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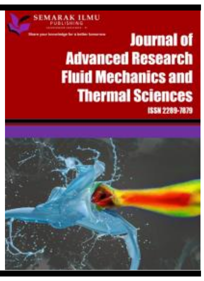

Rheological Properties of Natural Fiber Reinforced Thermoplastic Composite for Fused Deposition Modeling (FDM): A Short Review

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ABSTRACT

In the development and manufacturing industries, fused deposition modeling (FDM) receives the greatest attention. It is the most important additive manufacturing (AM) technique, which refers to the process of depositing multiple layers of material in a computer-controlled environment to form a three-dimensional product. Research is presently focusing on the development of 3D printed bio-composite polymers with improved performance. Many studies on the development of new composite materials using natural fiber as a feedstock filament for FDM have recently been published. As a result, conducting a rheology characteristics analysis of new composite materials made from natural resources is required. Its major purpose is to describe the flow behavior of the fiber composite material and determine the optimal melting temperature for the extrusion process of producing wire filament. Thus, this paper focuses on rheological properties of fiber-reinforced thermoplastic composite for FDM.

1. Introduction

Various applications have successfully used additive manufacturing (AM) technology. Fused deposition modelling (FDM), one of the most prominent AM techniques, is the most extensively used method for producing thermoplastic components, which are mostly utilized as fast prototypes for

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functional testing because of their low cost, limited waste, and ease of material changing [1]. In general, AM may be separated into three types: liquid, solid, and powder. As indicated in Figure 1, the primary processes of AM technology include sheet lamination, material extrusion, powder bed fusion, direct energy deposition, binder jetting, material jetting, and VAT photopolymerization. 3D printing technology is emerging as a revolutionary method for the faster fabrication of complicated shapes. It enables for customization, which results in more complicated structures while reducing waste and increasing design flexibility [2]. AM techniques were solely employed for concept visualization and validation. However, as the approach has progressed, end-use components and tools have been developed [3]. The AM process shapes the component layer by layer utilizing digital data produced using CAD and CAM. For many years, industry and academic organizations have devoted growing attention to the public's perceptions of environmental concerns and biodegradable polymer goods [4].

Thermoplastic polymers are commonly employed in FDM to print components or goods, however due to their weak mechanical qualities, there is an increasing demand for polymer composites that perform better. Kischlo *et al.,* [5] investigated the influence of various reinforcing agents and process factors on the mechanical characteristics of nanocomposites and found that additive manufacturing offers enormous potential for enhancing the qualities of polymeric composites. Over the last three decades, a number of researchers have conducted studies for attempting to control the settings of single and twin extruders as a standard techniques based on the extrusion concept for the preparation of feedstock filaments by mixing various size and weight reinforcements in polymeric composites for increasing the performance of 3D printed FDM. However, there has been limited studies on the use of rheological data to forecast material qualities. Rheology analysis is critical for determining the ideal melting temperature for the extrusion process of manufacturing wire filament and studying the flow behavior of the fiber composite material. Thus, this work identifies and summarizes past research on the rheological characteristics of fiber-reinforced thermoplastic composites for FDM.

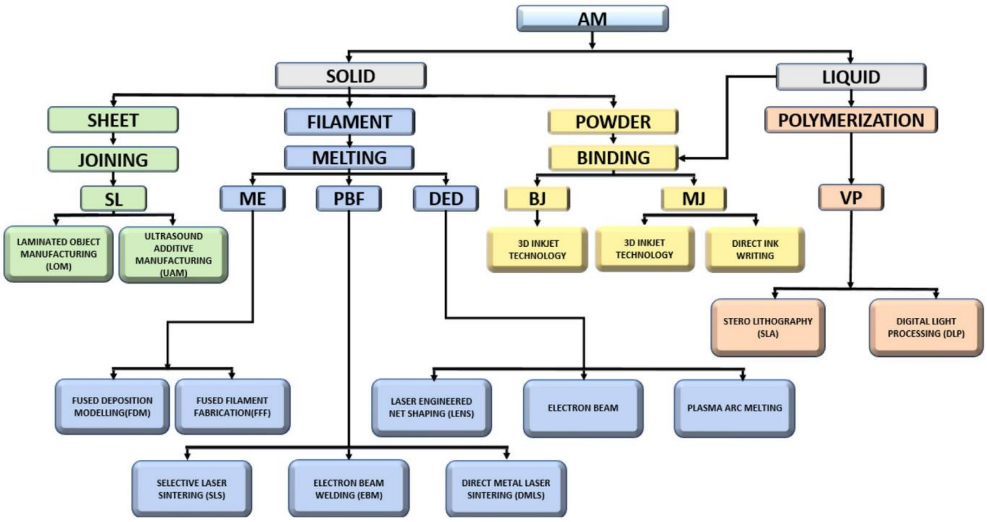

Fig. 1. Types of AM technology and process [6]

2. FDM Technology

FDM is a well-known AM technique since it is inexpensive and has a wide range of materials accessible on the market [7]. PLA, ABS and PP are common FDM materials. Furthermore, this method might be constructed entirely on the functional features of the product [8]. The polymeric filament is driven through the nozzle and fed over the build plate and the product is constructed composite structures at a consistent speed and pressure [9]. Pre-processing, printing, and post-processing are the three basic operations in FDM. Pre-processing includes CAD design and the conversion of CAD data to an STL file. The data was sent to the FDM machine using slicing software such as Creality Slicer, Cura, etc. The printing process then started when the proper parameters, such as layer thickness, printing speed, pattern, etc., were determined. Post-processing is essential in FDM since the printed components are not completely ready for use. And after the printing process, the product is removed from the printing bed platform, and the supporting materials are removed and then started the post processing. According to Kumbhar *et al.,* [10], post-processing procedures are typically utilized to increase surface smoothness. Ahmad *et al.,* [11-12] has discovered the optimum parameters of FDM using ABS material and used PolyJet 3D printer to print 30 samples of molar teeth. The primary advantages of this FDM method are ease of access, lower equipment costs, and multicolored product printing; when compared to other RP processes, this approach is less expensive and more cost-effective. Shanmugam *et al.,* [13] in his research reported that the use of recycled polymer in AM was the first invention to challenge how consumers perceive recycled materials. The primary constraints of this technology are poor surface quality and the necessity for support structures.

3. Natural Fiber as Feedstock For FDM

Natural fibers have been widely utilized for reinforcing polymeric materials due to their environmentally friendly nature, great stiffness-to-weight ratio, biocompatible, and inexpensive cost when compared to manufactured fibers such as carbon or glass fibers. Because of environmental challenges such as pollution and global warming, renewable and biodegradable materials have been brought into the manufacturing sector as eco-friendly materials for health and the environment. According to Wang *et al.,* [14], natural fiber materials are used as key material fillers in the automotive, sports equipment, aeronautics, marine, and even building sectors. Organic and inorganic fiber are the two types of natural fiber. Organic fiber is often derived from living things like plants and animals, whereas inorganic fiber comprises mineral fibers. Various countries use various organic fibers in their industrial goods, occasionally importing or exporting them to other places. Jute and kenaf from India and Bangladesh were needed by European countries, as well as banana from the Philippines and sisal from South Africa, the United States, and Brazil. Flax fiber is the most often used fiber in automobile manufacture in Germany. Figure 2 depicts the percentage of natural fiber utilization in the European automotive sector, with wood accounting for 37%, cotton 25%, flax 18%, kenaf 7%, hemp 5%, and other fibers 8%.

ABS and PLA are the most common polymers used as the primary material in FDM. They are consistent in the printing of products and specimens. According to Petchwattana *et al.,* [16], the benefits of employing PLA include the fact that it is recyclable and biodegradable, with a temperature range of 145-160°C. Tuan Rahim *et al.,* [17] also confirmed that a 1.75 mm size of filament with a tolerance of 0.01 mm is superior in the FDM printing process. The tolerance provides for major difficulties that may develop during maintenance. Such as, smaller diameter of filament size, might cause the gripping filament in the extrusion to fail, but a filament too large for the nozzle will not be forced out by the servo motor. Table 1 shows some of researchers have printed specimens and functional products using natural fiber reinforced composite (NFRC) materials such as ABS-fiberglass [18], PLA-pineapple leaf fiber [19], iron-nylon [20], ABS-carbon fiber [1], ABS-oil palm fiber [21], and PLA-wood dusk [22]. As a result, natural fibers have made a significant contribution to the development of feedstock material for FDM. However, there are several difficulties in the fabrication of the fiber composite filament and throughout the printing process.

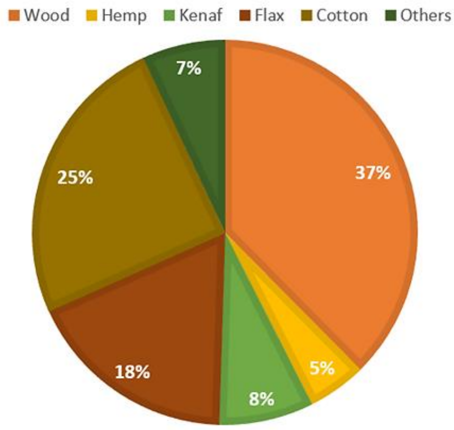

Fig. 2. Percentage of automotive industries in Europe using natural fiber for the year of 2012 [15]

Table 1
Previous studies on natural fiber composite for FDM

Authors	Filler Material	Matrix Material	Parameters	Results
Zhong *et al.,* [18]	Glass fiber	ABS	Composition: 30wt% FDM: MEM- 250 Multi-functional Parameters: 250 °C and 60 °C nozzle and bed temperature	The tensile strength of an ABS filament was found to be greatly increased by the addition of glass fibers, despite the sacrifice of flexibility and handleability.
Suteja *et al.,* [19]	Pineapple leaf fiber	PLA	Composition: N/A FDM: Prusa I3 Parameters: 205 °C nozzle temperature, 65 °C bed temperature, 0.5mm layer thickness and 100% infill density	The tensile strength of the printed part was increased if adding pineapple leaf fiber as reinforcement.
Ahmad *et al.,* [21]	Oil palm fiber	ABS	Composition: 3wt% FDM: FlashForge, Creator Pro Parameters: 240 °C nozzle temperature, layer thickness (0.2, 0.3, 0.4mm) and printing speed (10, 50, 100 mm/s)	The fiber composites' tensile strength ranged from 0.95 to 35.38 MPa, while their Young's modulus ranged from 0.11 to 1.88 GPa.
Tao *et al.,* [22]	Wood	PLA	Composition: 5wt% FDM: 603S model, Shenzhen Aurora Technology Co., Ltd. Parameter: 210 °C nozzle temperature	The material fracture surface's microstructure was altered by the addition of wood.

4. Rheological Studies on Natural Fiber Composite For FDM

The flow of a fluid is significantly influenced by rheological behavior, which has various implications, especially in the manufacture of fiber reinforced composites, either for Newtonian fluids or non-Newtonian fluids [23]. Some researchers have blended fibers and thermoplastics to create composites, crushed them into granules, and then tested their rheological characteristics using a capillary rheometer. As a result, improving the mechanical properties of fibre reinforced composites above a certain limit by increasing fiber loading would be extremely difficult unless a thorough knowledge of the effects of fibre intensity on rheological characteristics, fiber-matrix interactions during feed stock fabrication, and AM processing is established [24]. Rheology describes the flow and deformation of materials under tension. It is a fundamental principle in chemical engineering and, after particle size distribution, the physicochemical trait that receives the second-highest number of references in engineering research [25]. Capillary rheometer is the simplest and oldest rheology equipment for measuring a fluid's flow via a tube that is significantly length to diameter ratio. Viscosity (η) of the material flow can be calculated by using a power law model as in Eq. (1).

$$\eta = K\gamma^{n-1} \quad (1)$$

where *n* denotes the flow index, *K* the consistency index and γ is shear rate. If *n* is equal to 1 for Newtonian fluid, *n* is in between 0 to 1 for a shear thinning behaviour and *n* is greater than 1 for a shear thickening behaviour. Normally, fiber composite exhibits shear thinning behavior. Therefore, to identify the true shear rate, Rabinowitsch-Mooney and Bagley correction can be applied as in Eq. (2) and Eq. (3) respectively. Consider a one-directional flow of fluid through a circular capillary tube.

$$\dot{\gamma_w} = \left[\frac{3n+1}{4n}\right]\left(\frac{4Q}{\pi R^3}\right) = \left[\frac{3n+1}{4n}\right]\dot{\gamma_a} \quad (2)$$

$$\dot{\gamma_w} = \left[\frac{(\Delta P)R}{2(L+e_oL)}\right] = \left[\frac{\Delta P}{2(\frac{L}{R})+e_o}\right] = \left[\frac{\Delta P-P_o}{2(\frac{L}{R})}\right] \quad (3)$$

where $\dot{\gamma_a}$ is apparent shear rate, $\dot{\gamma_w}$ true shear rate, *Q* is volumetric flow rate, *R* is capillary tube radius, P_o is pressure drop, *L* is capillary tube length and e_o is end correction factor.

The recent rheological analysis of fiber composite for FDM is shown in Table 2. Han *et al.,* [26] investigated the rheology of a Kenaf mixed ABS composite using a melt flow indexer set at 230°C. The study discovered that adding 2.5% Kenaf - ABS lowered the value of MFI, but adding 5% Kenaf - ABS enhanced the value of MFI. As the filler loading increased, the MFI values of the composites rose. The inclusion of Kenaf fiber hindered the flowability of the ABS matrix. This result was consistent with the findings of Ahmad *et al.,* [27], who conducted a rheology investigation on an oil palm fiber composite. He discovered that adding 3, 5, or 7 wt percent oil palm fiber improved the shear thinning effect. The composites' non-Newtonian index (n) rose as the number of shear rates increased, demonstrating that fiber loading or weight fraction had a major influence on rheological behaviour. The viscosity and shear stress results rose as the fiber loading increased.

Meanwhile, Nair *et al.,* [28] reported that PS-sisal composites have the opposite trend, with the viscosity increasing with temperature. At higher temperatures, this might be owing to greater contact between fibers and polymer molecules. At lower temperatures, higher wall-slip due to the presence of longitudinally distributed fibers along the wall-melt interface contributes to this impact. It was discovered that the sisal-filled PS composite had a lower flow behavior index than plain PS at a certain temperature, indicating that the composite had a higher degree of pseudoplasticity. Rotational rheometer was used by Arrigo and Frache [29] to analyse the flow characteristics of hemp fiber/PLA composite. They discovered that the viscosity rapidly increased at zero shear circumstances and rapidly decreased at high shear rates during the flow through the nozzle.

Table 2
Recent studies on rheological properties of fiber composite for FDM

Authors	Filler Material	Matrix Material	Parameters	Results
Han *et al.,* [26]	Kenaf fiber	ABS	Composition: 0, 2.5 and 5wt% Machine: melt flow indexer (Ray Ran) Die temperature: 230 °C Shear rate: 200, 400, 600, 800, and 1000 s^{-1}	The MFI values of the composites increased as the filler loading increased.
Ahmad *et al.,* [27]	Oil palm fiber	ABS	Composition: 0, 3, 5 and 7wt% Machine: Instron capillary rheometer (model SR20) L/D ratio: 5:1 Die temperature: 220, 230 and 240 °C Shear rate: 200, 400, 600, 800, and 1000 s^{-1}	As the fiber loading increased, the viscosity and shear stress values increased as well.
Nair *et al.,* [28]	Sisal fiber	PS	Composition: 10, 20 and 30wt% Machine: Instron capillary rheometer (model 3211) L/D ratio: 40:52 Die temperature: 180 and 190 °C Shear rate: 54, 541 and 1804 s^{-1}	The viscosity of the sisal composite increases with temperature.
Arrigo and Frache [29]	Hemp fiber	PLA	Machine: Rotational rheometer (TA Instrument) Temperature setting: 200 °C Frequency: 0.1-100 rad/s	Low viscosity values during the flow through the nozzle at high shear rates, and a rapid increase in the viscosity at zero-shear conditions.

5. Conclusions

In conclusion, rheology research is crucial to understanding the flow characteristics of fiber composite materials and identifying the ideal melting point for the extrusion process that creates wire filament. The benefits of these research in producing the composite filaments needed for the FDM process. Knowing how this composite polymer responds to changes in time and temperature can help with filament development by ensuring that inclusions are distributed properly in the matrix material with the appropriate volume fraction. According to prior research, less has been studied on the rheology of specially designed composite filament for FDM. Therefore, it is evident that studying the rheology of composite filament before printing or manufacturing processes is important. The proper extrusion temperature, viscosity, and shear rate for various fiber fractions may be determined through rheological study. Therefore, the latest research on the rheological characteristics of fiber-reinforced thermoplastic composite for FDM has been reviewed in this study.

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