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Internal Fiber Structure of a High-Performing, Additively Manufactured Injection Molding Insert

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Abstract. A standard mold is equipped with additively manufactured inserts in a rectangular shape produced with vat photo polymerization. While the lifetime compared to conventional materials such as brass, steel, and aluminum is reduced, the prototyping and design phase can be shortened significantly by using flexible and cost-effective additive manufacturing technologies. Higher production volumes still exceed the capability of additively manufactured inserts, which are overruled by the stronger performance of less-flexible but mechanically advanced materials. In this contribution, the internal structure of a high-performing, fiber-reinforced injection molding insert has been analyzed. The insert reached a statistically proven and reproducible lifetime of 4,500 shots, which significantly outperforms any other previously published additively manufactured inserts. Computer tomography, tensile tests and life cycle analysis have been performed in order to provide an understanding of the internal structure of the fiber-reinforced, additively manufactured injection molding inserts.

Keywords: Additive Manufacturing, Injection Molding, Inserts, Computed Tomography, Fiber-Reinforcement

INTRODUCTION

Injection molding using inserts from vat polymerization, an additive manufacturing technology, has been investigated for pilot production and rapid prototyping purposes throughout the past years. [1] Previously discussed fiber-reinforced injection molding (IM) inserts have proven to reduce the process and design cycle of IM parts by one order of magnitude due to flexibility in design [2], production speed, digital capacities, and cost efficiency [3]. Research presented in [4-7] has utilized short, virgin, and unsized carbon fibers (CF) with diameters of 7.2 μm and average lengths of 100 μm and 100 μm, which increased the lifetime of those inserts by a factor of 20 up to 4,500 to 4,600 shots per insert with 5 to 10 % in weight of CFs. By improving the fiber-matrix-interface and optimizing process parameters in both the additive manufacturing (AM) vat photopolymerization (VP) process as well as the IM cycle with additional cooling mechanisms (both forced and free convection) [4], the lifetime of the named inserts has been improved up to 4,500 shots. A significant challenge mentioned in several investigations [5, 8] was introduced by the layer-wise orientation of CFs due to process parameters including build plate movement and print orientation, as well as flow patterns. While a theoretical approach was conducted in [8], this contribution investigates the end-of-life parameters of a used IM insert, which was kept in the production cycle twice as long as the usual lifetime. Data analysis was conducted using X-ray computed tomography in order to gain fiber orientation, fiber volume fraction, crack orientation, crack length, width, depth, and air intrusions.

This study therefore contributes to a further understanding of injection molding inserts produced by additive manufacturing, which come with major advances in flexibility, cost efficiency, cycle time, and micro-features. The enhanced lifetime reduces the production cost share as well as the workforce required to change defect inserts. Moreover, the suitability for thermally more pretentious materials is increased.

METHODS

The AM inserts have been manufactured according to [6, 8] using the commercially available photopolymer resin HTM-140v2 and a bottom-up machine in a “hanging” configuration meaning that the printed layers were oriented in
parallel to the longer edge of the rectangular feature at a layer height of 20 μm. The light exposure was increased by 20% in order to compensate for the light extinguishing of the 10% in weight of CFs.

After productions, the inserts were then used in an IM machine running cycles until reaching twice the average lifetime of comparable inserts. One insert was selected for further investigations.

X-ray tomograms of the sample were obtained using a “ZEISS XRadia 410 Versa” device. The instrument was operated at 40 kV and 10 W using the low energy 1 (LE1) filter belonging to the system, and either a macro objective (LFOV) or a 4X objective. Three different configurations were determined according to the description in Table 1 based on chosen positions shown in Figure 1. Image reconstruction and beam hardening correction were performed using the built-in acquisition and reconstruction software package provided by ZEISS, while for further analysis and visualization the software “Avizo9.4.0” (FEI) was used.

Table 1 Measurement descriptions for positions according to Figure 1 (right).

<table>
<thead>
<tr>
<th>Position</th>
<th>Description of Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overview over the entire insert</td>
<td>For overview measurements, image acquisition was performed using the LFOV objective and 1601 projections with 2 s exposure time which resulted in a total measurement time of 1:56 h:min. A pixel size of 23 μm was obtained using a 2x2 binning.</td>
</tr>
<tr>
<td>Position 1 and 2</td>
<td>Using a 4X objective, a pixel size of 4.0 μm was obtained with 2x2 binning and tomograms were recorded with 3201 projections and 10 s exposure time resulting in 10:27 h:min total measurement time.</td>
</tr>
<tr>
<td>Position 3</td>
<td>The highest resolution measurements were acquired using the 4X objective and modifying the sample-to-detector distance, which resulted in a pixel size of 2.0 μm. The exposure time was adapted to 45 s and the total acquisition time was 42:44 h:min.</td>
</tr>
</tbody>
</table>

FIGURE 1. From left to right: IM insert after twice the usual lifetime, single unused insert in the IM machine before the first shot, measurement positions for the CT analysis.

“Avizo9.4.0” (FEI) was used to determine the length of cracks, to obtain pore size distributions in different sub volumes and to determine the volumetric amount of carbon fibers. The following procedure was used to examine the volumetric amount of fibers: 1) definition of a sub volume inside the material not covering regions affected by artefacts; 2) interactive thresholding using a threshold of 42,000 cts for fibers, 3) removing of spots smaller than 10 px; 4) using the “material statistics” module to obtain the volume of the thresholded material. To obtain the full volume, the threshold in step 2) was set to 1 cts and step 3) was skipped. In order to obtain the pore size distribution, the “porosities analysis wizard” provided by the software was used. A mask threshold of 38120 cts was used for the material, while the initial value to detect strong voids was set to 38385 cts. Neither a threshold for weak voids, nor areas of material without volumes were defined, and no separation of voids was performed. The pore radius was calculated from the pore volumes. The fiber orientation was determined using Matlab scripts based on [10].

RESULTS

The fibers are described as vectors oriented in space and theta describes the elevation and phi the azimuth angle. The fibers are predominantly oriented perpendicular to the azimuth plane (along 90 deg elevation (Θ)), and less
oriented in $\Phi$. This finding supports the assumption that the fibers are oriented along the printing direction, which is vertically to the surface containing the depletions in Figure 1 meaning that the insert has been printed in a “hanging” orientation in a bottom-up printing process. This printing technique allows for a higher part per machine ratio but requires a layered printing (unless e.g. an oxygen permeable membrane is used). The orientation of the extracted fibers shown in Figure 5 was sampled in a spherical coordinate system whereas $\Phi$ represents the orientation within the printing plane (Figure 2, left) and $\Theta$ represents the orientation outside the printing layer (Figure 2, right). Similar results have been achieved for the other two positions.

**FIGURE 2.** Fiber orientation analysis for position 1. As suggested in [3, 5], fibers are oriented along the printed layers. Similar distributions have been obtained for position 2 and position 3.

**FIGURE 3.** Cut through position 1. Cracks are mainly oriented in between the printed layers.

Crack orientations and dimensions have been analyzed and are shown in Figure 3 and Figure 4. The surface cracks have a tendency to orient randomly, but do not penetrate deeper than a few micrometers, while deeper cracks up to 1.76 mm length are present in between the printed layers. These cracks propagate deeper and longer through the insert. The reason for this behavior is the missing connection between the layers reducing the crack propagation velocity as investigated during the IM process in [8]. As an example, measured surface cracks are shown in Figure 4 (left) showing a smaller penetration of the insert than aligned cracks shown in Figure 4 (right).

Solutions to prevent this behavior are discussed in [9] and include a change from bottom-up printing technology to top-down printing technology with advanced build plates which are permeable for fiber-filled resins. This can e.g. be achieved by equipping the build plate with holes which significantly change the fluid orientation and subsequently the fiber orientation within the resin, which is later represented in the final printed part.
FIGURE 4. Projected view with surface crack orientation (left). Surface cracks originate from the steep temperature gradients during the IM process as investigated e.g. in [8]. Cracks are mainly oriented within the printed layers. Detailed view on deeper cracks through position 1 of the middle picture (right), which align in general with the printing layer orientation. Figure 6 (left) shows the extracted fibers and densified parts of the surface, or remaining beam hardening artefacts. The orientation proposed in Figure 2 resulting in the crack propagation is shown in Figure 4. Fiber extraction resulted in volume fractions between 0.2 and 0.3 % which might be explained by not all fibers being resolved by the CT analysis, or having reached the threshold. This might be connected to the voxel size of 4 μm (position 1 and 2) and 2 μm (position 3) per voxel, which is at the limit for detecting the thin fibers with a diameter of 7.2 μm. Furthermore, the analysis of the fiber content was only performed locally at these positions, which might allow higher fiber contents in other areas of the sample.

Other detections concerned air intrusions within the insert, which have already been mentioned in [3-6] as a result of irregularities during the manufacturing process weakening the overall strength of the part. Pore radii have been extrapolated numerically and range between 20 μm to 150 μm. The pores were studied in two sub-volumes shown in Figure 6.

FIGURE 5. Fiber extrapolation (left) and exemplary crack orientation and dimension measurements (right) at position 1 for smaller surface cracks. Projection view of deeper cracks in position 1 (right).

FIGURE 6. Sub volume 1 (left) and sub volume 2 (right) with numerically extrapolated pores.
CONCLUSION

Fiber orientation and defects within an IM insert have a significant impact on the lifetime. It is therefore necessary to understand the behavior of fibers as a result of the manufacturing process represented in the final insert. CT analysis has been used to track cracks evolving from the surface and the length, width, and depth of those cracks can be measured, as well as fiber orientations. The fibers show the expected orientation along the printing layers, which is also the preferred direction of cracks. Future manufacturing processes will therefore need to tackle the challenge of isotropically orienting fibers e.g. by changing to a top-down printing process with modified build plate.

Besides information about the fiber orientation, defects such as air intrusions could furthermore be investigated qualitatively and quantitatively using X-ray CT. A reduction of such defects will addressed in future manufacturing processes.

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