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Reviewed Paper

PROCESS AND MATERIAL OPTIMISATIONS FOR INTEGRATION OF CHOPPED GLASS FIBRES IN LASER SINTERED POLYMER PARTS

H. De Coninck*[1], A Dejans[1], S. Meyers[1], S. Buls[1], Y. Kinds[1], J. Soete[2], P. Van Puyvelde[3], and B. Van Hooreweder[1]

[1]Department of Mechanical Engineering, Manufacturing Processes and Systems (MaPS), KU Leuven, Leuven, Belgium

[2]Department of Materials Engineering, Structural Composites and Alloys, Integrity and Non-destructive Testing (SCALINT), KU Leuven, Leuven, Belgium

[3]Department of Chemical Engineering, Soft Matter, Rheology and Technology (SMaRT), KU Leuven, Leuven, Belgium

Abstract

Additively manufactured polymer composites gain popularity in a variety of industries such as aerospace, biomedical and automotive. Laser sintering (LS) is a well-known AM process that typically uses polyamide which can serve as matrix material. Hence LS has the potential to produce reinforced polymers that can meet demanding requirements. In previous research, issues with powder flowability and poor fibre dispersion led to limited increase of mechanical properties. To overcome this, a novel fibre deposition system was recently developed and optimised at KU Leuven to successfully produce fibre reinforced LS samples with random inter- and intralayer fibre orientations. A limited but promising influence of deposited glass fibres on produced LS parts was noted after mechanical testing. In this work, the influence of different (heat) treatments on glass fibres used during LS will be discussed as well as the resulting differences in the fibre/matrix behaviour as analysed through hot stage microscopy.

Keywords: Polyamide 12, glass fibres, fibre/matrix behaviour, glass fibre sizing, laser sintering, deposition system

Introduction

Laser sintering (LS) is an additive manufacturing (AM) technique that can be used for almost every material available in powder form but is most often used to process polymer powders [1]. As a powder bed-based AM technology, LS uses a CO_2 laser to scan cross sections of the desired component on preheated powder layers to selectively consolidate the polymer together. When this process is repeated layer after layer, the desired component is built and can afterwards be retrieved. The sintered material forms the component whilst the unsintered powder remains in place to support it [2,3]. Semi-crystalline thermoplastics, like polyamide 12 amongst others, are most often used for LS as their melting and crystallization behaviour suits the production process [4]. LS is preferred over other polymer AM technologies for the production of structural polymer parts as final part properties are similar to injection moulded polymers, leading to strong and durable AM components [5]. As LS progressed from a rapid prototyping technology towards rapid manufacturing, the need for a broader material palette surfaced in the industry with an emphasis on materials with improved mechanical performance focused on high structural strength and stiffness.

Therefore, an increasing demand for additively manufactured polymer composite parts is manifesting in different industries, such as aerospace, biomedical and automotive, to meet stringent requirements with optimized mechanical properties. Fibres and fillers made out of different materials, such as for instance glass or carbon, can significantly enhance various mechanical properties of the polymer matrix material. Related to this trend, LS has gained renewed attention over the recent years as polymer AM technique as it already processes the polymers typically used as matrix material [6]. Some initial steps have been conducted to successfully produce polymer composites with the LS process. Previous research investigated the performance of commercially available glass bead filled polyamide 12 (GF-PA12) powder and reported the successful increase in stiffness of the LS parts but highlighted that this stiffness increase goes at the expense of tensile strength and strain at fracture. In addition, a

significant negative influence on the fatigue performance was noted for the produced parts. It is assumed that upon significant or repeated deformation, the glass beads detach from the polymer matrix and are unable to carry any load whilst at the same time introducing stress concentrations, leading to significantly reduced fatigue characteristics [7]. Further research is required to get a better understanding of possible reinforcement/polymer powder combinations, application processes and final mechanical properties of the produced parts. Therefore, in this work, the combination of glass fibre reinforcements and PA12 powder was explored. A novel in-house developed fibre deposition system was designed and used to produced LS parts reinforced with fibres on which tensile tests were conducted. To get a better understanding of the interaction between the glass fibres and the polymer powder different treatments and analysing techniques were applied including fibre heat treatments, plate pressing, hot stage microscopy, CT scanning and mechanical testing.

Materials and methods

Materials

As base material for sample production with the LS process and the plate press process, PA12 powder (PA 2200, d_{50}=56µm, EOS, Germany) was used. The base material for the glass fibre reinforcements consists of continuous strands of glass fibre (TUFRov type 4588, Nippon Electric Glass, Japan). The continuous strands have a silane-based sizing compatible with polyamide and were chopped in-house in short fibres with an average length of 3mm and a diameter of 10µm. To achieve the desired material properties of the chopped fibres to be successfully used by the in-house developed fibre deposition system, continuous fibres with a low tex-value of 300 was selected. This tex-value is expressed in g/km and denotes how many grams 1km of roving weighs. A smaller tex-value indicates a lighter roving.

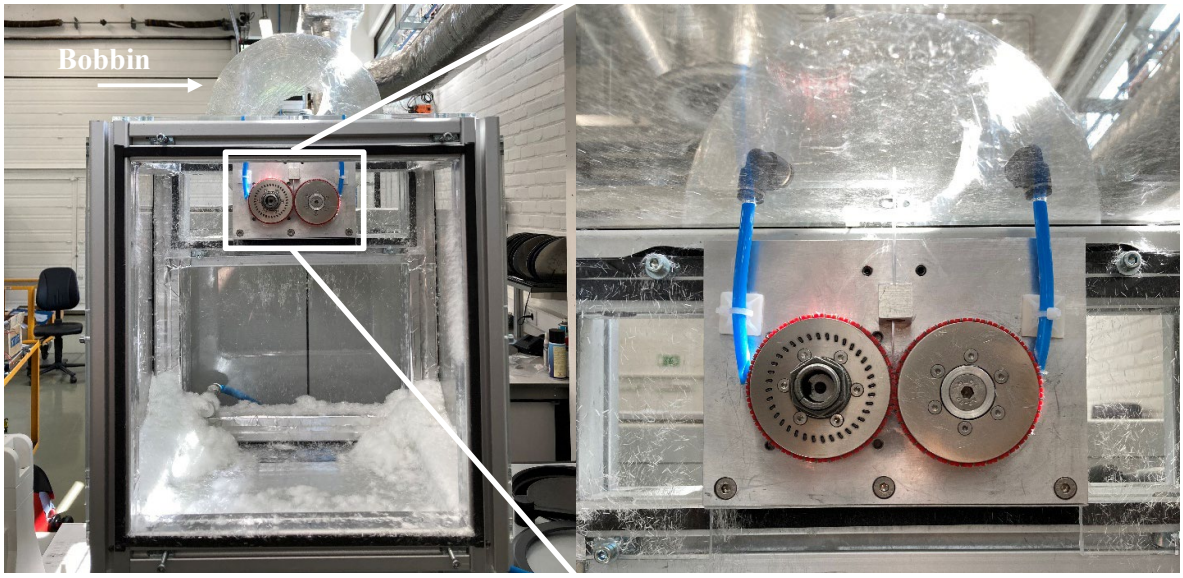

Figure 1 Innovative chopping technology (Chopcot, Van der Mast)

Fibre chopper

An innovative chopping technology (Chopcot, Van der Mast, The Netherlands) was used to chop the continuous glass fibre strands into chopped glass fibres with an average length of 3mm, shown in Fig. 1. One glass fibre strand can be fed to the chopper at a time and the chopping technology provides the possibility to chop into shorter lengths than currently available in industry. The cutting blades are evenly staggered over two rolls. As they pinch in between each other, the chopping length is half the distance between two blades at one roll, making strand release very straightforward.

Heat treatments

Different heat treatments were performed on the chopped glass fibres using a bench-top furnace (Borel, RI 1100-10) with a maximum temperature of 1100°C. Eight different heat treatments were applied on different batches of 76g chopped glass fibres. The oven was heated to 100°C, 150°C, 200°C, 250°C, 300°C, 350°C, 400°C or 450°C. When this temperature was reached and stabilized, the fibres were placed inside the oven for 1h. These tests were conducted to investigate the behaviour of glass fibres and their sizing under elevated temperatures.

Hot-stage microscopy

To investigate the melting behaviour of PA12 powder in the vicinity of the chopped glass fibres, a Linkam Optical Shearing System (CSS450) was used which allows to directly observe the melting and coalescence behaviour of different materials via a standard light optical microscope while these materials are under precisely controlled temperature and various shear modes. The microscope (Olympus BX14, Shinjuku, Tokyo, Japan) is equipped with Olympus SLMPlan 20x and 50x objectives and a Hamamatsu C4742-95 Orca 100 CCD monochrome Camera (Hamamatsu, Hamamatsu City, Japan) is used to take pictures. Images are taken with the HiPic acquisition software. A heating rate of 10°C/min was applied to reach a maximum temperature of 190°C. The hot stage microscope was used to observe the interaction between glass fibres heat treated at different temperatures (with and without sizing) and melting PA12 powder.

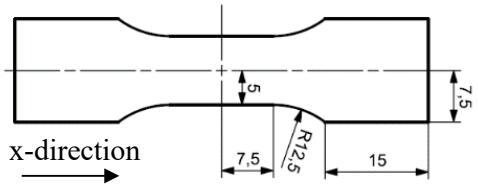

Figure 2 Geometry of specimens produced with the plate press after milling and produced by LS

Plate press

Test samples were produced with a plate press using the above mentioned PA12 powder and chopped glass fibres. A mould with six rectangular openings (15mm x 60mm) was filled and covered with Teflon sheets on either side. Three openings were filled with PA12, three openings were filled with a mixture of PA12 powder and 2wt% chopped glass fibres with sizing, and three openings with a mixture of PA12 powder and 2wt% chopped glass fibres without sizing (heat treated at 450°C). In total three plate press cycles were performed. A 2wt% of chopped glass fibres was chosen after analysis of the number of fibres deposited by the in-house developed deposition system and thus the expected number of fibres present in the LS produced parts. The mould, accompanied by the Teflon sheets and a bottom and top metal plate, was placed in a Collin plate press 200E (Collin, Ebersberg, Germany), which was heated to 180°C and 190°C. The plate press was closed and when the targeted temperature for both the top and bottom plate was reached, an additional two minutes at this temperature and additional pressure of 50bar was applied. Afterwards, the mould was cooled to 40°C after which the rectangular samples can be demoulded.

After demoulding, the rectangular samples were milled to create dog bone samples with a geometry as shown in Fig. 2, all dimensions in mm.

In-house developed fibre deposition system

A novel fibre deposition system was designed, developed and implemented in a conventional LS machine (DTM Sinterstation 2000) to overcome problems with the powder flowability during the LS process. When fibres with a significant length are homogeneously mixed into the polymer powder, severe problems with powder flowability during the LS process occur that need to be avoided. In addition, by the development of the fibre deposition system in combination with the fibre chopping technology, issues with impregnation of the fibres in the produced parts are limited and the chopped glass fibres can be successfully integrated in the laser sintered polymer parts. These issues can be related to phenomena mentioned in literature, being the poor dispersion of fibres and fillers in the powder feedstock and high internal porosity present in areas of the produced parts with a high fibre content which result in limited increases of the final parts' elastic modulus and strength [8].

The in-house developed deposition system (shown in Fig. 3) allows the deposition of chopped glass fibres every two layers during the LS process. The set-up consists of five main components connected to the standard recoating roller:

1. Test sieve with a mesh of 3,35mm;
2. Vibrating system;
3. Support structure connected on top of the recoating roller by two vibration dampers;
4. Grounding cable to the machine;
5. Four blad mixer with shown also in Fig. 4, with a height of 10mm and controlled by a miniature stepper motor.

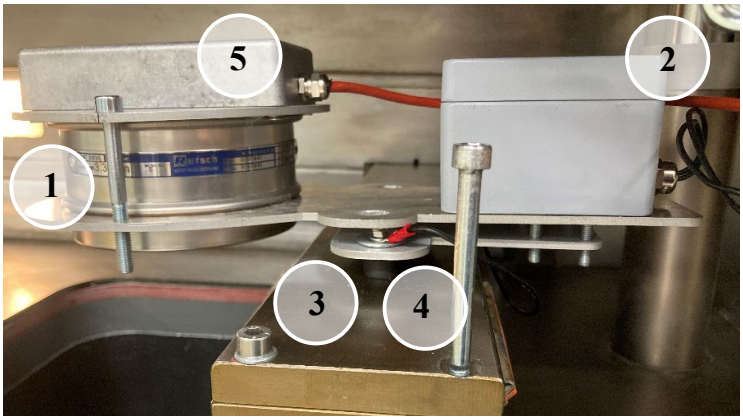

Figure 3 In-house developed fibre deposition system

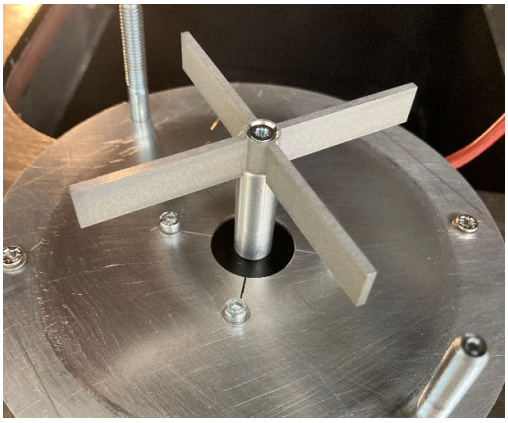

Figure 4 Close-up mixer in-house developed deposition system

Laser sintering

During the LS process, chopped glass fibres were injected onto the powder bed by the in-house developed fibre deposition system. The geometry of the specimens produced by LS is shown in Fig. 2. All samples were built in the x-direction so parallel to the powder bed and along the movement of the recoating roller.

A commercial DTM Sinterstation 2000 equipped with a CO_2-laser was used to produce the samples. First a LS parameter optimisation was conducted For the PA12 powder without fibres, based on maximising Archimedes density (Acculab atilon ATL-244-1) of the produced samples [7]. Various cubes were produced for which the laser power (P) and scanning speed (v) were varied while keeping the layer thickness (l) and scan spacing (s) constant at 100µm and 150µm respectively. The resulting LS process parameters used in this work for both the PA12 and the PA12 with fibres are shown in Table 1. During the LS process, the powder bed was preheated to a temperature of 168°C and an inert, nitrogen atmosphere was sustained throughout the whole process. No post-processing was applied to the produced samples.

Table 1 Optimised process parameters for laser sintering of PA12 (PA 2200)

Material		PA12 (PA 2200)
Parameter	Unit	
Average grain size	[µm]	56
Sintering temperature	[°C]	168
Removal chamber temperature	[°C]	30
Scan spacing	[mm]	0,150
Feed temperature	[°C]	65
Layer thickness	[µm]	100
Laser power	[W]	12

Mechanical testing

Small dog bone tensile samples were produced from PA12 powder and from PA12 with chopped glass fibres with the plate press and LS. For the plate press base material, the fibres were homogeneously mixed in the powder on beforehand. For the LS process, the glass fibres were deposited every 2 layers with the in-house developed fibre deposition system.

Tensile testing was performed on an Instron 3367 quasi-static machine equipped with a 5kN load cell and an Instron AVE2 video-extensometer. The tests were conducted at 5mm/min. The width and thickness of the test section of each sample were measured with a calliper and used as input for the software to calculate the dimensions of the cross-sections of the samples and subsequently the correct stress values [7]. The results were used to understand and compare the influence of the glass fibres on the produced parts and their mechanical properties.

CT scanning

CT scanning was performed at the KU Leuven XCT Core Facility on two different PA12 samples with glass fibres produced by LS and the plate press process. A 230kV/300W TESCAN UniTOM XL CT system (TESCAN XRE, Ghent, Belgium) was used, equipped with a tungsten target, a voltage of 100kV, a current of 150µA and 2400 projections. Three averages for each projection ensure a strong signal to noise ratio. A 0,1mm thick brass filter was installed to remove low energy photons from the X-ray spectrum. The magnification of 418,75 allowed to obtain a voxel size of 8µm.

Reconstruction of the cross-sectional images was performed in the TESCAN Panthera software. Segmentation of the dataset and quantitative analysis was performed in Avizo 2022.1 (Thermofisher), where gray scale hysteresis thresholding was used to differentiate between glass fibres and polymer matrix. The fibre volume fraction was determined as the ratio of the volume of fibre voxels to the total volume of the analysed sample.

Rule of mixture for composites

The rule of mixture (ROM) of composites can be used as a theoretical reference to approximate the elastic mechanical properties of composite polymers [9]. For this work, the ROM was applied to the results of the preliminary testing.

The upper and lower values of the elastic modulus for composites can be calculated based on assumptions. When the load would be applied longitudinal to the fibre and according to the iso-strain assumption, the highest elastic modulus of the composite material can be calculated with the ROM:

$$E_{c,max} = fE_f + (1 - f)E_m \quad (1)$$

With:

- $E_{c,max}$ indicating the upper value of the elastic modulus for the composite;
- f the volume fraction of reinforcement which can be calculated by;

$$f = \frac{V_f}{V_f + V_m} \quad (2)$$

- E_f the elastic modulus of the reinforcement material;
- E_m the elastic modulus of the matrix material.

Equation 1 can also be used to predict other elastic properties such as the ultimate tensile strength (UTS).

In the case that the load is applied transverse to the fibre, the lowest elastic modulus of the composite can be estimated by the ROM according to the iso-stress assumption:

$$E_{c,min} = \left(\frac{f}{E_f} + \frac{1 - f}{E_m}\right)^{-1} \quad (3)$$

With $E_{c,min}$ indicating the lower value of the elastic modulus of the composite.

Results and discussion

Preliminary testing

Preliminary tests with and optimizations to the in-house developed deposition system were performed until parts could be successfully laser sintered with a significant number of fibres. Four different LS build jobs were performed to produce tensile bars for initial mechanical testing. In each LS build, three tensile samples were built with chopped glass fibres deposited by the in-house developed deposition system and three tensile samples without fibres. By positioning three tensile samples in the top half of the build platform, no fibres were deposited

in these parts as the deposition system only covers the bottom half of the build platform with fibres. An accurate comparison can be made between the two sets of tensile samples as they are built in the exact same environment. A variation of sintering temperatures, laser powers and feed temperatures were applied between the different preliminary test builds. Thus, only the comparison between the samples with and without fibres from the same build jobs was relevant. An increase of approximately 2% in tensile stresses can be noticed for the samples reinforced with fibres compared to the samples without fibres in the same LS build job. This limited increase in tensile strength can be linked to the limited number of fibres deposited by the deposition system, thus the deposition system was optimized and updated.

Different tests were conducted to find the optimal amount of fibre throughput of the in-house developed fibre deposition system in combination with the LS process. The addition of a mixer to the set-up (Fig. 4) had a significant influence on the amount of deposited glass fibres. An optimal, average fibre weight fraction of 2wt% was found to be suited for the LS process. Following the rule of mixture [9], a fibre weight fraction of 2wt% could in an optimal scenario (all fibres aligned in the direction of the stresses applied on the part) increase the tensile stress by approximately 50%. However, after LS production of tensile samples with the optimized amount of glass fibres in the parts, no significant increase in UTS was observed when samples with and without fibres from the same build job were compared. Further investigations were needed to get a profound understanding of the influence of glass fibres and their sizing on the produced parts.

CT scanning

The CT scans shown in Figure 5 and 6, show that the sample produced with the plate press (Fig. 6) contains more fibres compared to the sample produced with LS (Fig. 5). This was expected and can be explained by various reasons:

- During the LS process, fibres are only deposited every 2 layers, limiting the number of fibres in the produced parts.
- For the plate press process, the fibres can be mixed into the powder and as pressure is applied during the process less issues occur (compared to the LS process).
- In the plate press sample, the fibres can be more randomly oriented in all directions compared to the LS sample where the fibres tend to stay in the xy-plane as a result of the LS process.

Table 2 Fibre volume fractions of the two CT scanned samples as the ratio of the volume of fibre voxels to the total volume of the analysed samples

	Volume Fraction	Label Volume (mm^3)	Total Volume (mm^2)	Label Voxel Count	Total Voxel Count
PP_PA12_GF	0,0347	130,7360	377,1850	25.534.449	736.689.162
LS_PA12_GF	0,0186	670,7810	359,8470	13.101.186	702.826.541

Further analysis of the CT data confirms what can be seen on the CT scans (Fig. 5 and Fig. 6). For the plate press sample, a volume fraction of 0,0347 or 3,47vol% was found which is equal to 8,94wt%. Based on the ROM, a theoretical maximum UTS increase of approximately 160% can be expected (when the load would be applied longitudinal to all the fibres). For the LS sample, a volume fraction of 0,0186 or 1,86vol% was found which equals 4,92wt%. Based on the ROM, a theoretical maximum UTS increase of approximately 110% can be expected. The CT data is summarized in Table 2.

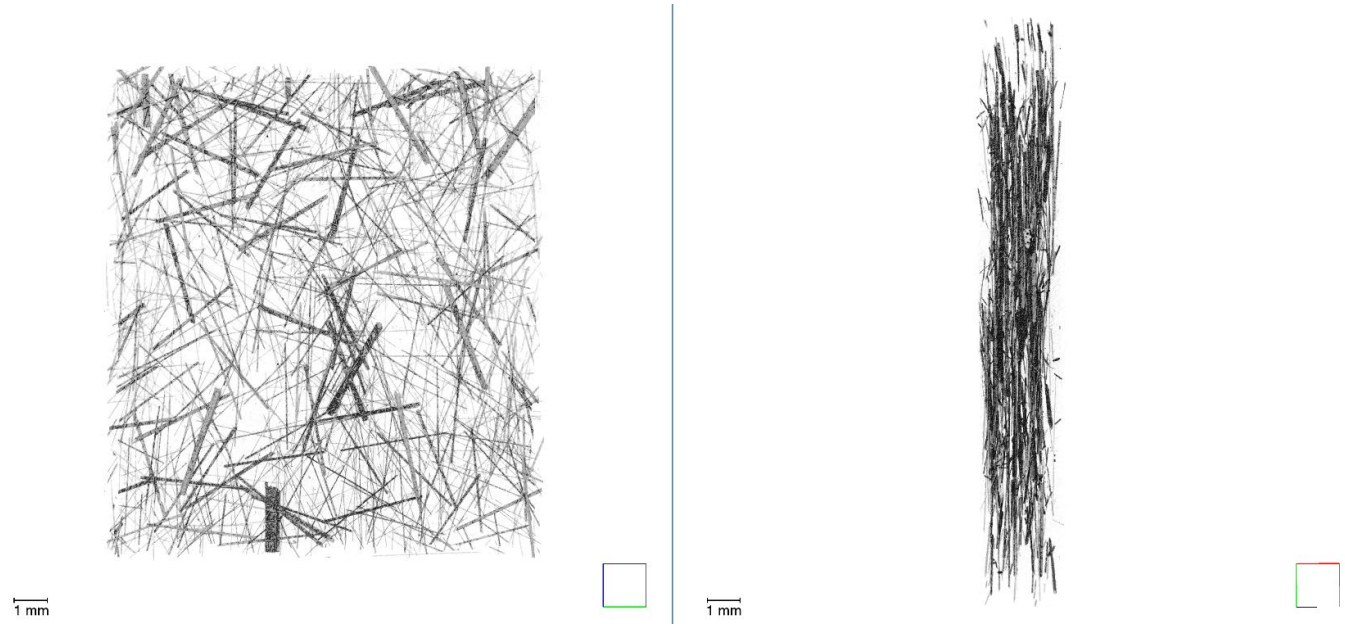

Figure 5 CT scan of PA12 sample with glass fibres produced with the laser sintering process

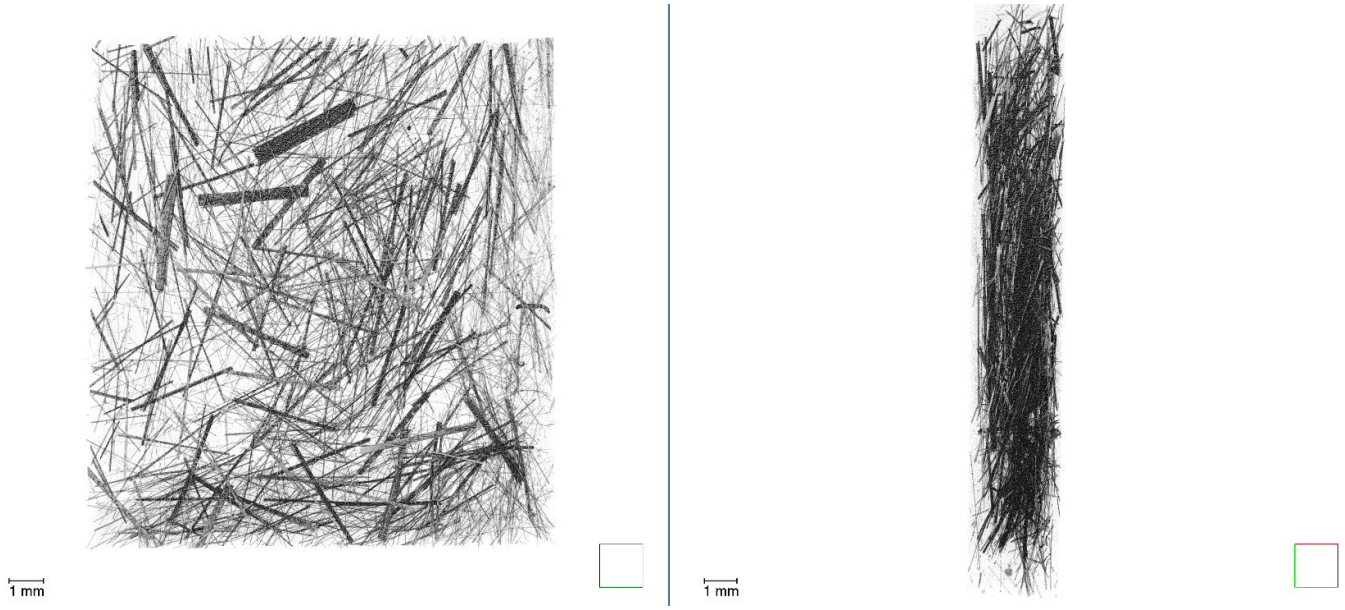

Figure 6 CT scan of PA12 sample with glass fibres produced by the plate press process

Heat treatments

After the oven heat treatments of different batches of 76g chopped glass fibres, a discoloration of the glass fibres could visually be noted. The samples are becoming darker when the temperature of the oven treatment was increased in the range of 150-350°C, as can be seen in Fig. 7. When the chopped glass fibres were placed in the oven for 1h at 450°C, the discoloration disappeared. As the temperatures used for the heat treatments are far below the melting temperature of glass (±1600°C), the decolorization can be explained by degradation of the glass fibre sizing present on the fibres. The majority of sizing present on glass fibres is thermally degraded when heated in an air atmosphere in the range 200-300°C [10]. The assumption was made that by heating the glass fibres for 1h at 450°C combined with the fact that the decolorization disappears after this heat treatment, these fibres do not have a sizing anymore as the sizing is burned of the fibres. These heat treatments were performed to get a first understanding of the influence of heat on the glass fibres and their sizing. As mentioned before, during the LS process the build chamber gets preheated to a temperature just below the melting point of the polymer material. The laser heat source is used at low powers to tip the polymer powder over the melting point to sinter and

consolidate the powder together. These temperatures (preheating temperature and heat produced by the laser) might already influence the glass fibres and their sizing, although, the laser sintering process is conducted under a nitrogen atmosphere which might change how heat affects the fibres. These initial heat treatments confirm the influence on the glass fibres and mostly on the sizing. Therefore, further research was conducted to understand the influence of this glass fibre sizing on the LS produced parts and their mechanical properties.

Figure 7 Chopped glass fibres after different heat treatments in air atmosphere (from left to right: 150°C, 250°C, 350°C, 450°C)

Hot stage microscopy

Hot stage microscopy was used to investigate the behaviour of melting PA12 powder particles when combined with chopped glass fibres with and without sizing. The temperature was gradually increased to 190°C, slightly above the melting temperature of the polymer powder. Whilst the polymer powder was melting, the interaction of the melt with the present glass fibres was observed. A subtle difference could be noted when the interaction of the melting PA12 powder with glass fibres with and without sizing was compared. In combination with glass fibres with sizing, the melting PA12 powder was 'drawn towards' the surface of the glass fibre. The molten polymer tends to flow and incapsulate the fibres (Fig. 8). For the combination of PA12 powder with fibres without sizing this phenomenon was not observed. The PA12 powder melted but there was no clear interaction with the present fibres. A pool of molten PA12 was formed with glass fibres 'floating' on the molten polymer (Fig. 9).

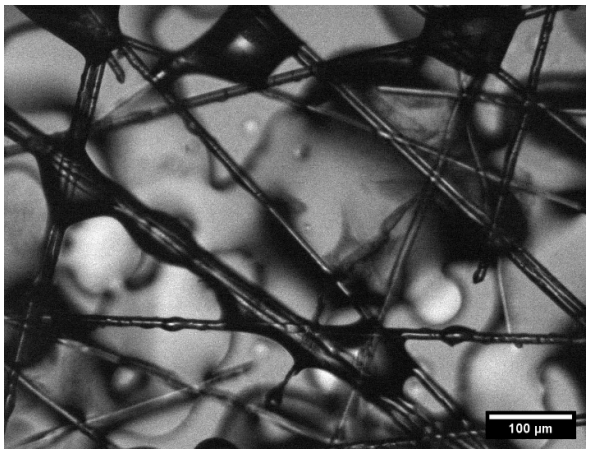

Figure 9 Melting behaviour of PA12 powder mixed with chopped glass fibres (with sizing)

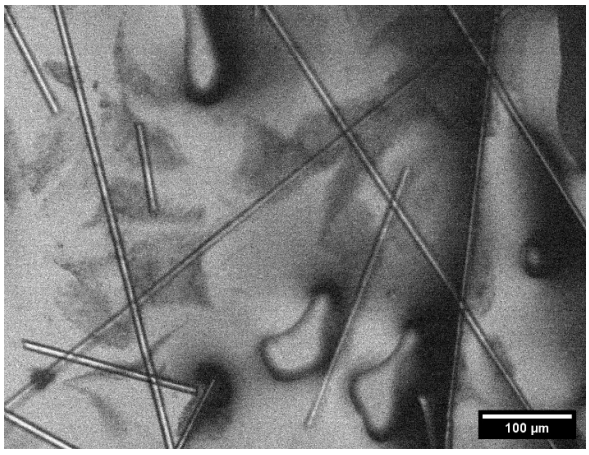

Figure 8 Melting behaviour of PA12 powder mixed with heat treated chopped glass fibres without sizing

These observations highlight the importance of the glass fibre sizing for good impregnation and adhesion of the polymer matrix material with glass fibres in composite materials. In addition, the hot stage microscope observations gave a first impression of the interaction between the glass fibres and the PA12 powder during the LS process.

Plate press

To investigate the influence of the glass fibre sizing on the mechanical properties of parts produced with the PA12 polymer powder, tensile samples were produced with the plate press process and tensile tests were performed. The results of these tests are summarized in Table 3 and the tensile curves of these tests are shown in Figure 10.

The following phenomena can be noted:

- No significant difference between the ultimate tensile strength (UTS) of neat PA12 samples and PA12 with glass fibres without sizing can be noted. An increase of 4% in UTS is noted for PA12 samples containing glass fibres with sizing. This highlights the importance of the glass fibres sizing for the final mechanical properties of the produced parts.
- The difference in modulus of elasticity (E-modulus) and fracture strain (ϵ-fracture) indicate that the samples with glass fibres and sizing have a higher stiffness and are more brittle. It is expected that because of the applied temperature and pressure during the plate press process, the samples have a high density for the matrix material and a good adhesion between the glass fibres and the polymer matrix material leading to the increased stiffness and strength. Also, for the samples containing glass fibres without sizing, an increase in E-modulus and decrease in ϵ-fracture can be noted, although, this is less pronounced compared to the samples containing fibres with sizing. This highlights, again, the importance of glass fibre sizing on the final mechanical properties of the produced parts.

The results are consistent with previous research on degradation and compatibility of glass fibre sizing at elevated temperatures and applied with different polymer matrix materials [10,11]. In addition, these results confirm the compatibility of the current sizing present on the chopped glass fibres with the used PA12 powder during the LS process.

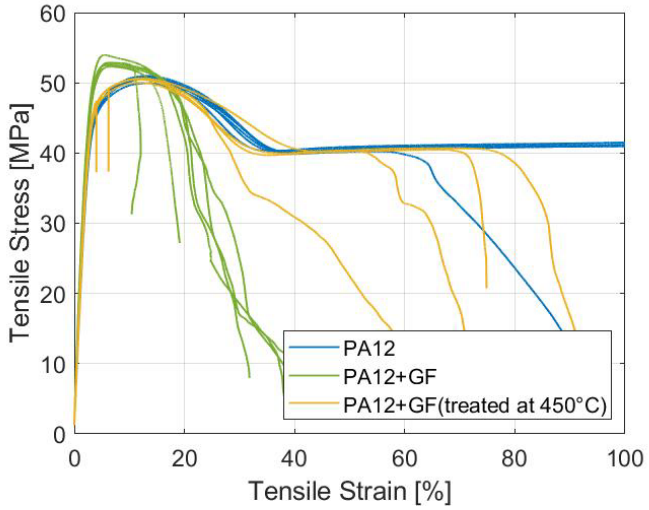

Figure 10 Tensile curves of the tensile tests performed on samples produced with the plate press process

Table 3 Results tensile tests of samples produced with the plate press process

Material		PA12	PA12+GF	PA12+GF (450°C)
Parameter	Unit			
UTS	[MPa]	51±0,3	53±0,5	50±1,1
E-modulus	[MPa]	1596±11,7	1818±26,1	1634±25,7
ϵ-fracture	[%]	193±58,6	29±12,1	52±34,5

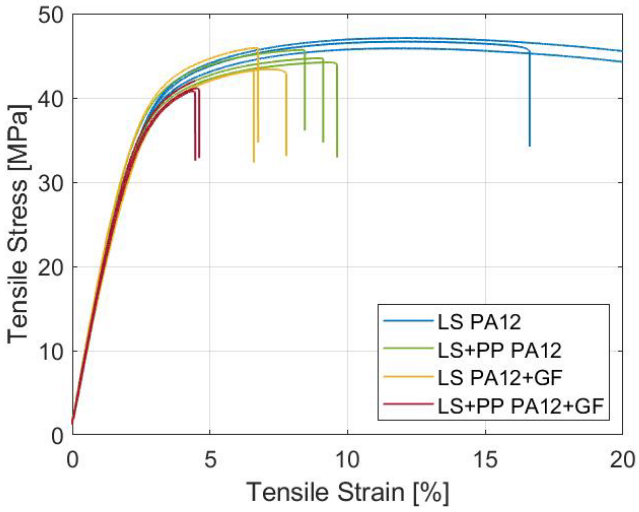

Figure 11 Tensile curves of the tensile tests performed on samples produced with the laser sintering process and post-processing with the plate press process

Laser sintering with post processing

To investigate the influence of post-processing the LS parts with an elevated temperature and pressure on the mechanical properties of parts produced, tensile samples were produced with the LS process, post-processed with the plate press process and tensile tests were performed. The results of these tests are summarized in Table 4 and the tensile curves of these tests are shown in Figure 11.

When the laser sintered samples are post-processed with the plate press process, different results are gathered compared to samples only produced by the plate press process. For both the LS samples and the LS samples post-processed with the plate press, a drop of 6% in UTS can be noted when chopped glass fibres are added to the produced parts. When the samples without post-processing are compared to the samples with post-processing produced from the same material (PA12 and PA12+GF), a drop of 4% in UTS can be noticed thus the plate press post-processing process has a detrimental effect on the mechanical properties of the LS produced parts.

As the previous results from the plate press samples produced from the same PA12 powder and chopped glass fibres showed more promising results, the assumption can be made that the LS process has a detrimental effect on the production of these PA12 parts with fibres. A possible explanation could be that the adhesion between the fibres and the polymer matrix is not fully realized and thus the fibres cannot significantly improve the mechanical properties of the part. This missing adhesion between polymer matrix and the fibres could be caused by the glass fibre sizing that is degrading during the LS process either by the heat of the laser or the preheating temperature in the build chamber to which the fibres are exposed. Another explanation could be that the sizing is still present on the surface of the fibre but due to the absence of pressure or shear stresses during the LS process, this fibre sizing is not activated and no bond is formed between the sizing and the polymer matrix (which does happen when the plate press process is applied to produce samples). Further research will be needed to fully understand the effect of the LS process on the applied glass fibres.

Table 4 Results tensile tests of samples produced with the laser sintering process and post-processed with the plate press process

Process		LS		LS+PP	
Material		PA12	PA12+GF	PA12	PA12+GF
Parameter	Unit				
UTS	[MPa]	47±0,5	44±1,2	45±0,6	42±0,9
E-modulus	[MPa]	1477±11,4	1498±103,1	1549±37,4	1517±31,5
ϵ-fracture	[%]	21±3,3	7±0,5	9±0,5	5±0,5

Conclusion

In this work, the combination of PA12 powder and combined with chopped glass fibre was explored for implementation of potential reinforcements during the laser sintering process. By designing and implementing an in-house developed fibre deposition system in a conventional LS machine, PA12 samples could be produced with chopped glass fibres. In addition to the in-house developed fibre deposition system, an innovative fibre chopping technology and careful selection of the used continuous glass fibre strands, contributes to the successful integration of chopped glass fibres during the LS process. The fibres are randomly oriented in all directions and a high fibre volume fraction (1,86vol%) is reached. As a result, significant increases in the UTS and E-modulus of the produced LS parts can be expected. The preliminary tests with the fibre deposition system resulted in promising but limited results regarding strength of the produced parts, therefore further research into the combination of chopped glass fibres and PA12 powder was conducted.

To understand and investigate how the polymer powder interacts with the glass fibres and what influence the glass fibre sizing has on the mechanical properties of produced parts, CT scan images, heat treatments, hot stage microscopy observations and another production process, the plate press process, were taken into account and analysed. The most important conclusions of this research are summarised below.

- With the in-house developed fibre deposition system, a fibre volume fraction of 1,86vol% was reached which equals 4,92wt%. Based on the ROM, a theoretical maximum UTS increase of approximately 110% can be expected. For the plate press samples a fibre volume fraction of 3,47vol% was reached which is equal to 8,94wt%. Based on the ROM, a theoretical maximum UTS increase of approximately 160% can be expected. The tensile tests show an increase in UTS of 4% for the plate press samples and a decrease in UTS of 6% for the LS samples when chopped glass fibres are included, leading to the assumption that the LS process has a negative influence on the implemented glass fibres.
- From the results of the heat treatments and the observations with the hot stage microscope, it could be deduced that the influence of heat on the glass fibres and their sizing is significant. A hypothesis is that the glass fibre sizing is burned off by the laser heat source (in combination with the preheating temperature in the build chamber during the LS process which means that there is no adhesion between fibre and polymer, resulting in limited to no increase in strength of the produced parts.
- Another possibility is that the sizing is still present on the fibre surface (not burned off by the laser heat source in combination with the preheating temperature). A post-processing technique could be investigated to increase the adhesion between the fibre and the polymer matrix. During the plate press process heat and pressure is applied on the polymer powder with glass fibres resulting in an increase in UTS of 4%. During the LS process, only heat is applied to consolidate to polymer powder and glass fibres. It can therefore be reasonably assumed that pressure is needed to activate the fibre sizing and as a result to reach sufficient adhesion between the fibre and polymer matrix for successful stress transfer from fibre to matrix. The plate press was used as a post-processing method to apply pressure on LS samples. However, the tensile test results of LS samples that were post processed with the plate press also show a decrease of 6% in UTS. These results seem to confirm the previous hypothesis that the sizing on the fibres is actually burned off by the heat of the LS process. Nevertheless, other post-processing techniques such as WIP (Warm Isostatic Pressing) can be explored to increase the adhesion between the polymer matrix and the fibres as the plate press is suboptimal.

Future work is needed to successfully integrate glass fibres into the laser sintering process to optimise the mechanical properties, such as strength and stiffness, of produced PA12 parts. As most issues are linked to the sizing on the glass fibres, the addition of carbon fibres can also be explored as the sizing is less important and good adhesion between the carbon fibre and polymer matrix can happen without. Changes to the in-house developed fibre deposition system are required to successfully work with carbon fibres as the density of carbon fibres is different compared to glass fibres (1,9g/cm³ and 2,54g/cm³ respectively).

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