correlation (DIC) (Q-400, Limess, Germany), the deformation behavior was observed. A thermal camera (TIM 450, Micro-Epsilon, Germany) was used to monitor the temperature change. The constant load levels for IM and AM specimens depend on the ultimate tensile strength σ_{UTS} from the quasi-static investigations. The maximum stress level σ_{max} is 70 %, 60 %, and 50 % of the corresponding σ_{UTS} and allows a comparison of different variations. Taking into account the stress ratio R = 0.1 results in a mean stress σ_m and stress amplitude σ_a. Table 3 lists the main test parameters for all variations. The experimental setup for cyclic tests, including measurement systems, is shown in Figure 3. The specimen geometry, according to DIN 527-2 type 1BA for quasi-static and cyclic investigations, is given in Figure 4.

#### Quality assessment.

A systematic approach according to Tanikella et al. [16] was adapted to estimate the quality of the specimens. The first steps are a visual inspection followed by a weight comparison of the specimens determined under extrusion. A high resolution scale (AB204, Mettler-Toledo, USA) was used to compare the weights of the specimens. The systematic quality assessment is extended by micro-

![Figure 2: Manufacturing orientation of additively manufactured specimens according to ASTM F 2791-13](image)

![Figure 3: Experimental setup for cyclic investigations including different measurement-systems](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>CarbonX™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle diameter</td>
<td>mm</td>
<td>0.4</td>
</tr>
<tr>
<td>Extrusion width</td>
<td>mm</td>
<td>0.5</td>
</tr>
<tr>
<td>Layer height</td>
<td>mm</td>
<td>0.2</td>
</tr>
<tr>
<td>Manufacturing orientation</td>
<td>-</td>
<td>XY (0°), YX (90°), ZX (Z)</td>
</tr>
<tr>
<td>Extruder temperature</td>
<td>°C</td>
<td>260</td>
</tr>
<tr>
<td>Printing speed</td>
<td>mm × s⁻¹</td>
<td>30</td>
</tr>
</tbody>
</table>

**Table 2: Selected Simplify3D parameters for generating additively manufactured specimens**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Stress level</th>
<th>σ_{UTS}</th>
<th>σ_{max}</th>
<th>σ_m</th>
<th>σ_a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>%</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
<td>MPa</td>
</tr>
<tr>
<td>0°</td>
<td>70</td>
<td>46.1</td>
<td>32.3</td>
<td>17.6</td>
<td>14.4</td>
</tr>
<tr>
<td>0°</td>
<td>60</td>
<td>46.1</td>
<td>27.8</td>
<td>15.4</td>
<td>12.6</td>
</tr>
<tr>
<td>0°</td>
<td>50</td>
<td>46.1</td>
<td>23.1</td>
<td>12.7</td>
<td>10.4</td>
</tr>
<tr>
<td>90°</td>
<td>70</td>
<td>29.7</td>
<td>20.8</td>
<td>11.5</td>
<td>9.5</td>
</tr>
<tr>
<td>90°</td>
<td>60</td>
<td>29.7</td>
<td>17.8</td>
<td>9.9</td>
<td>8.1</td>
</tr>
<tr>
<td>90°</td>
<td>50</td>
<td>29.7</td>
<td>14.9</td>
<td>8.3</td>
<td>6.8</td>
</tr>
<tr>
<td>Z</td>
<td>70</td>
<td>10.6</td>
<td>7.4</td>
<td>3.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Z</td>
<td>60</td>
<td>10.6</td>
<td>6.4</td>
<td>3.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Z</td>
<td>50</td>
<td>10.6</td>
<td>5.3</td>
<td>2.8</td>
<td>2.3</td>
</tr>
<tr>
<td>IM</td>
<td>70</td>
<td>61.9</td>
<td>43.3</td>
<td>23.7</td>
<td>19.4</td>
</tr>
<tr>
<td>IM</td>
<td>60</td>
<td>61.9</td>
<td>37.1</td>
<td>20.4</td>
<td>16.7</td>
</tr>
<tr>
<td>IM</td>
<td>50</td>
<td>61.9</td>
<td>31.0</td>
<td>17.1</td>
<td>14.0</td>
</tr>
</tbody>
</table>

**Table 3: Test matrix with different stress levels for cyclic investigations (R = 0.1, f = 5 Hz)**
computed tomography (CT) to detect the quantity and distribution of the voids [17]. Therefore, a universal micro-CT inspection system (XT H 160, Nikon, Japan) was used.

### Results

#### Quasi-static tests

Figure 5 shows representative curves of nominal tensile stress $\sigma_n$ vs. total strain $\epsilon_t$ for each variation. Furthermore, the results for ultimate tensile strength $\sigma_{UTS}$ are shown with the corresponding standard deviation. The IM specimens exhibit higher mechanical properties compared to AM specimens. The IM specimens yield a Young’s modulus of 6,352 ± 160 MPa and a tensile strength of 61.9 ± 1.0 MPa. The quasi-static material response is separated into an elastic deformation at the beginning, followed by a plastic deformation until failure. Both the 0° specimens and the 90° specimens have qualitatively similar material responses compared to the IM specimens. However, the mechanical performance is affected by a reduction of Young’s modulus, tensile strength, and strain at fracture.

![Figure 4: Specimen geometry and dimensions (mm) for quasi-static and cyclic investigations according to DIN 527-2 type 1BA](image)

![Figure 5: Nominal tensile stress $\sigma_n$ vs. total strain $\epsilon_t$ curves and resulting ultimate tensile strength $\sigma_{UTS}$ for IM, 0°, 90°, and Z SCFRP specimens](image)

This results in a Young’s modulus of $4,540 \pm 93$ MPa (0°), $2,291 \pm 82$ MPa (90°) and a tensile strength of $46.1 \pm 0.7$ MPa (0°), $29.7 \pm 0.6$ MPa (90°). By contrast, the quasi-static material response of Z specimens is solely due to elastic deformation. The brittle failure results in significantly reduced values for Young’s modulus $1,436 \pm 104$ MPa and a tensile strength $10.6 \pm 1.8$ MPa.

#### Cyclic tests

On the basis of the quasi-static investigations and the resulting ultimate tensile strength $\sigma_{UTS}$, cyclic investigations were executed. Figure 6 shows exemplarily the results of a constant amplitude test for an additively manufactured 0° specimen at a maximum stress of 60% ultimate tensile strength. Thereby, the constant maximum stress level $\sigma_{max}$, the change in temperature $\Delta T$, the total max. strain $\epsilon_{max,t}$, and the dynamic Young’s modulus $E_{dyn}$ are plotted as a function of the number of cycles to failure $N_f$. The abscissa is given in a logarithmic scale; the different ordinates are displayed in linear scales. The total max. strain $\epsilon_{max,t}$ measured via DIC, is based on an initial length of 30 mm and serves only for qualitative comparison within the test series. The dynamic Young’s modulus is calculated in a retrospective process from the maximum values for stress and displacement measured by the position of traverse according to Equation (1) [18]. The resulting curve of dynamic Young’s modulus serves as an indicator of stiffness degradation over the number of cycles.

$$E_{dyn} = (\sigma_{max} - \sigma_{min}) \times (s_{max} - s_{min})$$

The temperature increases slightly during the test but does not exceed the overall temperature change of 4 K. Thus, a thermal failure cannot be assumed. The logarithmic scale leads to an exponential increase of total max. strain to approx. 2.7% strain at fracture. The dynamic Young’s modulus constantly decreases from the beginning until abrupt failure.

The results of all constant amplitude tests with a maximum stress level of 70%, 60%, and 50% of the ultimate tensile strength are shown in Figure 7. The number of cycles to failure is given at the abscissa in a logarithmic scale, the maximum stress level on the ordinate in a linear scale. The reference specimen manufactured via IM achieve the highest numbers of cycles to failure for each stress level. Furthermore, the slope of the regression line is lower, indicating better performance under cyclic loading compared to AM specimens. The 0° and 90° specimens represent an almost similar plot with a selected...
scale. The absolute values and the slope of the regression line are quantitatively at the same level. The Z specimens have significantly reduced numbers of cycles to failure despite the relative stress levels as a function of ultimate tensile strength.

The absolute values for maximum stress are summarized in S-N curves in Figure 8. The IM specimens show an increased number of cycles to failure at the highest stress levels. Due to their varied ultimate tensile strength, the difference between 0° and 90° specimens is greater than the relative stress levels in Figure 7. The significant reduction of material performance with respect to the number of cycles to failure for Z specimens is reflected in the absolute values for maximum stress.

**Quality assessment.** The quality assessment for tested specimens was done according to a systematic approach, including visual inspection and weighing of the specimens as well as through micro-CT observations. Figure 9 depicts representative examples for 3D-models out of micro-CT that show a section of the testing area and corresponding voids. No voids are visible within the IM specimen at a voxel resolution of 9 μm. The additively manufactured 0° and 90° specimens show a uniform distribution with a similar void volume. The primary appearance of voids is between two extrusion beads (XY plane) and between two layers (Z direction). Furthermore, a dependency of void orientation in the direction of the extrusion head is visible. This results in void volume contents of 6.5% (0°) and 4.8% (90°). The Z specimen has a higher defect volume per void with a primary occurrence between two layers (Z direction). The overall void volume content of the Z specimen is 4.7% and has an unsteady void distribution compared to that of the 0° and 90° specimens.

**Discussion**

For the mechanical characterization of additively manufactured SCFRP, quasi-static and cyclic investigations as well as a quality assessment were performed. IM reference specimens were compared with the AM manufacturing orientation 0°, 90°, and Z. For quality assessment, an adapted systematic approach through micro-CT investigations achieves more information. The quasi-static investigations demonstrate a significant difference in Young’s modulus and tensile strength depending on the AM manufacturing orientation. Within the AM test series, the 0° specimens achieved the highest values, the Z specimens the lowest.
AM specimens cannot yield the mechanical properties of the IM specimens. The higher mass and correspondingly lower standard deviation, as well as the lower void volume content of IM, indicate a more reproducible manufacturing process compared to AM. The injection pressure of IM at 100 MPa was defined and controlled. AM generated components with varied bond regions between two beads (XY plane) and two layers (Z direction). Both weaken the component and have different characteristics with respect to void content, void distribution, and manufacturing pressure. The interbead bonds on the XY plane, which are primarily described by the 90° specimens, have a qualitatively similar material response to the IM specimens. The interlayer bonds specified by Z specimens differ in their mechanical behavior. The void distribution in the Z direction indicates anomalies in material flow during printing and difficulties in reproducibility. The different void volume contents and void area shares allow for a calculated correction of the tensile strength as a function of the effective cross-sectional area. This correction due to the decreasing cross-sectional area was carried out by several researchers [17, 19]. Despite the corrected effective tensile strength, there is still a significant difference within the AM test series. This indicates that there are additional effects, which affect tensile strength. One possibility is that stress concentration origin at the voids negatively influences tensile strength. The general trend within the AM test series is that Z specimens are clearly weaker and 0° specimens stronger, which has been confirmed by other researchers. Faes et al. [20] highlighted that intralayer bonds are stronger than interlayer bonds. Within the test series of Ziemian et al. [11], the 0° specimen achieves the highest tensile strength as well. Another possibility for the strength degradation of Z specimens is the polymer compaction between the layers. Several researchers recognized the relevance of this topic. Bellehumeur et al. [21] described a model for polymer compaction focusing on the neck growth between two extrusion beads. Dawoud et al. [10] outlined that the higher compaction of IM leads to higher strength. Due to undefined manufacturing pressure for generating the bonds in the Z direction (between layers) and the obvious weakness of this connection, the focus has to be on the mechanical behavior in the Z direction. The experimental setup for the quasi-static investigations in this study verifies a characterization of interlayer tensile strength in a first approximation. Because the strength between the two layers (Z direction) is the limiting factor for AM components, the characterization procedure has to be extended to shear strength [22]. The varied void characteristics in AM specimens indicate changes in the manufacturing process, e.g. an unsteady material flow, which affects the reproducibility of the manufacturing process. On basis of the quasi-static tensile tests, cyclic tests with stress levels dependent on ultimate tensile strength are performed. Despite a percentage reduction of 70%, 60%, and 50% of the ultimate tensile strength, the significant difference in the quasi-static material properties within the cyclic test series is reduced. The IM specimens achieve the highest numbers of cycles to failure at each stress level, the Z specimens the lowest. 0° and 90° specimens show similar behavior under the same relative stress level regarding ultimate tensile strength. The experimental setup using 0° specimens describes the testing of intralayer bonds; the Z specimens characterize the interlayer bonds. The strength degradation with respect to the manufacturing orientation within the AM test series is confirmed by other findings in the literature [20]. The cyclic investigations with absolute stress levels demonstrate a similar trend within the overall test series. Based on the absolute stress levels, the fatigue properties can be approximated. The AM specimens cannot achieve the material properties of IM specimens under cyclic load. The results identify an influence of the process-induced defects on the fatigue behavior of the material. Nevertheless, additional effects of typical process characteristics have to be considered. The trend within the AM test series is similar to quasi-static investigations. Therefore, the results yield design guidelines for highly-stressed components under quasi-static and cyclic loading. During loading under tension, the component has to be aligned in the 0° direction. Loading in the manufacturing direction Z has to be avoided wherever possible.

Conclusions and outlook

The reference properties for SCFRP were determined with IM specimens according to DIN 527-1. The quasi-static investigations show that the ultimate tensile strength of AM specimens is significantly reduced compared to IM specimens (61.9 MPa), depending on the manufacturing orientation. Within the AM test series, the 0° specimens achieve the highest ultimate tensile strength (46.1 MPa), Z specimens the lowest (10.6 MPa). On the basis of the quasi-static investigations, three different stress levels were tested under cyclic loading based on the specific ultimate tensile strength. Both, the relative stress levels depending on ultimate tensile strength (50%, 60%, and 70%) and the absolute stress levels showed a similar trend in the test series. Despite of the relative stress levels, the differences in number of cycles to failure within test series increased. The 0° specimens of AM test series achieved the highest number of cycles to failure, the Z specimens the lowest. The material performance of IM specimens could not be reached in the AM test series. Using the Z specimens in the experimental setup, the characterization of interlayer tensile strength is possible.

In further investigations, the characterization of interlayer behavior will be adapted with additional load cases. The characterization of interlayer shear strength and interlayer compressive strength under quasi-static and cyclic loading will be carried out for a better comprehension of the fatigue behavior of additively manufactured polymer. The quality assessment was based on a systematic approach consisting out of visual inspection, weight comparison, and consideration via micro-computed tomography. Micro-computed tomography shows a higher defect volume for AM specimens compared to IM specimen as well as a different void characteristic depending on manufacturing orientation. In further investigations, the varied void characteristics will be qualified more precisely in order to create a predictive model for critical void volume contents and void area shares.

The results demonstrate deficits in the overall characterization of additively manufactured polymers. In particular, the fatigue behavior of additively manufactured polymers and the relationships to the generation of interlayer tensile strength were not yet the focus of attention. Based on current information, a design guideline is presented for highly stressed components, demonstrating that the main load direction be designed not along the manufacturing direction Z.

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