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Investigation of digital light processing using fibre-reinforced polymers

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Abstract

Literature research shows multiple applications of fibre-reinforced polymers (FRP) respectively in fused deposition modelling and gypsum printing influencing the quality of the products in terms of stress and strain resistance as well as flexibility. So far, applications of fibre-reinforced polymers in digital light processing (DLP) are limited.

Fibre-reinforced polymer composites were manufactured into test objects using digital light processing. Short fibres were used in an unordered manner. An anisotropic property due to fibre orientation within the material was observed. The importance of fibre length and shape compared to layer thickness has been investigated including concepts to circumvent clustering of the fibres.

This research contributes to the implementation of fibre-reinforced polymers in additive manufacturing technologies. Digital light processing allows generation of miniaturized objects with relatively high surface quality compared to other additive manufacturing technologies. This paper aim to move fibre reinforced resin parts one step closer towards mechanically strong production-quality components.

Additive Manufacturing Technologies, Digital Light Processing, Fibre-reinforced Polymers, Surface Quality

1. Introduction

Fibre-reinforced polymers (FRPs) are not yet common in additive manufacturing technologies (AMTs). A literature survey [1-9] showed multiple experiments with fibre-reinforced fused deposition modelling (FDM) as well as stereo lithography (SLA), gypsum printing, laminated object manufacturing (LOM), ultrasonic consolidation (UC) and selective laser sintering (SLS). SLA was already inspected by [1] and [2] using glass fibres.

So far, there have been no investigations towards the embedding of carbon fibres using SLA or DLP in a layered structure, but only experiments using UV cured moulds with carbon nanotubes and photopolymer performed by [3]. Moreover, the alignment of the fibres in comparison to the manufactured layers has not been investigated in detail. These aspects were investigated in this paper.

In this paper, Digital Light Processing (DLP), which is related to SLA, was used to test a photopolymer resin combined with short carbon fibres with dimensions of 7.2 µm diameter and 100 µm average length. The density was 1.75 g/cc with a carbon content of 99 % [10]. A bottom-up style DLP photopolymerization platform was used. The interest in the printed objects was among others the distribution of the fibres within the object.

For the resin without fibres, two products that are freely available on the marked were chosen. The FunToDo [11] resin has a density of 1.016 g/cc and is cured at wavelengths between 350 and 450 nm. The VenusCreator [12] resin can be cured at a range of 340 and 410 nm.

2. Method

2.1. Experimental setup

The fibres were mixed into the resin at a ratio of 5 %wt and 10 %wt. The composite photopolymer resin was cured from the bottom in the DLP machine. The light passed from the projector through the bottom of the vat and the resin onto the build platform. After the exposure of one layer, is was necessary to lift the build platform by one layer height plus 5 mm allowing the resin to flow beneath the build platform and provide a uniform distribution of the fibres. The axis resolution was 0.625 µm. For the entire printing process, a machine built by [13] was configured to expose a fibre-filled resin.

The objects were then inspected under a Zeiss Stemi 2000-C optical microscope with a TV2/3''C adapter for the view from top and bottom as well as under a JSM-5910 scanning electron microscope using cuts orthogonally to the layered structure cutting in the middle of the object. The probes were moulded, polished for 1 µm resolution and gold-plated.

2.2. Investigated objects

As an object to investigate, a cubic brick with attached cylinders was chosen for its thin walls and combination of round and flat geometries. Moreover, multiple exposure parameters were chosen for the two different photopolymer resins. Layer thickness was set to 35 µm allowing the fibres to be placed aligned with the layers, but not orthogonally to the layers.

3. Results

The build plate had to be lifted after the exposure of every layer in order to allow the resin to flow beneath the build plate and create a uniform distribution of fibres.

3.1. Optical microscopy

Due to the nearly transparent photopolymer, it could be investigated in terms of a view from top (orthogonal to the layered structure) shown in Figure 1 (left). The figure shows a random distribution of fibres within the object. The fibre direction in the view layer is random within the layer, but not orthogonally to it. It can also be seen that the standard deviation of the fibre length is high compared to the average fibre length of 100 µm.

Investigation of the borders shown in Figure 1 (right) showed that, as the fibres did not stay within the cured photopolymer but were standing out of the object. This makes it necessary to post-process the object in order to receive the favoured surface quality.

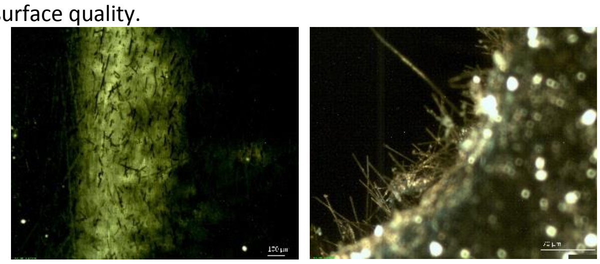

Figure 1. Fibre distribution at top view (left) within the photopolymer and fibres at the border (right) for 5 5wt fibre content.

3.2. Scanning electron microscopy

A rough cut through a sample orthogonal to the layers is plotted in Figure 2 and shows the layered structure of the object as well as the fibres. Except for some fibres, the direction of the fibres lies within the manufactured layers. Note again the different size of the carbon fibres.

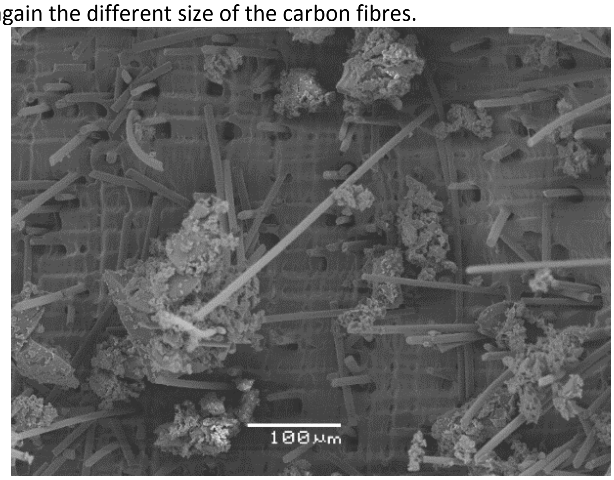

Figure 2. Rough cut through the layered structure under the scanning electron microscope for 5 %wt fibre content.

Fibres were orientated along the layers as can be seen in Figure 3 (left) allowing a reinforcement of the printed part by placement of it during the printing process. An uneven distribution of the fibres as discussed by [14] for conventional manufacturing could not be concluded from the results of the SEM observations. Figure 3 (right) shows an inner corner of the part with evenly distributed fibres among the layers. The upper right corner or the figure shows moulding material.

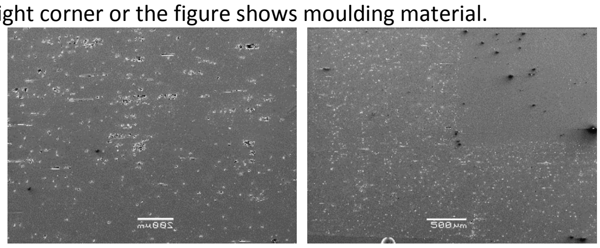

Figure 3. Fibre distribution and orientation in the middle of the printed part (left) and at an inner corner (right) showing an even fibre distribution among the layers for 5 %wt.

Clustering of the fibres was recognized in 30 % of all detected fibres under the SEM resulting in holes within the photopolymer as shown in Figure 4 (left). The fibres themselves were surrounded by gaps between the fibres and the photopolymer reasoning in the shrinkage of the photopolymer during and after exposure. Figure 4 (right) also shows a crack in the photopolymer which might result in decreased mechanical strength and durability. The fibre diameter is shown to be consistent with the product specifications of around 7.2 µm given by [10].

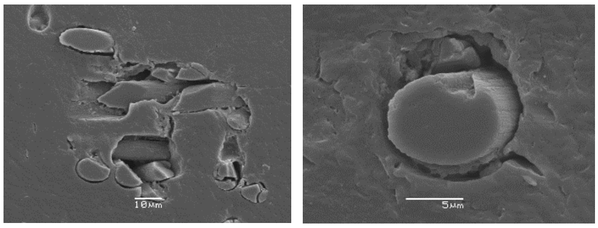

Figure 4. Detailed view of clustered fibres (left) and single fibre with gap and crack for 5 %wt fibre content.

4. Conclusions

It can be concluded that a fibre-filled structure was printed using DLP technology showing an even fibre distribution in the direction of the manufacturing layers. This allows reinforcement in the orientation of the layers by placing the part according to the desired reinforcement direction. Other directions were only minimally bound by the carbon fibres for physical reasons as the layer thickness of 35 µm was significantly smaller than the average fibre length of 100 µm.

No clustering around edges was detected allowing the conclusion of an even distribution of fibres which stands in contrast to injection moulding.

Post-processing is necessary due to the fact that the carbon fibres are not affected by the visual curing in the DLP machine. Therefore, the fibres are standing out of the boundary of the object. This results in an uneven surface, which needs to be processed again.

It was inspected that a clustering of 30 % of all fibre placements happened among the fibres. This resulted in holes in the polymer affecting the strength and durability of the material. Looking at the entire part, the fibres were evenly distributed among the photopolymer allowing the conclusion that no major sedimentation due to the different material densities occurred during the printing process.

Gaps between the fibres and the polymer with the diameter of 1 µm to 2 µm resulted in cracks of the polymer with an average length of 3 µm to 4 µm which will affect the strength of the final part.

References

[1] Cheah C, Fuh J, Nee A, and Lu L 1999 *Rapid Prototyping Journal* **5** 112

[2] Garoushi S, Säilynoja E, Vallittu P K, and Lassila L 2013 *Dental Materials* **29** 835-841

[3] Wagner K S 2014 Investigate Methods to Increase the Usefulness of Stereolithography 3D Printed Objects by Adding Carbon Nanotubes to Photo-Curable Resins *University of Minnesota Duluth*

[4] Vaneker T, and Hofand E 2014 Additive manufacturing with additives: Improving the properties of products produced with mask stereolithography *University of Twente*

[5] Monaghan T, Capel A J, Christie S, Harris R, and Friel R J 2015 *Composites Part A: Applied Science and Manufacturing* **76** 181-193

[6] Chiu S-H, Wicaksono S T, Chen K-T, Chen C-Y, Pong S-H 2015 *Rapid Prototyping Journal* **21** 262-269

[7] Christ S, Schnabel M, Vorndran E, Groll J, and Gbureck U 2015 *Materials Letters* **139** 165-168

[8] Saari M, Cox B, Richer E, Krueger P S, and Cohen A L 2015 *3D Printing and Additive Manufacturing* **2** 32-39

[9] Studart A R 2016 *Chemical Society Reviews* **45** 359-376

[10] Zoltek 2015 ZOLTEK™ PX35 Milled Carbon Fibers *Technical Data Sheet*

[11] FunToDo 2016 http://www.funtodo.net/properties.html *Technical Data Sheet* - visited 22/01/2016

[12] 2Engineers 2016 http://www.2engineers.com/shop/optimized-clear-resin/ *Technical Data Sheet* - visited 22/01/2016

[13] Jørgensen A R 2015 Design and Development of an Improved Direct Light Processing (DLP) Platform for Precision Additive Manufacturing *Master Thesis at DTU Mekanik*

[14] Baran I, Cinar K, Ersoy N, Akkerman R, and Hattel J H 2016 *Archives of Computational Methods in Engineering* 1-31