Development of a Direct Feed Fused Deposition Modelling Technology for Multi-Material Manufacturing

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Abstract. Fused Deposition Modelling (FDM) is one of the most widely used Additive Manufacturing (AM) technologies to fabricate a three-dimensional (3D) object via melt processing of a thermoplastic filament. However, it is limited in the variety of materials that can be fed and mixed during the process. In this study, a concept of direct feed FDM technology was presented, which allowed co-feeding of multiple materials in any available form. Different materials were mixed at predetermined ratios and deposited together to form a 3D object with variable properties and functionalities that meet specific requirements. To demonstrate the capability of this AM system, heat-sensitive polyvinyl alcohol (PVOH) and its additives were processed. A geometry with various features was successfully manufactured with dimensions closely matching those of the design specification. The FDM processed PVOH showed insignificant thermal decomposition as it retained its original colour, flexibility, and water solubility. During the process, a fluorescent whitening agent was successfully incorporated into the polymer melt. Therefore, the printed sample exhibited a strong fluorescence effect from the UV-visible and fluorimeter results.

INTRODUCTION

Continuing development of Additive Manufacturing (AM) technologies has driven a rapidly growing interest from both research and industry across various sectors. Thermoplastic products are often fabricated using Fused Deposition Modelling (FDM), an extrusion based AM technology. A typical FDM requires a pre-process to produce filament feedstock. It extrudes the filament through a hot liquefier and then deposits the melt in a layering pattern to build a three-dimensional (3D) object. A limited range of thermoplastics is available for FDM manufacturing and it is incapable of mixing and depositing multiple materials during the process.

In order to overcome these limitations, a novel AM system has been proposed in this study. It modifies the FDM technology through hybridisation with traditional polymer single screw extrusion technology, which allows co-processing of multiple materials directly in their powder/pellet forms, at variable feeding rates. It therefore, enables a printed product to comprise of a greater material heterogeneity that renders variable properties and functionalities. Also, a direct feed FDM system is potentially able to process the following groups of materials that are currently difficult to be processed using traditional FDM: (1) thermosets that are cured irreversible by heating; (2) heat-sensitive thermoplastics that require short residence time in melt processing; and (3) materials not possessing sufficient strength or stiffness in filament form. For example, polyvinyl alcohol (PVOH) is a heat sensitive material, which has a starting decomposition temperature (approx. 180°C) overlapping its melting temperature (approx. 180-240°C) [1], leading to thermal degradation of the polymer during deposition. In this study, the direct feed FDM technology was developed and investigated via processing heat sensitive PVOH and additives.

MATERIALS AND METHOD

A small-scale single screw extruder (50mm x 63mm x 197mm) has been designed and constructed (**Fig. 1**). It was vertically laid out and designed to have multiple feeding ports located at different heights from the liquefier, which allowed co-feed of multiple materials into the extruder at different feeding rates. The barrel was heated via two cartridge heaters, which were inserted at both sides of the screw inside the barrel. Materials to be processed in this equipment could be in any available form, such as powder, pellet, tablet, liquid, and filament. It works using the same principle as a typical single screw extruder in that the material fed is heated to its molten state and the screw shears the melt flow to convey it towards the nozzle. In this processing system, the melt flow was extruded via a connecting tube into the liquefier of an existing FDM machine, and subsequently deposited onto the printbed. The output rate of deposited material was determined by the screw rotational speed, which laid down layers of material under computer control. Integration with an FDM platform enabled the system to move in the Cartesian x, y, and z directions while depositing polymer melt, thus generating a 3D object from a computer-aided design (CAD) model.

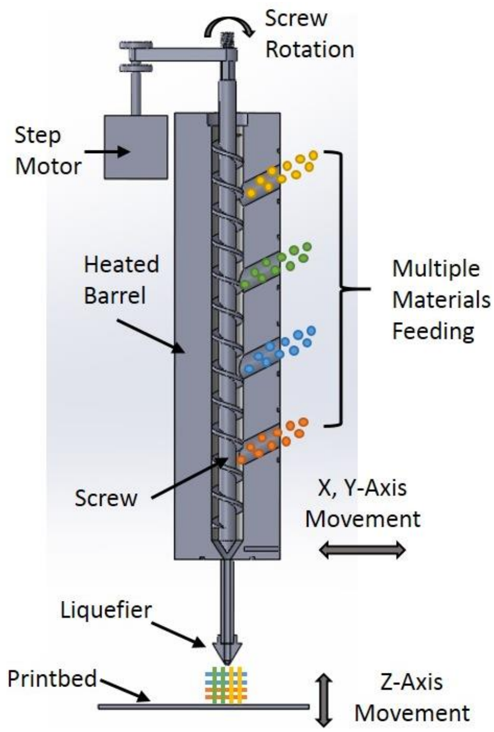


FIGURE 1. Schematic of the single screw extrusion-based AM system developed in this study. Barrel, liquefier and their connecting tube were displaced in section view to expose their interior construction.

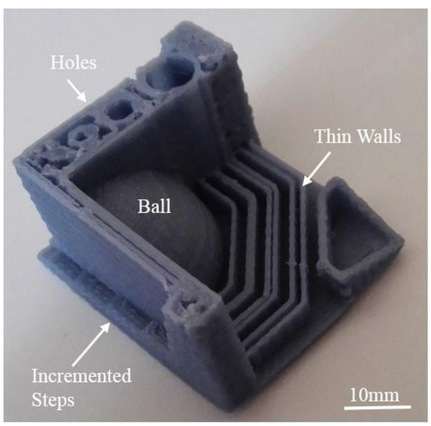
A Touch 3D FDM machine (Cubify, US) was modified to remove the original material feeding system, which allowed subsequent installation of a proprietary extruder onto the machine. A PCB heatbed (Reprap, UK) was also integrated into printbed to reduce residual stress of a printed structure. The cartridge heaters were under temperature control from an InstCube 3216L SSR Unit (TMS Europe Ltd., UK), using a thermocouple located in the side wall of the barrel.

A PVOH-based commercial compound was used in this study. Due to confidential reasons, details of all chemicals (trade name, manufacturer) used in this study are not included. The PVOH material was provided in pellet form. After initial trial runs, suitable processing parameters were determined to be: layer thickness = 0.25mm, extrusion temperature = 166°C, liquefier temperature = 190°C, and motor rotation speed = 70RPM. PVOH was fed via the lowest feeding position, allowing it to have a shortest residence time. A 3D structure comprising thin walls, holes with different diameters, incremented small steps and a ball feature, was designed and manufactured from PVOH using the direct feed FDM system. Dimensions of different features were measured and compared with the original CAD design. A rectangular shape (50mm x 15mm x 1mm) was also printed from PVOH material. It was immersed in 50ml purified water at 50ºC under magnetic stirring at 3000rpm to observe dissolution. Samples with the same shape were also quickly formed using hot press compression moulding (P200 P/M, Collin, Germany). An identical dissolution test was also performed on the compression moulded PVOH samples, which were considered to have minimum heating residence time.

Multiple material printing was performed by co-feeding PVOH with a fragrance and a fluorescent whitening agent (FWA), respectively. Fragrance was in liquid form and FWA was in powder form. Due to its strong fluorescence effect, the FWA is a good chemical indicator to demonstrate compositional distribution within a sample [2]. The feeding rates of PVOH:FWA and PVOH:fragrance were both 100:1 by weight. Samples with a rectangular shape were printed using PVOH with and without any additive. Each obtained PVOH and PVOH:FWA sample was sectioned to small pieces and then immersed in purified water at a concentration of 0.63 x 10^{-2}g/ml. The aqueous solution was subsequently characterised using UV-vis (Cary 60, Agilent Technologies, US) and fluorescence spectroscopy (FP-6500, Jasco, UK). The excitation wavelength for fluorescence emission scanning was 312nm.

RESULTS AND DISCUSSION

The 3D structure with different features was successfully printed out using the direct feed FDM system (**Fig. 2**). All the features were clearly shown on the structure except the smallest hole due to the resolution limitation of the original FDM liquefier. There were slight increases in the dimensions of printed features compared to the original design, which was normal for FDM manufacturing due to die swell. Nevertheless, this printing trial demonstrated that the developed AM system had a good 3D printing capability. It allowed a high degree of design flexibility. This has been further demonstrated by printing various 3D structures following the trial process. For example, PVOH is commonly used as laundry and fishing packaging material due to its water soluble characteristic. Capsules and lids with various shapes have been designed and successfully manufactured from PVOH material using the direct feed FDM system.



	Design Specification	Printed Results
Thin Wall Thickness	0.5mm	0.62±0.03mm
Incremented Steps	1mm	1.26±0.12mm
Hole Diameter	0.5mm 1.5mm 3.5mm 6mm	0mm 1.63mm 3.75mm 6.11mm
Ball	A Ball Structure	A clear ball structure demonstrated

FIGURE 2. A 3D structure with various features printed to demonstrate the 3D printability of the direct feed FDM technology.

PVOH material is subjected to thermal decomposition via gradual elimination of hydroxyl (-OH) side groups, causing discoloration and brittleness [1]. However, the sample printed using this novel AM system had a consistent blue colour throughout the whole structure, which was similar to that of the pellets feedstock. Also, the material still retained a good flexibility after the thermal process, indicating insignificant thermal decomposition. By integrating extrusion with FDM, this AM system allows the samples to form in a one-step process. It is important for materials, such as PVOH to be processed within a relatively short residence time to minimise thermal decomposition. PVOH rectangular samples printed using the direct feed FDM system dissolved in water within 9min. A similar dissolution rate was recorded for compression moulded PVOH samples. Therefore, the PVOH material after the direct feed FDM process still retained its functionality and can be used for any water solution application.

Both fragrance and FWA are widely used additives in the laundry sector to incorporate into either detergent or polymer capsules. Therefore, they were chosen in this study to co-process with PVOH. The samples with fragrance added demonstrated significant scent compared to the control ones. It proved that fragrance was successfully incorporated into the PVOH melt during the process.

The capability of the direct feed FDM system to co-manufacture multiple materials was also evaluated by characterising the fluorescence effect of FWA filled samples. The UV-vis absorption spectrum showed a strong peak between 300nm and 450nm for the sample containing 1wt.% FWA additive, which did not occur for the spectrum of the PVOH sample (**Fig. 3 left**). This peak corresponded to the π-π* transition in planar conjugated system [3], suggesting that FWA had been successfully mixed with the PVOH melt during the process. In addition, a strong fluorescence emission peak centred at 439nm was also demonstrated for sample with FWA (**Fig. 3 right**). Contrarily, the PVOH sample without FWA did not show the same absorption and emission peaks. Therefore, the material from the printed sample was able to absorb light in the UV region and re-emit light in a higher wavelength, thus demonstrating a strong fluorescence effect. This effect was also observed when the sample was exposed to UV light. Different parts of the printed sample were characterised using the same methods and all of them exhibited the strong fluorescence effect. Therefore, FWA was homogenously distributed within the PVOH melt during the process and subsequently deposited together to form a 3D structure.

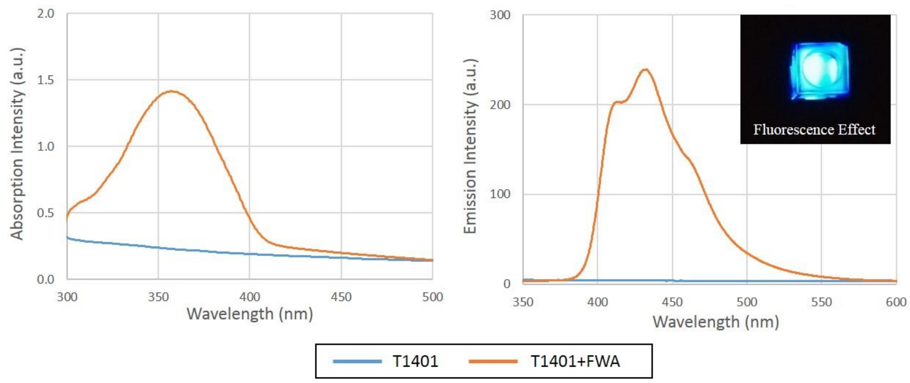


FIGURE 3. (**Left**) UV-vis absorption spectra and (**right**) fluorescence emission spectra of T1401 and T1401+FWA. A photo of the T1401+FWA sample exposed to UV light was also showed.

CONCLUSION

This study has designed and constructed a novel direct feed FDM system, which combines the merits of traditional polymer extrusion to directly process materials in any form available and advanced AM technology to fabricate pre-designed 3D objects. It has successfully and elegantly solved several major limitations of the current FDM technology. A greater variety and combination of materials could be processed using this technology. It allowed mixing and printing multiple materials to form a 3D object that can offer highly complex functionalities.

Also, this technology potentially has the capability to print a structure with controllable and variable compositions. Investigation on this matter is currently ongoing. If that is the case, then it can allow each voxel of a 3D printed structure to contain different compositions, properties, and information. Therefore, a much wider range of industrial and research applications will be created and open to AM in the future.

ACKNOWLEDGMENTS

The authors acknowledge funding by Innovate UK under research project grant (101491) entitled 'PVOH Composite Active Packaging'.

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