Tensile behavior of lightweight foam filament

Nithin Kamath*, Rajesh Anawal and Mrityunjay Doddamani

Lightweight Materials Laboratory, Department of Mechanical Engineering, National Institute of Technology Karnataka, Surathkal, India

E-mail: *nithinkamath007@gmail.com

Abstract. Filaments of high-Density Polyethylene (HDPE) with Glass Microballoons (GMBs) by 20, 40 and 60 volume% are developed and studied for tensile characterization. Density of syntactic foam filaments are lower compared to pure HDPE filaments. The syntactic foam filament developed results in weight saving potential of 28% owing to inclusion of hollow GMBs in matrix resin making them suitable for marine applications. Modulus of syntactic foam filaments increases with increasing GMB volume % compared to neat HDPE. Tensile strength of syntactic foams is lower as compared to pure HDPE filament. These developed lightweight filaments can be used for 3D printing of complex geometries.

Keywords: Tensile behavior, Syntactic foam, Fused filament fabrication, HDPE, GMB.

1. Introduction

Additive manufacturing (AM) is one of the fastest developing research area in recent years[1, 2]. AM is a method of combining materials layer by layer to make objects using 3D model data[3]. AM methods reduces the life cycle of product development, which is able to produce parts in small production runs[4]. Among various AM methods, fused filament fabrication (FFF) is commonly used method because of accessibility of verity of filaments and easy processing when compared to other methods[5]. FFF require thermoplastic polymeric filaments to get deposited in layers via nozzle to create a component based on CAD model. Filaments of thermoplastic material such as acrylonitrile butadiene (ABS), polylactic acid (PLA), polyethylene terephthalate etc., of 1.75 or 3mm diameter are widely used for FFF printers[6]. Interests are growing in developing new filaments with different compositions based on the final component requirements[7].

Closed cell syntactic foams are particulate composites in which hollow particles are distributed in matrix material[8-14]. These lightweight composite materials find applications in marine and aerospace structures[15]. GMB and fly ash cenosphers are commonly used particles in the manufacturing of syntactic foams[16, 17]. Recent studies are successful in developing filaments of HDPE/fly ash cenosphere composites, in which better modulus and strength are observed as compared to neat resin[6]. The present work focuses on developing lightweight HDPE/GMB based filaments and to characterize them for tensile behavior.

2. Materials and Methods

2.1. Filament Material

HDPE is used as matrix material while hollow GMBs are used as hollow reinforcements. The specifications of GMB used in the present work are presented in Table 1. The average diameter of the GMBs found to be 18μm. Radius ratio of the GMB is determined by considering fully solid walls using[18],

$$\mu = \left(1 - \frac{\rho_{sl}}{\rho_g}\right)^{\frac{1}{3}}$$ (1)
where, \( \rho_{td} \) is true particle density of GMB (0.6g/cc) and \( \rho_B \) is taken as 2.540g/cc[19]. Thickness of the GMB wall is determined using[20],

\[
W = r_0(1 - \mu)
\]

where, \( W \) is wall thickness of GMB and \( r_0 \) is outer radius of particle.

### Table 1. Properties of glass micro balloon.

| Properties                  | Value | Unit |
|-----------------------------|-------|------|
| True Density                | 0.6   | g/cc |
| Softening Point             | 600   | °C   |
| Theoretical Thermal conductivity | 0.2   | W/mK |
| Wall thickness              | 0.687 | mm   |
| Radius ratio \((\eta)\)     | 0.914 | --   |

2.2. Processing
HDPE/GMB blends were prepared using extruder. Measured quantities of HDPE and GMB are fed into the extruder hopper. The blending temperature and screw speed of 180°C and 20 rpm, respectively are used which is optimized from an initial set of experiments. The composite mixture is then extruded using single screw extruder to obtain the filaments. The temperature of heating zones is maintained at 175 °C. The screw speed is maintained at 20 rpm. The filaments are represented per the convention \( H_{\text{yy}} \), where ‘H’ denotes HDPE and subscript ‘yy’ represents GMB volume %. Syntactic foam filaments with filler content of 20, 40 and 60 volume % are prepared. Filaments of all the compositions of uniform diameter 1.75±0.05mm are extruded to be used in FFF 3D printer.

2.3. Density Measurement
Density of the extruded filaments are measured as per ASTM D792-13. In each composition, densities of five filaments are measured and average value of density is reported. The density of pure HDPE is measured to be 0.950±0.002g/cc. Theoretical densities of syntactic foams computed using rule of mixtures.

2.4. SEM Imaging
Scanning electron microscope (SEM) (JSM 6380LA, JEOL, Japan) is used to study characteristics of micrographs. All the filaments are sputter coated with gold using an auto fine coater (JEOL, Japan).

2.5. Tensile test
AZwick universal testing apparatus (ZwickRoell Z020, USA) which is computer-controlled with a capacity of load cell 20kN, is used to study tensile behavior of filaments with 175mm length. Tests are conducted at a strain rate of 5mm/min. The strain is measured using an Instron extensometer of gauge length 30mm. Five filament specimens are tested for each composition and average values are reported.

3. Result and Discussion
3.1. Microstructure of Filament
Micrographs of HDPE/GMB syntactic foam filaments is presented in Figure 1. A circular cross-section of the filament is evident as seen from Figure 1a. Uniform dispersion of GMB in the matrix with some air pores are seen for all the foam compositions as depicted by Figure 1. Void content present in the filaments is observed to be in the range of 2.42 – 7.68% with filler loadings.

3.2. Filament Density
Density of the syntactic foam decreases with increase in the volume % of hollow particles. The measured density of \( H_{20} \), \( H_{40} \) and \( H_{60} \) were found to be 0.858±0.064, 0.808±0.056 and 0.683±0.012 g/cc respectively. The measured density of filaments is 2.42, 0.17 and 7.68 % lower than theoretical
densities of respective materials. This difference is caused due to the porosity involved within the filament during the extrusion of filament. The weight saving potential of syntactic foam of H₆₀ is 28.09 % with respect to pure HDPE.

**Figure 1.** Micrograph of (a) H₆₀ Filament at lower magnification (b) Uniform dispersion of GMBs (c) H₄₀ and (d) H₂₀ filaments.

### 3.3. Tensile Characteristics
Tensile stress-strain plots of pure HDPE and HDPE/GMB syntactic foam filaments are presented in Figure 2. The filament containing 60 volume % of GMB shows highest modulus. The modulus values of all syntactic foam filaments increase with increasing volume % of GMBs as compared to pure HDPE in the range of 6.7-62.96%. The tensile modulus for syntactic foam filaments increases as compared to pure HDPE (Figure 3a). The Figure 2b represents syntactic foam filaments have lower failure strains compared to pure HDPE (Figure 2a). Increasing GMB content decreases failure strain. Ultimate tensile strength of all syntactic foam filaments shows lower value as compared to pure resin with increasing the volume % of filler (Figure 3b). Higher filler content reduces the load bearing matrix content resulting lower ultimate tensile strength. Similarly, specific modulus (Figure 3c) value of syntactic foam filaments are higher as compared to pure HDPE filament. Significant weight saving can be achieved over pure matrix. Figure 3d depicts decreasing trend of specific tensile strength for syntactic foam filaments with increasing the volume % of GMB.
4. Conclusion
The present work focused on development of HDPE and HDPE/GMB syntactic foam filaments for use in commercially available FFF 3D printing. The tensile properties of syntactic foam filaments are compared with pure HDPE filament. The results are concluded as follows.
Density of syntactic foam filaments having 20, 40 and 60 volume % of glass microballoons reduces by 9.09, 14.2 and 28.09% respectively as compared with pure HDPE filament resulting in their suitability in weight sensitive applications.

Tensile modulus of syntactic foam filaments shows increasing trend with increasing volume % of GMBs whereas strength of the syntactic foam filaments decreases with increase in GMB volume %.

Values of specific modulus and specific strength of syntactic foam filament shows increasing and decreasing trend respectively with increase in filler content.

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