IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: J Y Tey *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **268** 012019

Development of 3D printer for functionally graded material using fused deposition modelling method

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Abstract. 3D printing employed in additive manufacturing, converts digital data based on a computer-aided design (CAD) model into an object by adding material layer by layer. Unlike subtractive manufacturing, complex geometries can be printed with minimal wastage. The additive manufacturing process for 3D printers features several types of technology ranging from fused deposition modelling (FDM), laser sintering, stereolithography and laser melting to binder jetting and others. However, these technologies are limited to process one material at a time, which poses a challenge to print functionally graded material (FGM). This difficulty can be overcome by offering a unique solution which is proposed in this paper - by applying FDM customized with an extrusion screw to incorporate mixing and blending of the polymer matrix and filler as a continuous process during printing. The intent of this technique is to ease the production of FGMs (which vary in mechanical, electrical and texture gradually over volume) by incorporating additional filler into the polymer matrix during printing. Therefore, it could enable users to design and produce FGMs in a single printing process. A unique controllable mixer design is embedded in the printer to allow users to process and mix up bi-materials by varying the mixing ratio of two materials as required during the printing process. Through programmable logic controller (PLC), the printer is able to map the variation in material properties and control the mixing ratio required to achieve functionally graded 3D material.

1. Introduction

The Fourth Industrial Revolution (IR 4.0) is transforming the production and manufacturing industry. Among many emerging technologies behind IR 4.0, 3D printing or additive manufacturing (AM) is one of its major drivers [1]. 3D printing has found an important role, especially in the field of automotive engineering, medicine, product design and aerospace engineering. The technology was first introduced by Chuck Hull in 1983 as a solid imaging process known as stereolithography, which has served as a fundamental basis technology for AM [2]. Thereafter, various technologies have been developed such as vat photopolymerization, material extrusion via FDM, powder bed fusion, sheet lamination, direct laser metal sintering, stereolithography directed energy deposition, binder jetting and others [3-6]. Today, FDM is one of the most commonly employed 3D printing method used even as a household item [7]. FDM utilizes the material extrusion process to fabricate plastic parts of customized geometries. Objects can be printed layer by layer via the additive process even when dealing with complex geometries, whilst the process minimizes wastage in comparison to the conventional subtractive method

(CNC machining). However, there are limited choices of material which are applicable for FDM. To date, only some thermoplastics have been extensively used for this printing method. Recently, multi-material printing technology is sought-after for its ability to print multiple types of materials [8]. However, these 3D printing technologies are only able to process one material at a time [6]. Therefore, a new mechanism for 3D printing is developed to enable the possibility of printing composite materials using FDM by blending two or more materials through mixer and extruded in situ to widen the material selection for 3D printing and create unique material properties on the fly.

2. Review of Material Development for AM and Challenges

According to Stratasys Inc., there are only 11 types of commercial ready filament which are available in the market used in FDM [9]. These limited choices of thermo plastic material are not sufficient to fulfil prototyping wide variety of industry goods application. This challenge fuses researcher to further develop new material which possess properties such as high tensile strength, thermal resistance, chemical resistance, transparency, biocompatibility, etc. Development of new FDM material is now focused on metal/polymer composites. Metal/polymer-based filters such as aluminium oxide, iron, copper, ceramics, silicon carbide or fibres are promising composites used to enhance and widen the current choice of FDM materials [10, 11]. Dickson et al. demonstrated mechanical properties of 3D printed plastics can be improves with the use of reinforced with Kevlar, glass fibre and continuous carbon fibre [12]. The research has shown that the tensile strength of the 3D printed object can increase by 6.3 times when the volume fraction of carbon or glass fibre is increased [12]. Similarly, tensile strength and modulus of ABS can be reinforced with carbon fibre which yielded the increase of 115% and 700% respectively [13]. Conductive material can be form with polypropylene (PP)-based thermoplastic composites. This material can be formed by heating and blending homopolypropylene (SCG) with carbon black using a single-screw extruder. As a result, Figure 1 shows that an increase in weight percentage of carbon black in the composite material can decrease the resistivity of the composite and hence, allows electrical conductivity. With this behaviour, a modular 3D circuit can be printed by using this method to light up a LED with a 9V battery [14].

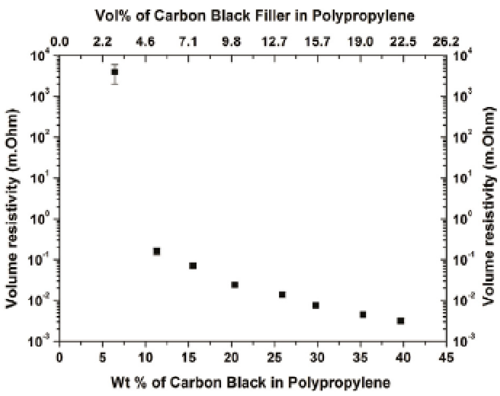


Figure 1. Electrical characteristics of PP-based composite filaments vs weight percentage of carbon black [14].

Furthermore, the research has also shown that the 3D printed wire can be used as a PTC temperature sensor. The 3D printed plastic wire acts as a PTC thermistor which increases in resistance as temperature increases [14]. Similarly, graphene-based polybutylene terephthalate (PBT), a polymer nanocomposite which was fabricated using a 3D printer, exhibited similar behaviour in terms of electrical conductivity and mechanical stability [15]. Besides, by combining the sintering process with FDM 3D printing, $CuFeO_2$ can be printed by using suitable amount of metal powder (Cu & Fe) which is blended with the polymer. Throughout the research, it is apparent that material properties can be varied by blending two or multiple types of materials or by changing the composition of the filler in the composite material.

This idea can be further expanded to form a functionally graded material (FGM). The composition in a FGM can change gradually over volume and hence, the properties of the material can change in a controllable direction. The most basic FGM is comprised of two different types of materials which change gradually i.e. continuous form and stepwise graded structure as shown in Figure 2. One of the famous FGM example was compositionally graded from metal to ceramic. Some of the useful properties of ceramics and metals can be incorporated into the FGM to achieve good wear resistance, oxidation and heat resistance, toughness, machinability and able to reduce the internal thermal stress [16].

Figure 2. (a) Continuous structure (b) stepwise graded structure.

These advantages of FGM are being employed in the development of a reusable rocket engine to reduce the thermal stress incur at ceramic coatings and joints [17]. It can be applied in many fields such as biomaterials, optics, nuclear energy, engineering, aerospace, chemical plant, electronics, energy conversion and commodities. The FGM concept can also be applied to many useful applications such as provide good thermal and sound insulation on structural walls. This could be achieved via gradation of both porosity and composition. Concept of FGM could be realizable with the used of polymer composite where changes of filler weight composition can produce gradient properties in strength, thermal insulation or electrical conductivity of the material as shown in previous discussion.

It is a difficult task to produce FGM using the conventional way. 3D printer using FDM offers a unique solution to resolve this difficulty since the object can be printed in layers. Therefore, by varying the material composition (material properties as well) during printing, an FGM can be easily achieved. However, the conventional FDM technology lacks the flexibility, this is mainly due to the use of feedstock filament to drive the extrusion process in FDM. This limits the printer's ability to work with different materials at different volume. The conventional FDM method requires each material to be customized into a single feedstock filament before it can be used with the printer. In this study, an FDM method 3D printer was created with the flexibility to customize mixing using an embedded screw extruder. This enables the printer to process two or more materials i.e. base polymer matrix with filler/metal particle simultaneously during printing. The printer can be controlled via a programmable logic computer (PLC) to automate the mapping and mixing process during printing. Users do not need to change filaments during the printing process.

3. Hardware setup of 3D printer with FGM using FDM

A customized single-screw extruder was integrated into the 3D printer to enable the blending of materials during the printing process. Single screw extruder is commonly employed to carry out blown film extrusion, film extrusion or mold injection on an industrial scale. The usage of screw extrusion can be applied to materials such as ceramics, concrete, or metal [18]. Conventionally, design of screw is based on volume flow rate of the extrusion process. This led to large diameter and lengthy screw dimension in order to handle large extrusion rate in mass production environment. It is impractical to just directly incorporate any single-screw extruder in the industry market to the 3D printer design as the size of the printer would become significantly large in size. Therefore, the extruder was redesigned to suit the 3D printing process, as the volume flow rate for printing process is significantly smaller than the volume needed on an industrial scale. The screw was downsized to be used with the printer. The screw is driven by a high torque stepper motor. The screw was fitted into a barrel which have heating elements and temperature sensor attached on it at different zones. A gravity-fed hopper and mixer were mounted on top to ensure that the mixed materials can be fed continuously into the feed zone of the screw. There are three zones in a single-screw extruder i.e. metering zone, transition zone and feed zone (Figure 3). Ratio between feed depth and metering depth will create a final compression ratio of 3:1. Additionally, these zones were heated with a custom temperature profile to ensure that the polymers will melt and mixed evenly along the extruder.

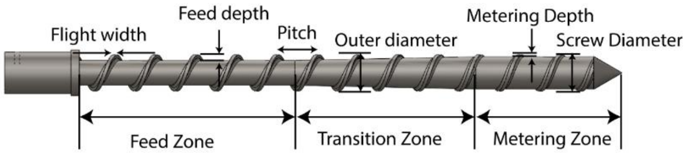
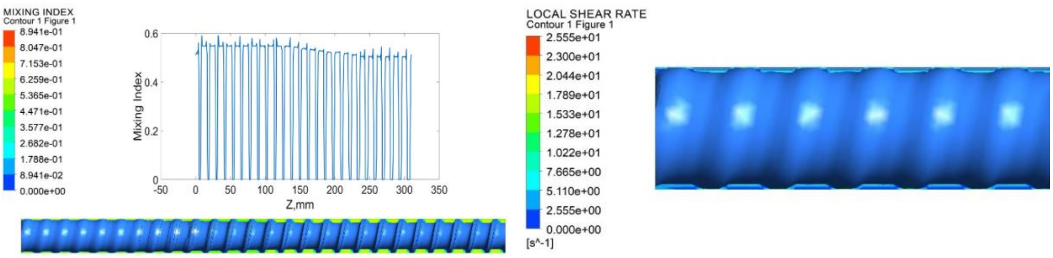


Figure 3. Dimensions of the extruder screw.

The dimensions of the screw were optimized using a flow simulation software. Table 1 summarizes the optimized dimension of the extruder screw as well as the properties of a semi-crystalline polyamide (PA66) used in this study. The extrusion process for PA66 as the base study material was simulated using the Cross-WLF viscosity model at different temperatures recommended for respective zone as shown in Table 1. The screw was modelled to operate at 2 rpm to obtain a printing speed of 30mm/s with a die opening of 1 mm. The interaction between a single screw and PA66 was examined to ensure that it complies with the extrusion process shown in the polymer extrusion handbook [19].

Table 1. Optimized screw design and material properties of PA66 [20].

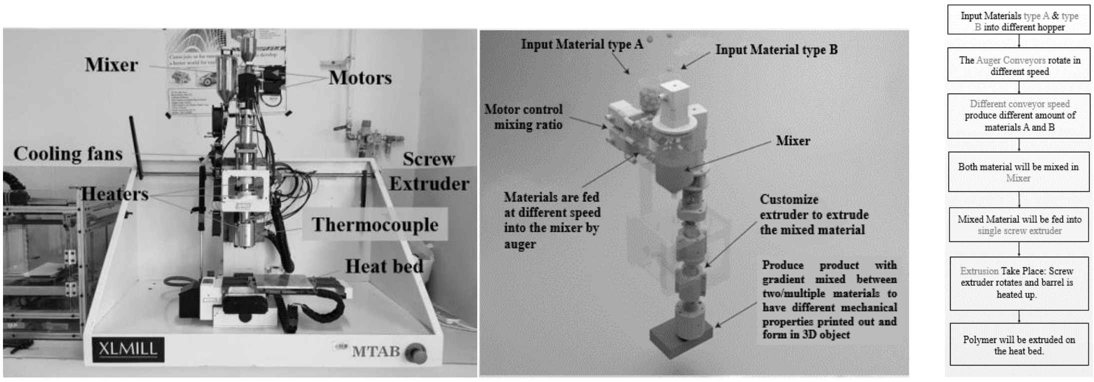
Screw Design	**Value**	**Units**	**Materials**	**PA 66**
Screw length	310	mm	**Melting point, T_m (°C)**	265
Clearance	0.1	mm	**Glass transition temperature, T_g**	50
Screw diameter	21.8	mm	**Density (g/cm^3)**	1.1339
Feed depth	3.45	mm	**Max shear stress (MPa)**	0.31
Metering depth	1.15	mm	**Max shear rate (10^3 s^{-1})**	100
Feed length	130	mm	**Feed zone (°C)**	277
Metering length	71	mm	**Transition zone (°C)**	280
Pitch	10	mm	**Metering zone (°C)**	285
Flight width	2.2	mm	**Die zone (°C)**	282



(a) (b)

Figure 4. Design simulation of the (a) mixing index and (b) local shear rate at the metering zone for polymer flow within a single screw extrusion

The simulated result in Figure 4(a) showed that the optimized screw was able to achieve the average mixing index of 0.5 (values closer to 1 refers to good mixing) from the feeding zone (Z = 0mm) to the metering zone (Z = 300mm). Additionally, Figure 4(b) showed that the material experienced a maximum local shear rate of 25.55 s^{-1} at the metering zone, which is significantly smaller than the maximum shear rate of 100×10^3 s^{-1}. The single screw design is known to show poor performance in mixing as it is only designed to function as an extruder.



(a) (b)

Figure 5. The (a) 3D printer setup and (b) mixer control flow chart

Therefore, a mixer system was installed before the extrusion screw assembly. It has a rotating blade built into the system to continuously mix the mixture within its chamber (Figure 5). This will help to premix the material before it enters the single screw extruder to achieve a better mixing output. The mixer consists of two different conveying channel which was controlled independently by a PLC using respective stepper motors. By varying the auger conveying speed, the extruder produces different volumetric ratio of the two materials. Realization of this mechanism will enable users to vary the composition of their material during printing, and thus 3D printing of a FGM can be achieved. The mixing is controlled using a PLC as shown in Figure 5(b). The overall physical construction of the 3D printer is shown in **Error! Reference source not found.**.

4. Conclusion

By using a PLC to control the printing process, an accurate mixing ratio can be achieved through varying the speed of the conveyors. Thus, a FGM can be created in a single printing process. This can reduce the time needed to fabricate a prototype whilst improving the efficiency and reliability of a manufacturing process. As a result, the types of material available to FDM can be extended to an infinite number of composite materials. In the near future, all newly developed materials can be directly used in the printing process without any issues associated to the availability of such feedstock's filament. These changes will enable designer to perform complicated design without constraint by the manufacturing process. Biomimicry design could soon be realized with this new printing method as most of the biomimicry design such as bones, bamboos are similar to FGM. Additionally, this concept is scalable as it is design based on the PLC platform used by the industry, which can be easily scaled to a larger size to accommodate large printing volumes. Overall, development of 3D printer to process FGM will be the turning point to widen the application of AM technology.

Acknowledgement

This project is funded by Universiti Tunku Abdul Rahaman through the grant number PSR/RMC/UTARRF/2018-C2/T02

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