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Compounding Composites from Raw Materials with Extrusion Directly on 3D Printer

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Abstract

The materials most commonly used in 3D-printers are in a filament form. This is a barrier for users who want to have new types of filaments with different material compositions. A 3D-printer which can extrude and print directly from the raw material was assembled. Compounding with the common additive types; fibres, and metal powders was performed. The size and volumetric output of an extruder was scaling down. Verification was done by mechanical testing, and electron microscopy. The positive result is opening the path to a more accessible composites for both researchers and home producers.

Keywords: extrusion, compounding, 3D printing, additive manufacturing, product design

1. Introduction

Additive manufacturing (AM) has greatly democratised the making and creating world, allowing people who do not have access to machining facilities or a workshop, to build and specialise products for their everyday life (Peng, 2020). For 3D-printing to be optimally used by the public, knowledge about AM has to be more widespread within its user base and by combining the knowledge of industrial AM (Diegel, 2019). The shared knowledge of creating and printing can be greatly increased with much faster pace than traditional production methods which are not as readily available to the public market. On one hand, filaments cost between €15 and €30 per kg and it can be a limitation when printing larger objects (https://www.azurefilm.com/en/3d-filaments). Plastic pellets or recycled plastic on the other hand are significantly mora affordable. One step towards spreading the use of AM and encouraged design creativity is to construct machines that can facilitate the creation of materials such as composites, which can be used in research, testing, and small batch production of new product ideas. To be able to create well homogenised composites in small batches, scaled-down extruders must be created that could be integrated into 3D printing machine. This raises the question; how well can composites be homogenised through extrusion in a scaled-down extruder?

2. State of the art: additive manufacturing and extrusion screw design

Additive Manufacturing, or 3D printing as it is more commonly called, is a relatively new production method which is based on the principle of creating a product by adding thin layers on top of each other (Diegel, 2019). The sophisticated methods can allow for moving parts to be printed whole, instead of separately manufacturing and assembling parts. There can also be an advantage in creating parts which could not be made traditionally, such as high-performance car parts or heat exchangers with very complicated internal structures (Diegel, 2019), (ISO 17296–2, 2015). AM is not a fix-all for every problem in production. It shifts the problems to new constraints and restrictions that must be

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considered, such as manufacturing times and the costs (Tavčar, Nordin, 2021), (Baumers, 2017), (Franchetti, Kress, 2017). Design for additive manufacturing must be applied already in the conceptual phase to consider advantages and limitation of AM (Diegel, 2019).

There is a multitude of materials available to those who want to 3D print, everything from pure polymer filament to composites and wooden filaments. The most common filaments are based on a pure thermoplastic, such as Acrylonitrile Butadiene Styrene (ABS) or Polylactide (PLA), where an additive can be used to change the colour of the filament (Patil, 2017). An additive can also be used to modify the mechanical properties or make the filament magnetic, fluorescent, or conductive (Wiese, 2020), (Bakir, 2021). Torrado et al. demonstrated that mechanical property anisotropy associated with build direction can be mitigated by various additives to ABS (Torrado, 2015). Technical facility for blending composites is a must for such research. Brenken et al. review of the extrusion process and its physical phenomena such as the flow and resulting fiber orientation, the bond formation between adjacent beads and the thermomechanical solidification behavior of the deposited material (Brenken, 2018).There is a large number of bio-degradable filaments that have a better effect on the environment (Niaki, 2019). Several of the polymers used theoretically allow for infinite reusability.

Extrusion is a fast-paced production method for manufacturing products of constant cross-section and infinite length, such as pipes, rods and films. This is done by using a screw, combining rotating and linear push, to force a heated polymer mixture through a die with an opening, shaping the extrudate. The polymer is fed into the extruder through a hopper and is transported through a heated barrel, gradually melting, and compressing it before being extruded (Bacalhau, 2017), (Turner, 2014). Serdeczny at al. designed an experimental test to investigate the influence of the filament feeding rate, the nozzle diameter, the liquefier length, and the liquefier temperature on the filament feeding force and extrudate swell (Serdeczny, 2020).

The screw design has a great impact on the dispersion of the additive throughout the matrix. Altering the screw from a standard conveying screw to a screw which allows for material to be mixed rather than only moved through the barrel can be done to increase the mixing of the extrudate. Extruder screw mixing variations include mixing pins, Dulmage section, Dray Mixer, and Maddock Mixer (Kimura, 2013). These can be combined in many ways to achieve desired mixing outcomes. The Dulmage section is commonly used and gives a great improvement in dispersion in single-screw extrusion, which is explored in The Evaluation of Mixing Characteristics of Dulmage Screw (Kimura, 2013). A comparison between a standard conveying screw and a Dulmage section shows that dispersion of a red coloring agent can be greatly improved in plastics when using a mixing section such as a Dulmage section (Kimura, 2013). Standard Length/Diameter ratio (L/D) of an extrusion screw is 24:1 to allow for the extrudate to properly melt and homogenise before being extruded but can vary from 18:1 – 40:1 depending on the specific extruder (Wagner, 2014).

Apart from filament, there are 3D printers that can print directly from the raw material, such as the BLB 3D printer, which uses a scaled-down extruder. This printer extrudes up to 35 kg/h from a pellet material which can be made from different polymers or prefabricated composites (Blb, 2021). Shibo at al. focused to the multi-color mixed color printing process that can use granule and waste materials (Shibo, 2019). At the moment of writing, there are no available solutions which can create a polymer composite in the extrusion process itself. The identified needs and the lack of available solutions motivate as to conduct the presented research.

2.1. Research hypothesis

The research aim is to construct a scaled-down extruder which can combine and extrude composites in the printing process, the following requirements need to be fulfilled.

- The temperature in the extruder must be high enough to properly melt the polymer extrudate. For most polymers used in AM, this process happens at temperatures around 170 - 260 °C.
- The quality of mixing and mechanical properties of extruded composite from pellets must be comparable to extruded filaments.
- Volumetric flow. The construction should match the current volumetric output found in standard 3D-printers, which is about 15 mm^3/s (George, 2020).

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- Weight < 1500 g. As the construction must be suspended in air and moved around during the extrusion process, the total weight should be low enough to make these movements possible.
- Durability. The chemical and mechanical wear on a polymer extruder is significantly higher than in a filament 3D-printer. This increase in wear is due to the forces that occur during the compression and compounding of the polymer and additive.

3. Methodology

The research goal is to demonstrate that extrusion of composites from raw materials such as pellets and additives for reinforcement can be integrated in the printing process. A known working principle was applied, and an existing product was upgraded. The DMAIC method from six sigma methodology was used as a frame. The steps or techniques are defined in Six Sigma Breakthrough and Beyond (Feo 2005) and are as follows: (i) Define; (ii) Measure and Analyse; (iii) Improve; (iv) Control (Figure 1). The presented procedure was repeated in several iterations. In the first step, focus was on design specification and selection of composite material. The goal was confirmation of research hypothesis with a practical experiment therefore several versions of extruder were designed and tested. Heat flow numerical simulation was used for better understanding of extrusion process.

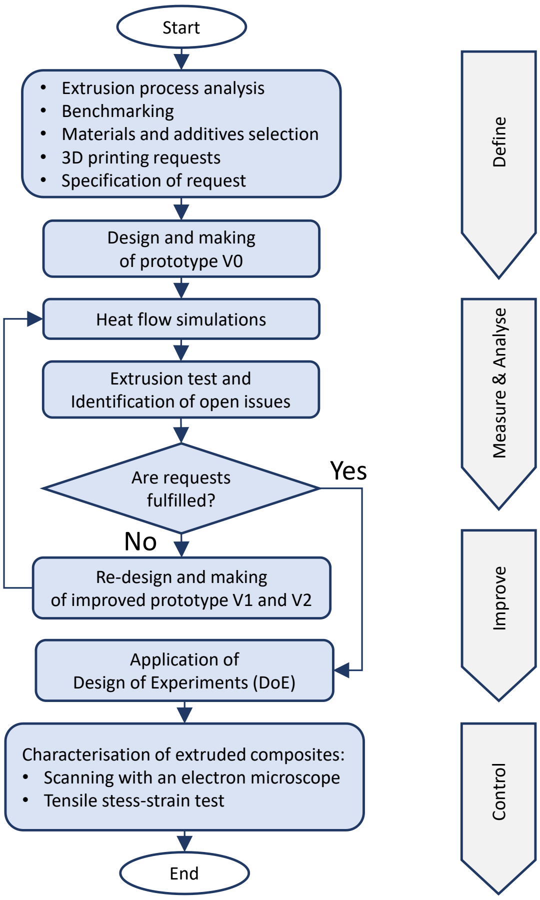

Figure 1. Flow chart of the conducted research

3.1. Material selection

The material chosen for the matrix is 4043D grade PLA plastic, which has a working temperature of 180 – 230°C (LLC, 2020) and is well suited for AM along with being biodegradable. Two different materials will be used as additives to give a broad reference view of the results. The materials used are a fibre, and a small particle metal (Table 1):

a) $CaSiO3$ Wollastonite, a calcium inosilicate mineral which may contain small amounts of iron, magnesium and manganese. It has great potential in replacing more expensive materials such

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as glass fibre due to low costs as well as its small, needle-like structure which aligns in a similar way to fibres and increases tensile strength by up to 30 %.

b) AlSi10Mg Aluminium alloy powder, produced for additive manufacturing and consists of a 90/10 Aluminium/Silicone mixture with small amounts of magnesium, iron and titanium.

Table 1. Material properties for used additives

Additive	Particle size (μm)	Density (g/mm^3)
Wollastonite	21 ± 19	2.84
AlSi10Mg	63 ± 20	1.54

4. Polymer extruder development

The extruder presented in Figure 2 was developed in several iterations. The initial version V0 was upgraded with V1 and V2. A modular design was chosen to easily accommodate for the creation of new parts as well as assembly with as few tools as possible. Heat resistant materials are also preferable as they have better mechanical properties under stress. The decision was made to keep the single screw extruder design, due to space constraints and a focus on maintaining a relatively simple design. As the original heaters can achieve a temperature 80 °C only, they were replaced with two 40 W elements, which theoretically generate the heat to reach temperatures of more than 400 °C. The casing is also equipped with a heating shield, which will limit the heat radiation and help stabilise the temperature of the module.

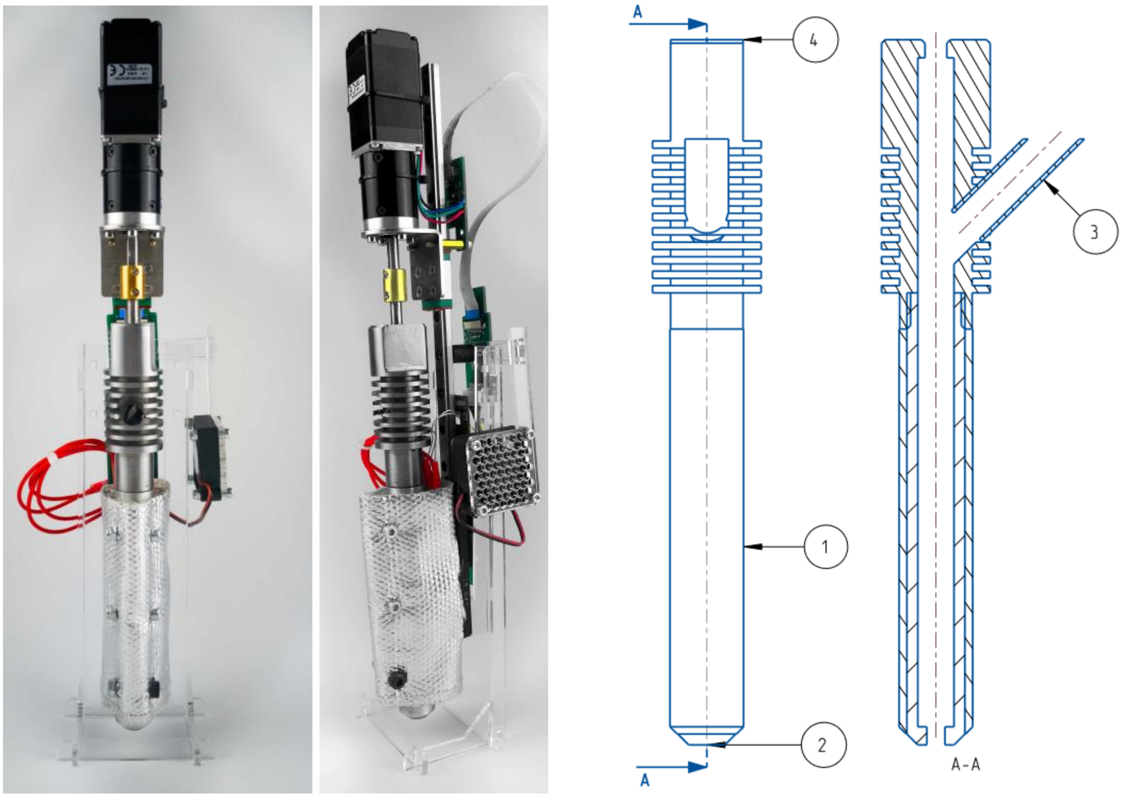

Figure 2. a) Extrusion setup, front and site view of V2. b) Technical details of V2: (1) Barrel - steel (2) Barrel - aluminium (3) Feeder - tube (4) Feeder, heat-sink (Rundbäck M.O., 2021)

The heater has a good basic design, which integrates a heat-sink, but initially contained a complicated electronic setup, which needs several power sources and lacks a common off switch for the entire system. A redesign of the heating element included insulation to minimize heat radiation, as well as integrating the electronics with the stepper motor and fan to keep the controls as simple as possible.

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Material selection for the extruder considers a requirement to make it heat resistant. A heat-sink structure was designed that increases the surface area of the printer head, allowing for greater heat dispersion in parts that do not need to be heated.

The cylindrical part was redesigned - it fits now better to a printer nozzle and enables a suitable mount for the feeder. The feeder is mounted to the cylinder and enables effective input for the extrudate to the screw. The screw is prevented from moving vertically during the printing process to ensure consistent printing.

By adding an internal barrier to the cylinder part, the extrudate movement through the process was randomised. This modification requires very precisely machined and fitted parts for the screw. The feeder part was made in stainless steel, which has a higher hardness and lower heat conductivity. This keeps the heat from dispersing into the surrounding air and helps to maintain heat in the extruder.

The barrel was remodelled to consist of two parts, one continuous stainless steel pipe, threaded on one side to match the feeder, and on the other side to match a standard 3D printer nozzle. This stainless steel part was encapsulated in an aluminium casing, which helps disperse the heat from the heating unit evenly throughout the barrel. This redesign helps increase the durability of the part as well as retain heat inside the barrel.

4.1. Simulation

Prior to construction of a second extruder (V1), finite element method (FEM) simulations were made on the planned parts with the goal to approximate the dispersion of heat through the planned module as well as the casing that will connect it to the printer head (Figure 3). The simulations were made in ANSYS on simplified versions of the aluminium casing and delivery tube. In these tests, two heat flow effects are tested, 30 W and 40 W, which are industry standard for the heating elements.

The material selected for the simulation was a standard grade aluminium for the casing as well as the module. When testing for effect was completed, a material comparison was made for the feeder part to find the optimal material. A standard steel was compared with aluminium, to compare heat diffusion throughout the complete module assembly. For both simulations, thermal isolation was assumed to be ideal around the casing. After simulations were made, the feeder was modified to implement a heat-sink structure which allows it to expel heat more effectively, protecting the stepper motor and parts close to the printer module.

4.2. Screw design

The screw design of the extruder is of large importance, as it determines how the material is compounded, and under what pressure it is processed. In this project, a standard concrete drill with a L/D of 20:1 is used in place of an optimised extrusion screw. This decision was made due to budget and time constraints. To approximate the design of an optimal extruding screw, the screw chosen has a shallow thread with a low rise, to allow maximal compression. Modifications were made to the purchased drill-bit, to optimise the compounding and throughput. This was done by grinding down the screw to get a thread depth which would decrease as the material moved through the extruder, increasing pressure and friction along the screw. The parameters of the final screw are specified in Table 3.

5. Results

5.1. Optimization of extruding parameters

Tests on pure PLA pellets were performed with two different parameters, screw rotational speed and printer temperature to optimize the extruding parameters. The screw rotational speed was varied between 9 - 12 rpm, and the temperature was varied between 180 - 205 °C in conformity with a 2 factor design of experiments (DoE), see Table 2. The results from the optimization according to Table 2 can be seen in Figure 4. They show the relations between temperature, screw rotational speed, and yield strength.

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Table 2. Parameters and levels for DoE testing of the extruder

Test	Temperature	Screw speed
1	200 °C	9 rpm
2	200 °C	12 rpm
3	180 °C	9 rpm
4	180 °C	12 rpm

Table 3. Final parameters of the screw

Parameter	Value
Screw Diameter (D)	10 mm
Metering depth (h)	1 mm
Screw length (L)	185 mm
Screw speed (N)	12 rpm

There shall be an interaction between the parameters for the measured results as the lines are not parallel. From observations made during preliminary tests, a rotational speed of 9 rpm is required to overcome the friction of the internal walls and convey the extrudate, and a temperature above 180 °C is required to achieve melting and extrusion. If the temperature exceeds 210 °C, the extrudate will seep out through the extruder nozzle and leak.
The highest recorded yield strength in the extrudate is observed in sample 3, with a yield strength of 55.31 MPa, and p-values of 0.1939 and 0.218 for temperature and speed respectively for the DoE. A large difference in volumetric output between the four samples produced in the DoE was noted, depending on the parameters. The highest volumetric output was observed in sample 2 with an estimated difference of 400 %, to the lowest output of sample 3. This difference, combined with the high p-values suggests that the correlation between temperature, rotational speed and yield strength, which have to be further evaluated to solidify the results. This motivates that the settings used for sample 2 should be preferred in the project, as real volumetric output is considered more important in this project than the possibility of a higher yield strength.

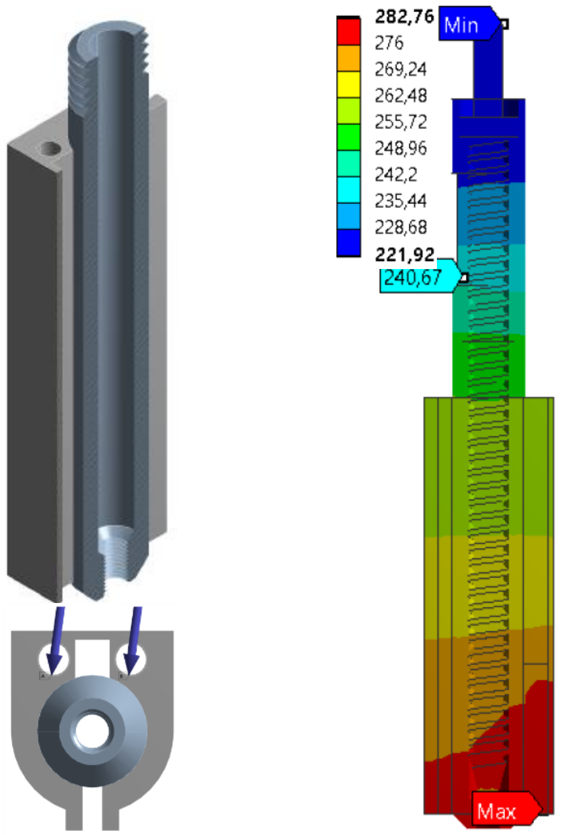

Figure 3. Heat flow setting and temperature distribution for V2

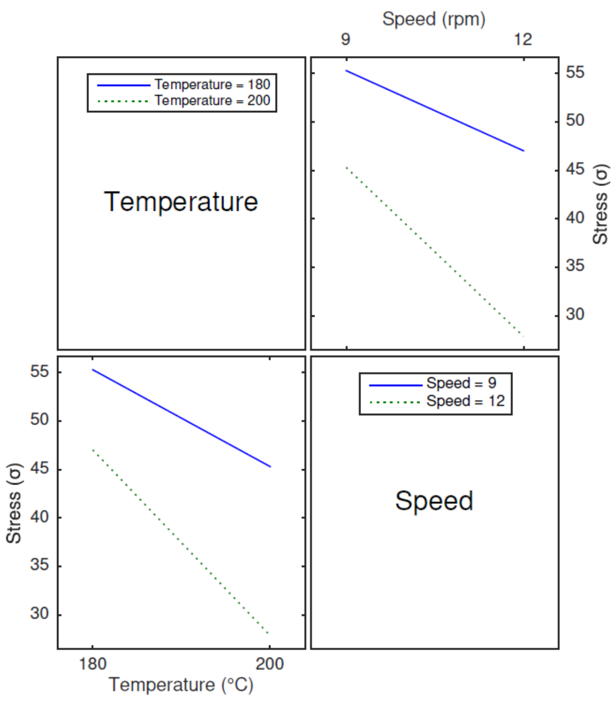

Figure 4. DoE plot comparing sample yield strength (stress) in relation to temperature and speed

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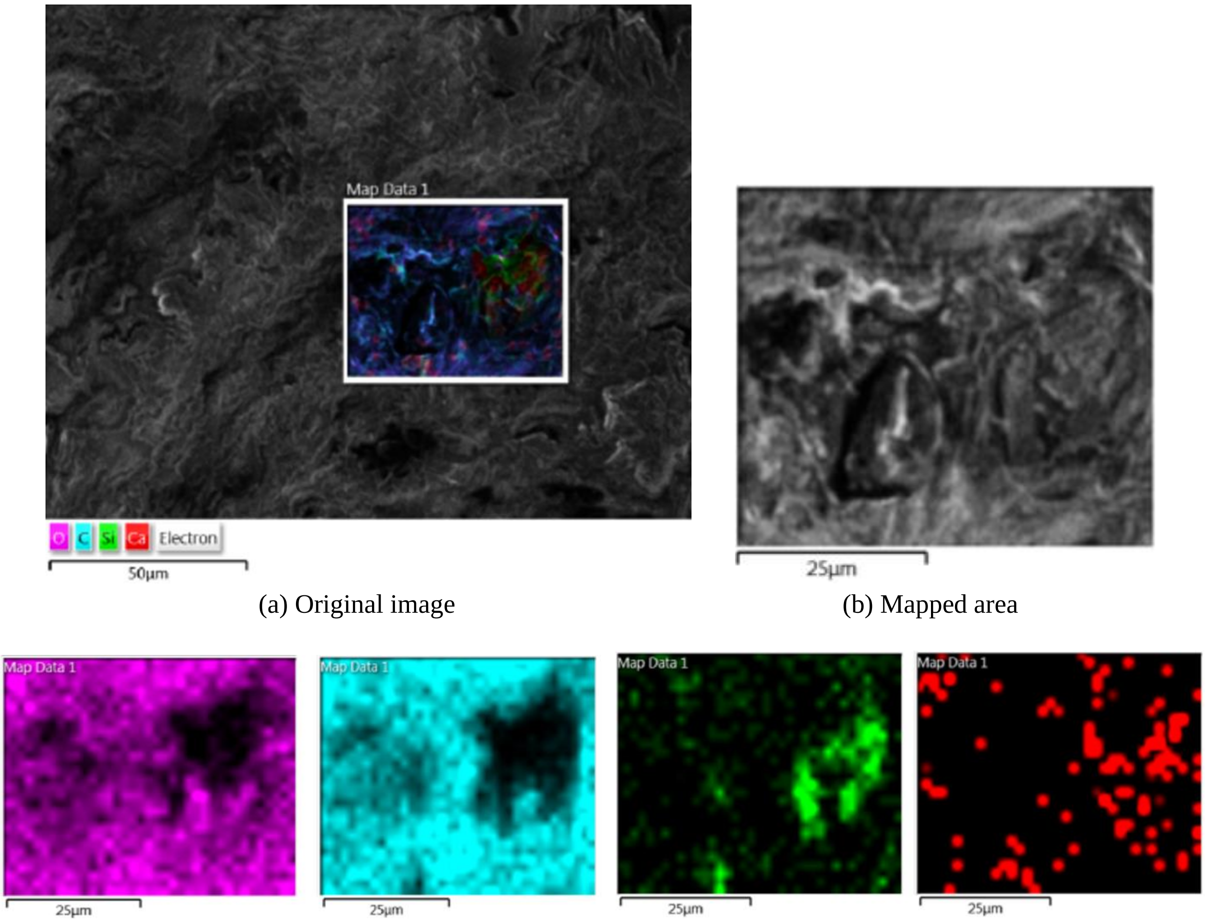
5.2. Quantification of samples with electron microscopy and tensile testing

The Scanning Electrode Microscope (SEM) results of the extruded samples are shown in Figure 5. The figures display an original image that uses elemental mapping to display the presence of elements. In Figure 5, an enhanced section is displayed in Figure 5b along with the mapping for compositional elements in the following figures. When comparing mappings, calcium, silicon, and oxygen can be seen inhabiting the same areas where there are black spots of carbon and oxygen.



(a) Original image (b) Mapped area

(c) Ca-map (d) Si-map (e) O-map (f) C-map

Figure 5. Elemental mapping of Sample 3 with 40 % Wollastonite. Mapping was done for calcium (Ca), silicium (Si), oxygen (O), and carbon (C)

In Table 4, the results from the mechanical yield strength tests can be seen. Wollastonite improved yield strength for 22 %, Aluminium has minor impact only.

Table 4. Tensile test results for the different additives

Basic material	Additive (weight in %)	Yield strength (MPa)	Relative change of yield strength (%)
PLA (4043D)	Wollastonite (40 %)	61.32	122
PLA (4043D)	Aluminium (40 %)	52.36	104
PLA (4043D)	No additive (0 %)	50.30	100

In Figure 6, a stress-strain plot can be observed. Each curve has been normalised with regard for the initial length and diameter of each sample.

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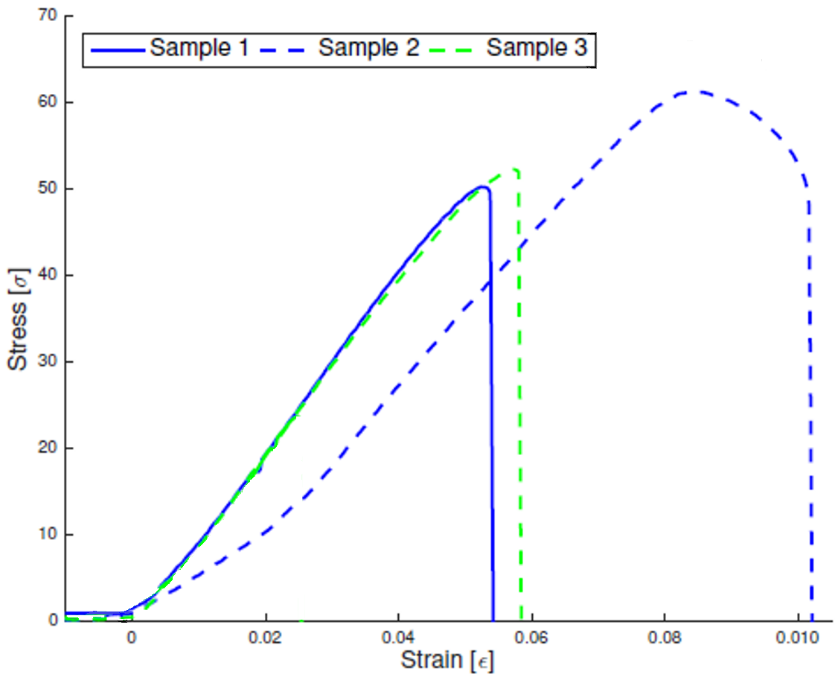

Figure 6. Stress - train plot for the basic and reinforced samples. Sample 1 - pure PLA, Sample 2 - PLA + 40 % of Aluminium, Sample 3 - PLA + 40 % of Wollastonite.

6. Discussion

The insulation built onto the printer head was necessary for the ability to achieve high enough temperature for extrusion. This insulation can be improved by building a better heatshield or decreasing the volume of the casing. The cooling-ribs helped the heat dissipate into the surrounding air, helping to protect the stepper motor from higher temperatures, they also help to increase cooling when the extrusion process is finished.

During the printing of wollastonite additive, the extrusion process went smoothly and resulted in a well compounded material. The printing process with aluminium additive went without any complications and extruded with ease. A consistently coarse surface can be observed on some of the extruded samples with aluminium, which are not observed on samples with wollastonite. A longer cooldown time was also noted compared to pure PLA. These additives behaved better than expected, considering the small size and rotational speed of the V2 module compared to industrial extruders.

As all the samples showed a thin outer layer of pure PLA, there is a possibility that this is a commonality between all extrusions in this module. This might be due to that the molten PLA expands out after exiting the extruder nozzle, encapsulating the other material. This can be both a positive, seeing it as a layer which protects the additive from corrosion, or negative where the material might lose conductivity.

The module designed and constructed in this research was made to be adaptable, it can easily be reconstructed into a fairly high-volume extruder by mounting it in a horizontal heater and fitting it with a high-capacity hopper, as well as exchanging the motor to a high speed and torque variant. This can then be used to create a filament which can be used in a separate filament-based 3D printer. A good future project could be to test a longer fibre, which can greatly increase the toughness of a matrix.

The tensile stress test displayed large differences from sample 1 which had an even elongation with a quick break. A large change in ductility can be seen in sample 2, containing wollastonite. This is consistent with the description of the additive, giving a smoother displacement curve and elongates the breaking process of the part. It also increased yield strength by 22 %, compared to pure PLA (Figure 6).

The results from the extrusion process could have been improved by increasing the amount of pure pellets that are put through the extruder to clean it between the different additives, to absolutely make

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sure that no remnants of previous additives can alter the tensile strength of the finished material. This is however seen as a small difference in the end product, as no trace elements of additives have been found during the SEM testing.

6.1. Limitations

The measuring using tensile testing is impacted by the shape of the parts tested, which are slightly differently shaped with small inconsistencies in thickness. Although the results from the tensile testing have been standardised to account for the different thickness in the samples, there is still a certain difference between the samples, which has to be considered. This project has been limited to not include the ability to 3D print a complete structure, as this is seen as trivial when the ability to extrude material has been benchmarked and fulfilled. The consistency of the parts used for tensile testing could conceivably be improved by using an injection mould to create identically shaped parts to test. However, this would probably require much improved throughput capacity of the extrudate to inject the required volume before the material cools below the melting point. More tests could have been performed on more samples and with new combinations of materials to verify the results and increase reliability. This is, however, recommended for further projects to give a broader understanding of the compounding of different materials in this extruder.

7. Conclusion

This research aimed to benchmark the composite compounding capabilities of a scaled-down extruder, to help lay the ground for further research into this area. The results are predominantly positive towards this goal. A relatively cheap and manageable single screw extruder can produce a usable extrudate quickly, and there are no real limitations to the public constructing these themselves to help increase the development of knowledge surrounding AM and material sciences in these areas. The quality of this extrudate is high enough to be used to effectively benchmark new material ideas. The raw materials used to produce filaments are cheap and commercially available materials, this could be an effective way of minimising costs for a small-scale manufacturer or large-scale hobbyist. It can also be used to effectively recycle plastics such as PET-bottles, which is a positive environmental achievement. Not all materials extrude easily, and this set-up is not suitable for every additive or composite. It is, however, very well suited for many popular additives such as metals and different colours, which improve or change material properties greatly. As these materials now theoretically could be made at home, the possibilities to create and invent new areas of application are multiplied as a small-scale producer now can test their own material combinations and compounds, without having to order large quantities from a large-scale producer. The research fulfilled initial requirements and it represents a contribution toward affordable and sustainable additive manufacturing.

Plans for future research include additional optimisation of extrusion parameters. Construction of a horizontal casing for the extrusion module, with higher torque and better heat control, will enable the creation of filament as well as faster 3D printing. There is a plan to construct a modular screw, based around a threaded (or hexagonal) rod, where the different parts can be replaced. New design freedom will be achieved by applying 3D metal printing for making modular screw parts. This mimics an industrial extrusion screw design, and we expect even better mixing of melted compounds.

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