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Challenges and opportunities of fibre-reinforced polymers in additive manufacturing with focus on industrial applications

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Abstract

Functional parts made by additive manufacturing of polymers have entered the area of industrial applications in recent years providing a wide range of materials with various mechanical, thermal, and electrical properties. These additive manufacturing processes can be combined with known fibre-reinforcements applying modified material parameters with the use of fibre-reinforced polymers.
An increase of tensile strength and Young's modulus result from the application of short fibres in a polymer matrix opening up perspectives for a variety of industrial applications such as injection moulding, biomedical engineering, aerospace, racing, and train technology. A literature survey was conducted in order to identify challenges and opportunities in these fields.

Additive Manufacturing Technology, Review, Fibre-reinforced Polymers, Industrial Applications

1. Introduction

A recent review on industrial applications of Additive Manufacturing (AM) of Fibre-Reinforced Polymers (FRPs) [1] has shown potentials in biomedical engineering mainly for individuality and easier manufacturing of complex shapes. NASA, SpaceX, Airbus and other companies and institutions focusing on lightweight materials, already drove applications in aerospace engineering. Industrial applications focus on process chains, flexibility and cost-efficiency whereas mobility applications focus on lightweight materials for fuel-efficiency purposes. AM is present with potentials in a multiscale regime allowing for features from the µm-scale to the m-scale.
The focus of the contributions lies on Material Extrusion (ME) and Vat Polymerisation (VP), which is also often referred to as Digital Light Processing (DLP) and StereoLithography (SLA). Investigations reviewed in [1] showed a significant increase in tensile strength and Young's modulus (EMod) of different AM technologies.
This contribution, however, focuses on industrial applications, among others, in the field of Injection Moulding (IM) as presented in earlier contributions [3-5].

2. Material Testing

2.1 Comparison of Mechanical Properties

In order to compare the mechanical properties such as EMod, tensile strength and strength at break, tensile tests were performed at a Zwick Roell Z005 machine with a test geometry according to DIN EN ISO 527-2BB. 9 specimen were tested for each sample with 3 specimen each at strain rates of 10 mm/min, 100 mm/min and 1000 mm/min.
Experiments showed an increase of Young's modulus of 15% by adding 5%wt or 10%wt of Carbon Fibres (CF) in a photopolymer matrix. Results are presented in Figure 1 showing multiple materials such as Acrylonitrile Butadiene Styrene (ABS) at different IM injection pressures as well as different commercially available photopolymer resins. It was shown in respect to the specimens 6-8 that EMod is increased by adding CF to the photopolymer resin as compared to the same plain resin as well as to ABS samples shown in samples 1-5. However, tensile strength and strength at break was significantly lower.
Nevertheless, the photopolymer configuration in terms of monomer and photoinitiator has a significant influence on the mechanical parameters and allows for optimization for specific applications as shown in samples 9-11.

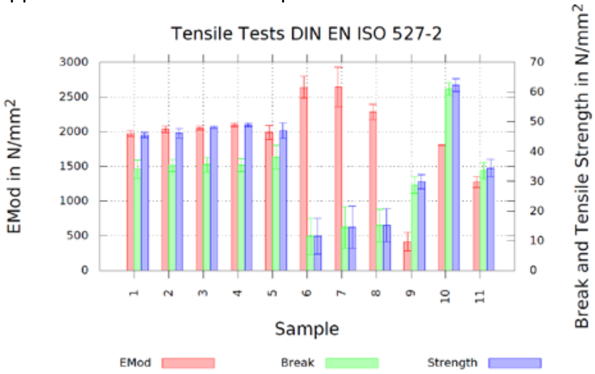

Figure 1 Tensile tests conducted by [2] on ABS injected with 250 bar (1), 300 bar (2), 350 bar (3), 400 bar (4), 450 bar (5), HTM 140v2 with 5% CF (6), 10% CF (7) and 2000 flashes (8), E-Tool with 2000 flashes (9), Nature resin (10), RCP30 with 1000 flashes (11).

A survey conducted over a number of literature sources was presented in [1] concluding that the variation in values for Young's moduli as well as tensile strength in SLA, ME and powder-based AM is significantly higher. However, a trend of increased tensile strength and Young's modulus was concluded whereas the increase in tensile strength of up to 250% was achieved for ME of 13%wt fibre content and an increase of Young's modulus of up to 800% was achieved for ME of 13%wt fibre content. The data has been modified and adapted from [1] and is shown in Figure 2 for tensile strength and Figure 3 for Young's modulus.

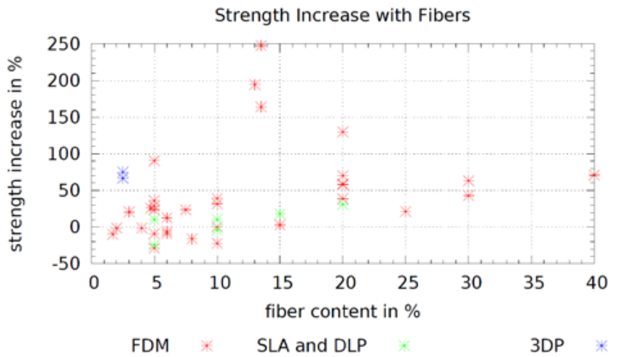

Figure 2 Tensile strength of FDM, SLA and DLP, and gypsum printing modified from data of [1] as gathered from literature.

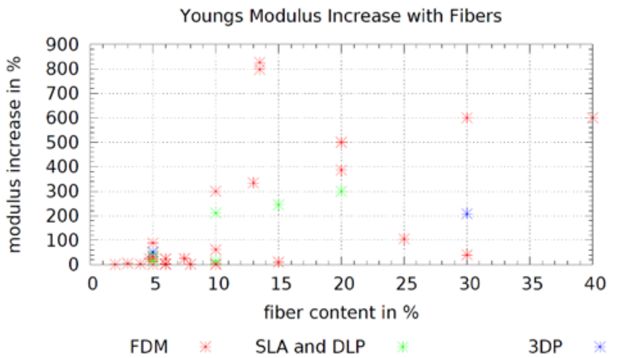

Figure 3 Young's modulus of FDM, SLA and DLP, and gypsum printing modified from data of [1] as gathered from literature.

2.2 Temperature-Dependent Mechanical Properties

Investigations performed by [6] were focusing on ME parts as well as Selective Laser Sintering (SLS) of ABS, Polyamide 12 (PA12) and DuraForm HST Composite (HST) at temperatures of up to 110 °C. The research concluded significantly anisotropic properties of the ME parts resulting from the printing structure that was applied. Especially the applied creep test showed significant depletion at higher temperatures. More complex internal structures such as honeycomb were considered.

2.3 Fibre-Matrix Interface

Investigations presented in [3] with the use of a JSM-5910 Scanning Electron Microscope (SEM) concluded a disturbed fibre-matrix interface of the used short virgin CFs with the photopolymer matrix due to the difference in the expansion coefficient of the materials. The interface could be improved by using a different surface finish of the CFs, different fibre- or matrix materials, curing procedure or curing temperature. Ongoing research shows that an increased curing temperature can improve the mechanical properties.

Another significant influence of thermal printing parameters applies to ME printing in terms of layer-interaction. A break surface of a dog bone produced from ME of 12%wt glass-filled nylon is shown in Figure 4 with focus on the layer interaction. Due to the extrusion mechanism with a pre-alignment of the fibre filler in the direction of the extrusion, the fibre-interface between the layers is essentially not applicable. However, the pre-alignment can benefit the mechanical properties when the alignment is used during the printing process in terms of an extrusion line orientation. Free-form extrusion is another field of application avoiding a mechanical weakening due to similarly oriented layers.

Other weakening points are air intrusions affecting the mechanical parameters of ME prints as shown in Figure 5 for 15%wt CF-filled PLA material under SEM investigations.

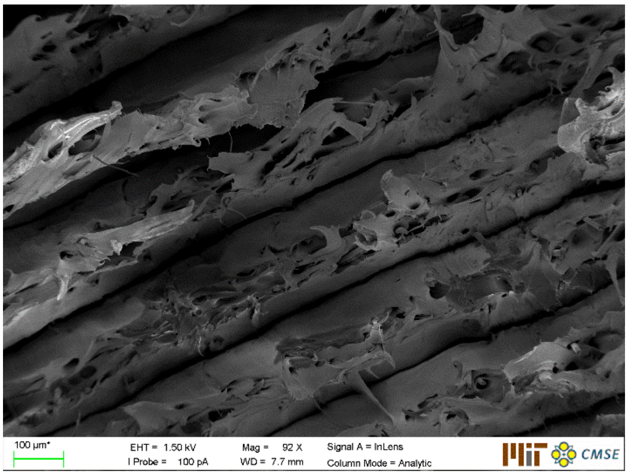

Figure 4 Break surface of 12%wt glass-filled nylon as seen at SEM investigations with special focus on layer interaction.

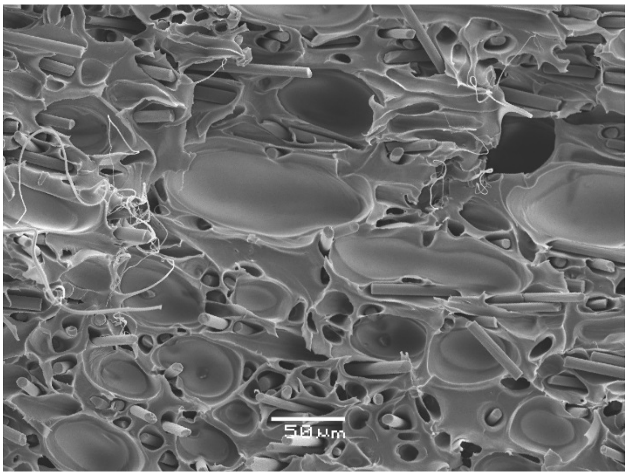

Figure 5 Break surface of 12%wt CF-filled PLA material from ME with air intrusions.

3. Fields of Application

3.1 Injection Moulding Inserts

In the field of IM inserts, a photopolymer resin was reinforced using short unseized carbon fibres (CFs) in the size range of 7.2 µm diameter and 100 µm length. The fibres were included in the manufacturing process of a layer-wise VP process forming IM inserts that later were applied to a standardised mould.

Lifetime expectancy of IM inserts made from VP is lower than for other comparable materials such as aluminium, brass or steel. A Life Cycle Assessment (LCA) has been performed by [7, 8] showing that smaller quantities favour the more flexible and cheaper AM inserts over the conventional materials in terms of Global Warming Potential (GWP) and Human Toxicity (HT). Especially the CF-reinforced inserts improved the lifetime of the IM inserts significantly [2, 4].

Surface texture and micro features are favoured by VP as the voxel size in the range of single µm allows sharper concave corners than computer-controlled milling machines. Moreover, the production time is only dependent on the height of the manufactured part, not on the complexity of the surface structure. This allows the combination of macro structures with potentially functional micro structures on the surface of the object. This is supported by CFs as described by [9].

Surface measurements so far have been performed by [4] showing only limited wear of the inserts over the number of IM cycles as can be seen from Figure 6.

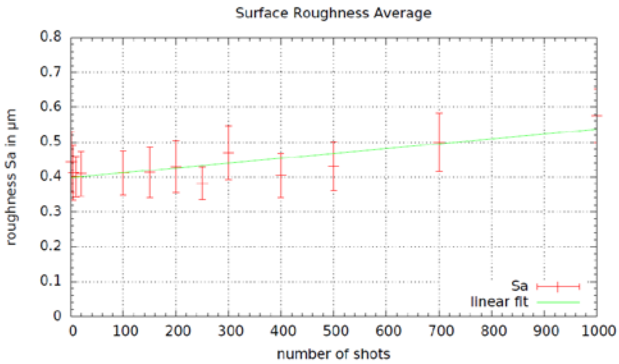

Figure 6 Surface roughness measurements performed by [4] on an injection moulding insert showing a slight but non-influential increase of surface roughness.

The surface of the insert after 2650 shots is shown in Figure 7 where it can be concluded that in comparison to conventional inserts using the same material without fibre-reinforcement, also macro cracks are limited in their propagation.

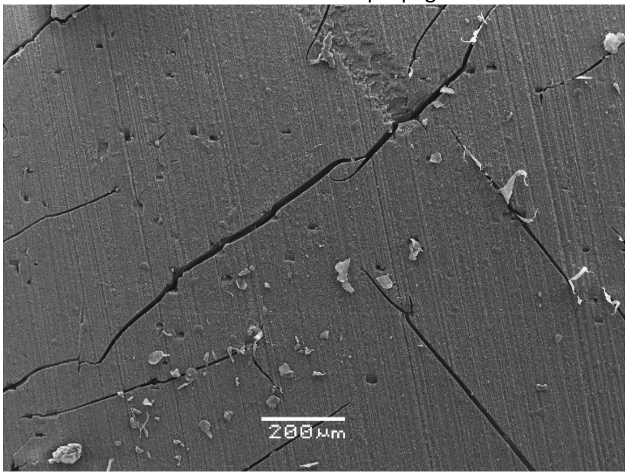

Figure 7 Surface of an IM insert after 2650 shots. Macro- and micro-crack propagation is significantly limited by the fibre-reinforcement of the photopolymer.

3.2 Biomedical Engineering

Further as reviewed in [1] were located in the fields of biomedical engineering where strategies of self-healing in FRP-based composites were considered. Challenges include the orientation of fibres in the polymer matrix [10]. Yet, no medical applications received official approval for applications on humans. Tissue and scaffold design are also considered a high-potential of FRPs in AM [11].

3.3 Aerospace

Lightweight is an important factor of aviation and transportation in general. AM contributes with novel stress-adapted shapes and polymer materials which can be strengthened by fibre-reinforcement. Prior research was performed by NASA [12]. Parts are also embedded in the Airbus A350XWB plane. Low production numbers as well as generally small part size enables the implementation of AM. [13]

The reduction of part count and assembly steps using AM in terms of aircraft makeup was discussed specifically by [14, 15]. Moreover, it was discovered that deformations during curing were reduced at a layup of continuous fibres with a resin matrix material. In this specific case, 40.6% of weight savings was achieved at a part count reduction of 50%.

Satellite applications with focus on design and functionality were mentioned by [14].

3.4 Racing

Individualism, high strength, lightweight, and low production number favour the use of FRPs in racing applications. Among metal AM, FRPs have been used in applications like wheel suspensions as well as an oil pump. [16, 17]

3.5 Train and big-area technologies

Research has been pursued at the Oak Ridge National Laboratory presented by [17] finding a significant reduction of warping of the part making a reduction of additional ovens to prevent curling possible for ABS parts with 15-20% fibre content. Big Area Additive Manufacturing (BAAM) was used in order to elaborate on a lightweight power train. BAAM is also a potential technology for wind turbine blades in direct and indirect manufacturing as currently investigated by the Oak Ridge National Laboratory (ORNL) [18].

All above-mentioned applications that are connected to motion and mobility profiting from new design possibilities, which allow for a lightweight manufacturing bearing significant cost decreases and performance increases in the applications.

4. Conclusion

Lightweight, individualism in form and improved mechanical properties as compared to non-fibre-reinforced AM can be concluded from literature research and experiments. While a wide range of industrial applications still use conventional manufacturing or metal-AM, FRPs in AM come with advantageous light structures as compared to metal-AM and increased strength as compared to conventional AM. Thus, parts that were previously manufactured from metals can be elaborated to FRP opening up new perspectives in lightweight production.

Flexible integration of cost-efficient and fast manufacturing of AM inserts improved by CF leads to an improvement in IM in terms of costs, speed, flexibility and environmental impact of prototyping and pilot production.

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