Mechanical and Experimental Study on the use of Sustainable Materials for Additive Manufacturing

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Abstract. In the present study multi-material 3D printing of acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and high impact polystyrene (HIPS) has been performed by using a low cost printing technology for manufacturing of innovative and sustainable composite materials. Further thermal (heat capacity at glass transition temperature, thermal conductivity) and mechanical (break elongation, break load, percentage elongation at break, break strength and young’s modulus in tensile as well as pull out test) properties have been investigated for 3D printed multi-material components.

1. Introduction

3D printing- a better known as additive manufacturing (AM) forms the object by successive layers of materials for different application areas. 3D printing has the potential/impact to transform manufacturing supply chain, distribution channel and business model. There are some of the 3D printing technologies which are presently used by the society to apply as specific solutions. In recent years, AM has become the most common technique for fabricating periodic lattices and mechanical and acoustic meta materials. Several fabrication methods have been proposed in this field, with resolution ranging from the centimeter- to the nanometer-scale. Worth mentioning here are: polyjet 3-D printing technologies; multi-material fused deposition modelling (FDM), electron beam melting; x-ray lithography; deep ultraviolet lithography; deep Ultraviolet lithography; soft lithography; two-photon polymerization; atomic layer deposition; and projection micro-stereolithography, among other available methods [1-5]. FDM is a low-cost technique of AM which is used to prepare the functional prototypes of polymers/composites [6-8]. In FDM, part is build layer by layer by heating a thermoplastic filament to a semi-liquid state and extruding it through a small nozzle per 3D CAD models usually in STL format [9-11]. Manufacturing and technology environments are fuelling a new generation of engineer, scientist and designers. Just as it made at- home polymer 3D printers a commonality today, the world could eventually see a metal or ceramic 3D printer become common in an average household. To achieve this goal, future inventions in next generation structures using existing materials via AM will surely need to revolve around cost reduction, improved performance, and advanced structural design [12]. The study conducted for 3D printing of multilateral component of ABS and thermoplastic polyurethane (TPU) reveals with support of 3D imaging that interface properties are found in control with good layers connectivity [13]. Multi-material 3D printing potentials to be a milestone in rapid manufacturing, customized design and structural applications. Being compatible of functionally graded materials in a single structural form can be applied potentially in structural application to get the benefit of combined/hybridised properties. The multi-material printing provides a fast and robust structure with compact functionality of all combined
materials [14]. The multi-material 3D printing applicable to fascinating application of new smart 4D structures which can provide the achievement of shape/property/functionality [15]. It was highlighted that existing AM techniques such as FDM can be modified to hybrid deposition manufacturing (HDM) with embedded component to produce more complex, integrated multi-material component than traditional technique [16].

Fewer studies have been reported in recent past to enhance the properties of thermoplastics by reinforcing with metals/ non-metals through extrusion and finally 3D printing of same by FDM. But hitherto no work has been reported on multi material printing of thermoplastics to enhance its mechanical properties. In the present study ABS, PLA and HIPS were 3D printed in multi nozzle FDM to explore the applicability of final product in structural application (repair/maintenance of heritage buildings).

2. Experimental details
Experimentation stage contains evaluation of melting and solidification characteristics, glass transition temperature determination, extrusion and multi-material 3D printing based upon an experimental design. ABS has high toughness, high degree of mould-ability and low thermal conductivity and PLA has good biodegradability/crystallinity whereas HIPS is of low cost with high impact resistance. These three thermoplastics have been selected for the fabrication/multi-material printing operation with FDM. Table 1 shows mechanical, thermal and rheological properties (average value of 3 consecutive repetitions) of feedstock material. It should be noted that ABS, PLA and HIPS are having significant differences in their melt floe index (MFI), glass transition temperature (GT), peak load (PL), peak strength (PS), peak elongation (PE), Young’s modulus (YM) and yield stress (YS). The aim of the present study is to fabricate the new composite of all three polymers so that final product must be comprised of advantages of all polymers. Following the design of experiment based upon Taguchi L9 orthogonal array, the multi-material parts have been prepared on FDM and mechanical properties have been evaluated as shown in table 2.

Table 1. Mechanical, rheological and thermal properties ABS, PLA and HIPS.

| Polymer | MFI (g/10 min) | GT (°C) | PL (N) | PS (MPa) | PE (mm) | %PE (%) | YM (MPa) | YS (MPa) |
|---------|----------------|---------|--------|----------|---------|---------|----------|---------|
| ABS     | 8.7            | 109.76  | 207.0  | 10.78    | 4.75    | 6       | 175      | 0.49    |
| PLA     | 13.5           | 62.57   | 282.4  | 14.71    | 5.13    | 7       | 47.9     | 0.27    |
| HIPS    | 7.5            | 100.41  | 80.8   | 4.21     | 3       | 112.5   | 3.44     |

Table 2. Experimental design for multi-material 3D printing on FDM and mechanical properties of 3D printed multi-material component.

| Exp no. | Material Combination | Infill (%) | Speed (mm/s) | PL (N) | PS (MPa) | PE (mm) | PE (%) | YM (MPa) | YS (MPa) |
|---------|----------------------|------------|--------------|--------|----------|---------|--------|----------|---------|
| 1       | APH                  | 60         | 50           | 133.9  | 6.97     | 2.85    | 4      | 72.92    | 2.73    |
| 2       | APH                  | 50         | 60           | 179.9  | 9.37     | 2.85    | 4      | 264.58   | 2.68    |
| 3       | APH                  | 100        | 70           | 206.9  | 10.78    | 4.37    | 6      | 73.29    | 0.21    |
| 4       | PHA                  | 60         | 60           | 161.3  | 8.40     | 3.04    | 4      | 325.00   | 1.00    |
| 5       | PHA                  | 80         | 70           | 189.9  | 9.89     | 3.99    | 5      | 79.17    | 4.54    |
| 6       | PHA                  | 100        | 50           | 187.9  | 9.79     | 3.23    | 4      | 108.33   | 5.13    |
| 7       | HAP                  | 60         | 70           | 149.0  | 7.76     | 3.99    | 5      | 85.42    | 0.28    |
| 8       | HAP                  | 80         | 50           | 174.8  | 9.10     | 3.42    | 5      | 161.84   | 0.17    |
| 9       | HAP                  | 100        | 60           | 164.4  | 8.56     | 3.61    | 5      | 249.67   | 0.16    |

The thermal properties have been checked by differential scanning calorimeter (DSC). The endothermic reaction was carried under the heating rate of +10°C/min from 30°C to 250°C, whereas exothermic reaction was carried under -10°C/min from 250°C to 30°C. In the present case extrusion with TSE was performed under the temperature of 230°C, rotational speed of 50rpm and with applied
load of 10Kg to prepare the feedstock filaments of 1.75±0.05mm. The extrusion parameters were determined by pilot experimentation based upon uniformity and dimensional accuracy. Commercial open source FDM setup (Company: Divide by Zero) configured with two nozzle head was selected for multi-material 3D printing. The static parameters for fabrication of composite parts were nozzle diameter of 0.3mm, filament diameter of 1.75±0.05mm, layer height 0.27mm, 3 perimeters (by adjusting 3 top and 3 bottom layers), rectilinear fill pattern, 30mm/sec perimeter speed, travel speed of 130mm/sec, at extrusion temperature of 250°C and bed temperature of 55°C. The two parameters were varied for fabrication (i) infill percentage of 60, 80 and 100%, (ii) under printing speed of 50, 60 and 70mm/sec. The multi-material printing was customized by total 12 layers with 4 layers of each material. The multi-material printing was configured as APH (4 layers of ABS on bottom, 4 layers of PLA in middle and 4 layers of HIPS on top), PHA (4 layers of PLA on bottom, 4 layers of HIPS in middle and 4 layers of ABS on top) and HAP (4 layers of HIPS on bottom, 4 layers of ABS in middle and 4 layers of PLA on top).

3. Results and discussion

It was observed that the extruded feedstock of ABS, PLA and HIPS resulted in the significant differences as regards to mechanical properties are concerned. The experiment average by three repeated trails outlined that ABS was having maximum YM, PLA was having maximum PL, PS, PE and minimum YM and YS, whereas HIPS resulted in minimum PL, PS, PE and minimum YM and YS (See table 1). Figure 1 shows 3D printed multi-material component and the load Vs. deflection curves of ABS, PLA and HIPS material undergone tensile failure.

![Figure 1](image1.png)

**Figure 1.** (a) 3D printed multi-material component, (b) load Vs. deflection curves of ABS, PLA and HIPS.

![Figure 2](image2.png)

**Figure 2.** Load Vs. deflection curve (a) for tensile properties (b) for pull out properties.

As per ASTM D 638 type IV, the material tested through ultimate testing machine. After the fracture of each sample, data were recorded and shown in table 2. It was observed that at experiment no. 3 with APH multi-material configuration, 100% infill percentage and 70mm/sec printing speed...
resulted in the maximum value of PL, PS, elongation properties and minimum YM whereas at experiment no. 1 with APH, 60% infill and 50mm/sec printing speed configuration it resulted in minimum values of PL, PS and PE properties. Component at experiment no. 4 resulted in the maximum YM. It was observed from here that at best setting of input variable, the PL, PS, PE, percentage of PE was achieved greater that HIPS but lower than PLA and ABS. The most important fact was observed in case of YM where at experiment no. 2, 4 and 9 resulted in the values greater than any of the parent material. Again, the YS at experiment no. 3, 8 and 9 resulted in the values lesser than each parent material (See figure 2 (a)). Since pull out test is one of the most important consideration to justify it for the structural applications. The pull-out test was conducted on all the samples with provision of evaluating the PL, PS, PE and percentage changes of PE. It was observed that strength of multilateral component was resulted greater than HIPS but lesser than ABS and PLA as shown in figure 2(b).

4. Concluding remarks
Following conclusions have been drawn from the present study of 3D printing of multilateral component for structural applications:

- Multi-material 3D printing of ABS, PLA and HIPS polymer is feasible because these thermoplastic possess similar heat capacities (13.63mJ for ABS, 14.71mJ for PLA and 11.71mJ for HIPS).
- From tensile properties investigations, it was observed that the peak strength of HIPS (4.21 MPa) was minimum to other material (PLA and ABS). But 3D printing of multi-material resulted in improved properties to a significant level (10.78 MPa) under controlled input conditions.
- It was observed that strength of multilateral component was observed greater than HIPS but lesser than ABS and PLA in pull out test.

The use of multi-material 3D printing techniques for the rapid prototyping of next-generation metamaterials and structures, whose mechanical response is largely derived from the geometry of the microstructure will form the subject of future studies [16].

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