Development of In-House Single-Screw Extruder for The Extrusion of Polymer Composite Filament

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***Abstract*—Single-screw extrusion is a practical and economical method used for the extrusion of polymer composite wires. It converts premixed polymer powder mixture into filaments that can be further used as a feedstock for fused deposition modeling (FDM) and other extrusion 3D printing processes. This method is widely used as it is simple to operate, economic in terms of initial investment as well as running cost. This paper demonstrates the extrusion of different compositions of High-Density Polyethylene (HDPE)-Hydroxyapatite (HA). To achieve dimensional consistency the processing parameters are set experimentally and HDPE-HA composite filaments have been successfully extruded in various compositions.**

***Index Terms*—HA, composite filament, single screw extruder.**

I. INTRODUCTION

The paper describes a single-screw laboratory extruder model for producing short fiber–reinforced filaments. The modifications include modifications of mixing zones, additional kneading elements, and improved compression ratio. This ensured better fiber dispersion and reduced fiber brakeage. Also, the geometry of die and controlled feeding mechanism were included. This ensured constant filament diameter. This resulted in homogeneous fiber distribution and enhancement in mechanical properties compared to conventional designs [1].

In a study, Gentamicin sulphate and PLA were mixed and process under heat. This ensured uniform distribution of Gentamicin sulphate into PLA before feeding to the extruder. Gentamicin did not affect the printability but when its content increases, the mechanical strength of the filament was reduced [2].

This study reports fabrication of filaments of PLA/TPU hybrid composites via single screw extruder. These filaments would be used for extrusion-based 3D printing. Extrusion stage was important in context with fiber distribution and interfacial bonding, as these two factors directly affects fracture performance. Results showed that addition of TPU improved toughness and reduced brittle failure. With optimized extrusion conditions, the fracture transits towards ductile fracture. This study emphasizes controlled single-screw extrusion achieves better mechanical and fracture properties [3].

The PLA/HA composite filaments reinforced with sugarcane powder were extruded using a single screw extruder. Study showed that extrusion conditions were found to strongly affect fiber distribution, interfacial bonding, and homogeneity. However, excess loading causes reduction in mechanical strength. Overall, it showed the optimization of single screw extrusion can give better results [4].

Similar observations were noted [5] emphasizing that the optimal settings vary depending upon moisture the content and percentage of fiber loading.

When single screw extruder was used for the extrusion of recycled and virgin HDPE blends, variations in waste content influenced the overall processibility of extrusion. But optimization of extrusion parameters gave uniform blending and stable filament production [6].

The study discusses the design and simulation of a micro single-screw extrusion system for 3D printing. Simulation results indicate that for improved mixing efficiency and uniform distribution, requires a optimized screw design, specially shear and temperature [7].

The proper parameter settings is a key factor for homogeneous filament extrusion. The parameters include the temperature of different zones, screw speed, the gap between screw and barrel, and feed rate [8].

In addition to parameters [8], these authors reported that the puller speed was also one of the key factors that affect the flow stability and filament diameter consistency of fiber reinforced composites. Higher screw speeds could cause diameter inconsistency, but controlled temperature and haul-off speed overcome these difficulties [9].

Similar to observations noted in [4] it showed that in a compposite of MWCNT-reinforced ABS control over process parameters and percentage filler loading is important. By optimizing above factors uniform nanotube dispersion could be obtained. Controlled single screw extrusion is necessary for homogeneous nano composite [10].

This study demonstrates the development and application of a novel computer-based optimization system for single screw extrusion. Th computer is used for optimizing screw speed, barrel temperature and metering section length. This maximizes output and minimizes energy consumption. The optimization was validated via simulation and experimentation with HDPE/PS filaments. When flow rate was given importance, pressure increases slowing down the melting. If energy consumption was priority, the pressure was low and faster output was obtained [11].

Another approach reported on designing emphasizes a low cost and efficient design. In addition to screw mechanism, and heating zone, a calibrated die was used to obtain consistent filament diameter. It gave importance to screw geometry, temperature control, and feed mechanism to obtain uniform melting and stable extrusion. It was found that the thermocouple should be at least 30 cms deep in barrel [12].

Another study reports a Design of Experiments (DOE) in the fabrication of composite filament of PCL/PLA. It suggested to measure the combined effect of composition ratio and extrusion conditions are on filament quality. The experiments had to be design properly so that the best results of various combinations can be obtained [13].

DOE was also used in the extrusion of recycled polypropylene (PP) blends. It showed the melt viscosity is the key factor for proper extrusion. It was affected by temperature. At higher screw speeds, higher outputs can be obtained but the speed was limited by the temperature rise in the process. It had to be decided experimentally [14].

In this study the extrusion of nylon-6–and reinforced with aluminum and aluminum oxide composite filaments was studied. The reinforcement increased mechanical strength but also causes brittleness. Therefore, optimal use if reinforcement is necessary [15].

This study also emphasises the significance of screw geometry as it affects the melt temperature consistency. Study found that screw geometry has a significant effect on melt temperature consistency [16].

This studies the development in screw extrusion technology. This is now used for manufacturing pipes, car parts etc. It covers wide range of applications from fiber spinning to film making. Improved product properties are obtained at higher efficiency. It is being used for mass production and for development work. Carbon and natural fibers are also being used for reinforcement. This is also supporting recycling [17].

This study shows that temperature measurement at one point is not sufficient to obtain good quality. It suggests mesh of thermocouples that will accurately reflect important process parameters such as screw speed, and melting zone barrel temperature at various points. It reveals that optimised barrel temperature settings can reduce the variance [18].

II. MODIFICATION AND FABRICATION

Usually screw extruder have four heating's zones. This modified version has two zones. As the feedstock used is the thoroughly blended powder of HDPE and HA, the temperature zones are reduced to two.

Modified Extruder Set Up:

Screw: The screw diameter selected as 11/16 inches (17 mm) and length is 460 mm for L/D ratio to be more than 20:1. This ratio is required for improved mixing and stable output.

Screw Lengths: The length of screw is divided into two different temperature zones. The Melting section is about half of the length. The transition section is about 1/3rd of length.

Barrel: The cylinder or barrel in which screw will rotate must be able to withstand temperatures and must be hard enough to resist wear due to friction between barrel and plastic flow. The inner diameter is taken as 19.2 mm and outer diameter is 22 mm.

Hopper: Hopper resembles a funnel made of GI sheets. The taper angle has to be in between 20^0 to 45^0. Width of hopper at the entry is taken in between 20 to 30 mm for free flow of bulk solids.

Barrel extension with die: It is made of gunmetal as it has to withstand high temperatures. The nozzle diameter is taken as 2.00 mm.

Heater bands: The heater bands are ceramic heater bands. Two ceramic bands of different lengths are used for different zones of screw.

Thermocouples, controllers and solid-state relay: 1 thermocouple, 1 controller and 1 relay is used for each section of screw.
Motor: DC motor controlled by PWM speed controller

III. MATERIALS AND METHOD

The feedstock consists of High Density Polyethylele, (HDPE) sourced form Relience Industries PVT LTD. Hydroxyapatite (HA) is synthesized in research centre's laboratory.

HA is used as reinforcement in HDPE matrix. Four different combinations of HDPE-HA mixture were created by varying HA percentage as 5, 10, 15 and 20. The corresponding percentage of HDPE will be 95,90,85 and 80. [19]

HDPE granuals were grinded into a grinder to make a powder. HA and HDPE powder were mixed in the required quantity to prepared a feedstock for HDPE-HA composite filament.
The composite filaments were tested for tensile strength and the fracture surfaced was observed through SEM micrographs.

IV. EXPERIMENTATION

After installation, first trial was taken on High Density Polyethylene (HDPE) only. When the extrusion was successful, the trials are taken for different compositions of HDPE and HA.

The modified extruder is shown in figure 1 and the picture of wire extruded is shown in figure 2.

Table I: HDPE-HA composite trial run data

Material	T1 ^{0}C	T2 ^{0}C	Screw speed, r.p.m	Wire diameter mm
HDPE (90%) and HA (10%)	130	158	28	0.49
	128	160	25	0.70
	130	162	35	1.73
HDPE (95%) and HA (5%)	130	162	32.5	1.75-1.8
HDPE (85%) and HA (15%)	130	162	28	1.7-1.8
HDPE (80%) and HA (20%)	130	162	20	1.72-1.82

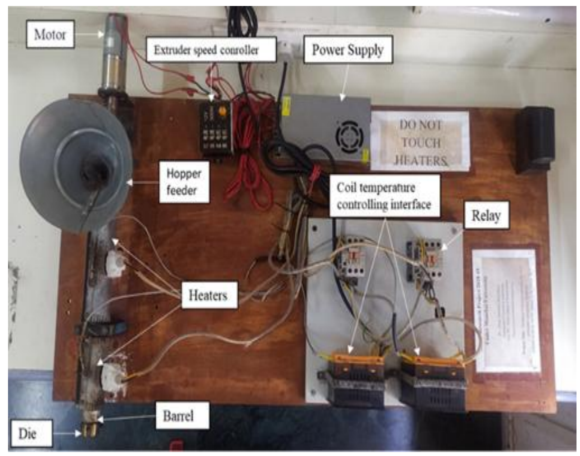

Fig.1: Laboratory extruder set up [19]

Fig.2: Composite Filament (10% HA)

For the extrusion of other three filament compositions the temperatures were not changed. The screw speed with 5%, 15% and 20% HA were drawn.

V. RESULTS AND DISSCUSSION

SEM:

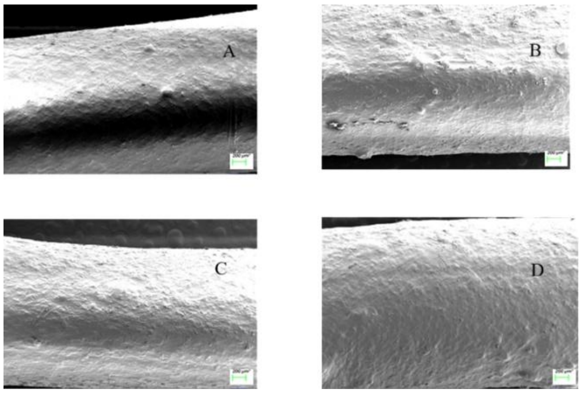

Fig. 3: SEM images of filament surface. A:5% HA, B:10% HA, C:15% HA, and D:20% HA [19]

From figure 3, it can be seen that, the surfaces of all four filaments were rough and non-homogeneous. The reason for this was, the process temperatures. Process temperatures were much lower than the melting temperature of HA, and HA will remain in the form of dispersed particles throughout the matrix in the filaments.

Tensile testing:

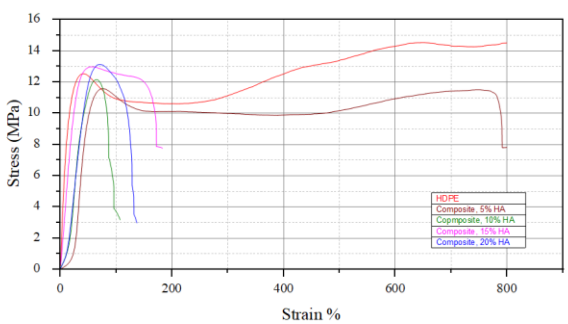

Fig. 4: Comparative Stress-Strain curve of HA-HDPE composite of various compositions [19]

The tensile test was conducted on 5 samples and the curves plotted are shown in figure 4.

Plain HDPE, 95% HDPE and 5% HA ,90% HDPE and 10% HA ,85% HDPE and 15% HA and 80% HDPE and 20% HA [19]. The stress-strain diagram of plain HDPE provides the datam of stress, strain and Modulus of Elasticity for all composite filaments. From figure 4, the plain HDPE graph shows ductile failure. Incomposite filaments as the percentage of HDPE decreases, the ultimate strength decreases, showing the appearance of brittle failure alogwith ductile failure. It becomes clearer as the percentage of HDPE go on decreasing in a composition. Young's modulus decreased with the decrease in HDPE content as compared to plain HDPE, however it was well within the range of Young's modulus of low load bearing applications which is 0.1 - 5 GPa [20]. The maximum tensile stress is found as 12MPa for 95% and 90% HDPE composition and 13 MPa for 85% and 80% HDPE composition.[19]

The filament with HDPE 95% and HA 5% did not fracture as the failur was a ductile failure. For Other filaments a fracture surface was available as the percentage of HDPE was decreased. These fractured surfaces were observed under scanning electron microscope and shown in figure 5.

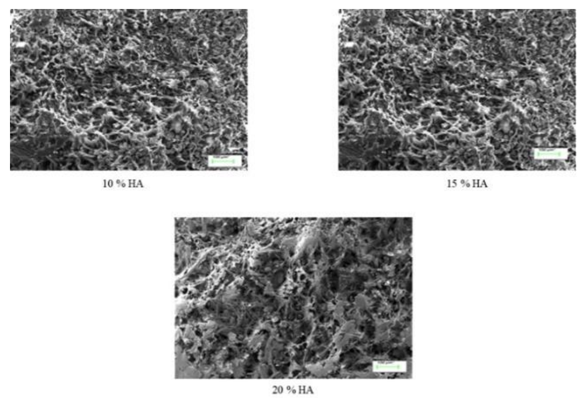

Fig. 5: SEM images of Fractured surface

10% HA and 90% HDPE [19] composite show ductile as well as brittle fracture. Brittle failure is visible as plain surfaces while ductile fracture as mesh as strained surfaces. The voids suggest particle deboning, indication of poor surface adhesion between HDPE and HA. For the 15% HA and 85% HDPE [19] composition, surface reveals a more ductile fracture morphology compared to 10% HA and 90% HDPE [19] composite image. This is in accord with stress strain curve (figure 4) of both compositions. The reason for this may be the 85 % HDPE and 15% HA [19] mixed better during the extrusion process than 10% HA and 90% HDPE [19] composite and the resulting filament become more homogeneous in natute. This highlights the need for efficient control over extrusion parameters as screw speed, zone temperatures. to achieve uniform reinforcement distribution and better mechanical properties. The

20% HA and 80% HDPE [19] show more brittle fracture. This is because the increase in HA percentage. This is supported by stress strain curve (figure 4).

VI. CONCLUSION

Smooth and continuous composite filament extrusion was possible via single screw extruder. The surface of all filaments shows irregularities undre SEM. As per the Stress-Strain curve, the mechanical behavior of 5% HA composition is as expected ie. More ductile fracture. This means the composition having 5% HA is properly mixed during extrusion. The 10 % HA composite shows more brittle fracture nature compared to 15% indicating improper mixing during extrusion. Thus, we can conclude that for mixing, the feed rate, screw speed and zone temperatures are to be simultaneously monitored and controlled to achieve an optimum combination for the extrusion of homogeneous campsite filament.

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