A VISUAL INVESTIGATION OF THE EFFECTS OF PRINTING TEMPERATURE AND THE PRESENCE OF KENAF FIBERS IN FUSED DEPOSITION MODELING 3D PRINTING

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ABSTRACT: The printing temperature is crucial for producing high-quality parts in fused deposition modeling 3D printing. Filament properties are influenced by material composition, with fibers increasing polymer viscosity and altering raw polymer properties. This paper investigates the effect of printing temperature on kenaf fiber-reinforced ABS filament. The dimensional accuracy of printed parts was measured using a coordinate measurement machine in three directions, with eight geometries analyzed for both 100% ABS and 7.5% kenaf fiber reinforced composite kids' building blocks. Results indicated that a higher nozzle temperature (245 °C) produced poor quality, while a slightly lower temperature (215 °C) yielded better results. Lower platform temperature (95 °C) caused warping, while higher platform temperature (105 °C) resulted in elephant foot at the edges of the printed block. An optimal platform temperature of 100 °C, reaching the composite's glass transition temperature, solidified the filament with good quality. In summary, proper characterization of filament material properties is essential to set the appropriate printing temperature.

KEYWORDS: *Fused Deposition Modeling; 3D printing; Fiber Reinforced Polymer Composite*

1.0 INTRODUCTION

Fused Deposition Modeling (FDM) is one of the technologies in additive manufacturing that applies the thermal extrusion technique to fabricate an object by depositing filament through a heated nozzle that can move along X, Y, and Z directions above the heated platform. Initially, a roll of thermoplastic filament on a spool is prepared by acknowledging its thermal properties, such as melt and glass transition temperatures. These important parameters are useful for the operators to set the printing temperature and printing speed to adequately satisfy the characteristics of the material. Next, the filament is fed into a temperature-controlled nozzle head with the desired diameter and heated to a semi-liquid state. Generally, if the material of the filament is adequately heated, the deposited material will be extruded smoothly without any interruption. The deposited material is laid on the heated platform to form a horizontal thin layer according to the stereolithography (STL) file that programmed the nozzle movement. The material solidifies before the next layer, laminating the preceding layer and confirming the bond of each layer. This process is repeated until the scaffold is complete. Hence, the construction of the object is based on the built stacked layers according to the computer-aided design (CAD). The FDM technique is illustrated in Figure 1.

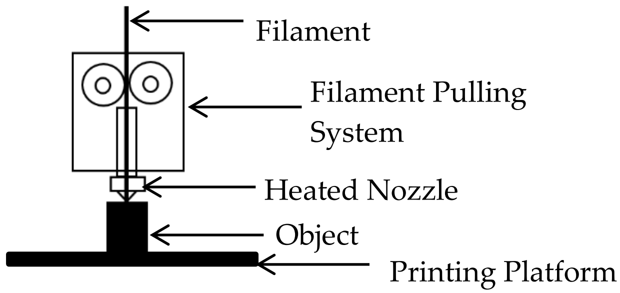


Figure 1: Technique of Fused Filament Fabrication.

Generally, the filament material is chosen from a group of thermoplastic polymers, which can be cooled and heated repeatedly without any change in its properties. Acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyamide (PA), polycarbonate (PC), and high-impact polystyrene (HIPS) are the most common materials used as filament for FDM [1]. ABS has been used widely in various applications, offering excellent material properties such as good tensile strength, fast solidification, impact resistance, resistance to chemicals, and machinability. Moreover, the low melting temperature and low price of ABS have made it a better selection of material for FDM. F. Cerdas et al. [2] stated that ABS is cheaper and tolerable with higher temperatures, but it is harmful as it will produce dangerous fumes and may affect human health. J. Milde et al. [3] reviewed that ABS has many advantages: excellent toughness, manufacturability, good chemical resistance, good dimensional and geometrical stability, and low cost. Certain applications require better strength of the material, which led to the development of ABS composite. Natural and synthetic fibers are compounded as reinforced materials in ABS filament to produce superior material properties for ABS. Fibers such as rice straw, coir fibers and kenaf have been studied as natural fiber reinforced materials in ABS filament, where they showed better strength with the contents of 2.5-30% of fibers [4]. However, it has been found that the fabrication of parts using FDM 3D printing from fiber reinforced polymer composite has raised some challenges. Past researchers have studied and investigated the challenges, which are summarized in the next section. In this study, a physical investigation of the effect of printing temperature and the presence of kenaf fiber as reinforced material in ABS composite is presented. Until now, no studies have been related to natural fiber reinforced ABS polymer composites in the 3D printing research area. Moreover, several studies have been done by the part researchers that focused more on the mechanical strength and other technical performance of the composites. Therefore, this study is conducted to investigate the physical and visual appearance of the 3D-printed composite part. The printing process parameter is set up based on previous studies [5-7].

1.1 Factors Affecting the Quality of Printed Objects

Printing Process Parameter

Initially, operators need to identify the material properties of the filament to obtain good quality of the fabricated object. FDM 3D printer operates with a principle of thermal extrusion where the material must be in a perfect semi-liquid state at the right thermal processing parameters such as nozzle temperature, ambient temperature, and platform temperature and able to be properly extruded. Different polymers have different chemical compositions that will result in diverse desired printing temperatures [8]. Glass transition temperature is an important material property for the filament of FDM 3D printing. Information on the glass transition temperature of the materials is highly desirable, as the operator will know at which level of temperature the filament material is able to change its phase from crystalline to liquid state without damaging its integrity. Improper set-up of thermal processing parameters would affect the mechanical and physical properties of the fabricated object [9]. Additionally, incorporating natural fibers into the raw polymer can deteriorate the polymer's thermal properties, and the fibers exposed to elevated temperatures may suffer from a degradation in their structural integrity. Consequently, it is crucial to optimize the printing temperature to avoid defects in the printed components. Therefore, with the reinforcement of fibers in polymer filament of FDM 3D printing, a varied range of printing parameters are required with specific values to ensure the quality part is fabricated.

Nozzle Clogging

Fibers as reinforcing materials in polymer filaments of FDM 3D printing have been studied by many researchers to add variety to the material of filaments and investigate the compatibility of the materials with the FDM 3D printing principle. Successful development of fiber reinforced polymer filament has been achieved by many manufacturers such as Markforged, 3DXTech, and eSun, and the filaments are readily available on the market. However, when the fibers are added to the polymer matrix, the whole properties of the polymer are changed, and the printing process parameter needs to be reset. Improper preparation of fiber-reinforced polymer composite filament of FDM 3D printing can cause nozzle clogging, and a poorly printed object will be produced. The presence of fibers in the polymer increases the brittleness and decreases the toughness of the materials [10]. This condition would make the filament easily break and melt inside the nozzle before being deposited. Moreover, a weak interfacial bonding condition between the fibers and molecules of the polymer matrix would cause fiber separation. Consequently, the fibers are pulled out and agglomerated inside the nozzle. Both conditions can cause a physical blockage caused by the accumulation of residues at the critical region, the nozzle orifice. In addition, FDM 3D printing can operate well with a composite that contains up to 40% of filler, and more than 40% of fillers can cause nozzle clogging [11]. In nature, the addition of fibers as reinforced material in a polymer matrix would increase the viscosity of the polymer, and excessive amounts of fibers can resist its flow. Moreover, insufficient force in the feeding system can cause nozzle clogging where the machine design cannot sufficiently process the polymer composite. Therefore, it is important to prepare the composite filament properly with consideration of fiber modification to ensure the strong bonding condition of the fibers and molecule of the matrix occurred and reduce the risk of nozzle clogging during the FDM 3D printing process.

2.0 MATERIALS AND METHODOLOGY

2.1 Materials

In this study, 7.5 wt.% of kenaf fiber reinforced with ABS (7.5KRABS) filament was used in FDM 3D printing as a case study. Kenaf fiber reinforced ABS filament was prepared previously [5] using a twin-screw extruder with a diameter of 1.75 mm. The average length of the kenaf fibers was 120 μm. Glass transition temperature and melt temperature of the composite were 100.97 °C and 220.97 °C, respectively. The material properties of the 7.5KRABS and ABS are summarized in Table 1.

Table 1: Material Properties of 7.5KRABS and ABS.

Properties	7.5KRABS	ABS
Tensile strength	13.42 MPa	23.2 MPa
Tensile modulus	205.11 MPa	328.17 MPa
Flexural strength	27.00 MPa	40.56 MPa
Flexural modulus	78.33 MPa	113.05 MPa
Glass transition temperature	100.97 °C	108.46 °C
Melt temperature	220.97 °C	213.67 °C

2.2 Printing Process

FlashForge Creator Pro 3D Printer is used in this study. The printer was equipped with a nozzle diameter of 0.4 mm, suitable for a 1.75 mm filament. The process parameters set up for the printing process are shown in Table 2.

Table 2: Printing Process Parameters.

Material	Resolution	Temperature		Infill		Speed	
7.5 KRABS	High	Extruder	215°C	Density	15%	Print	50mm/s
	Brim	Bed	100°C	Pattern	Hexagon	Travel	70mm/s

The design of the kids' building block was taken as a case study. The kids' building blocks were fabricated using a 3D printer with 100 wt.% ABS (100ABS) filament and 7.5KRABS composite filament with dimensions of (32 x 32 x 23.75) mm. This object was chosen to measure the accuracy of the printed object and analyze the possible printing defects that may occur in the final object. The dimensional accuracy of the printed object was measured using the ZEISS Duramax Coordinate Measurement Machine (CMM) to measure the geometry in the X, Y, and Z axes using a touch-trigger probe. The geometry of the 100ABS kids' building block and the 7.5KRABS composite kids' building block was measured to observe the dimensional difference between these two types of materials. The dimensional measurements were taken from eight geometries, as shown in Figure 2. Numbers labelled in Figure 2 are referred to as measurement parts.

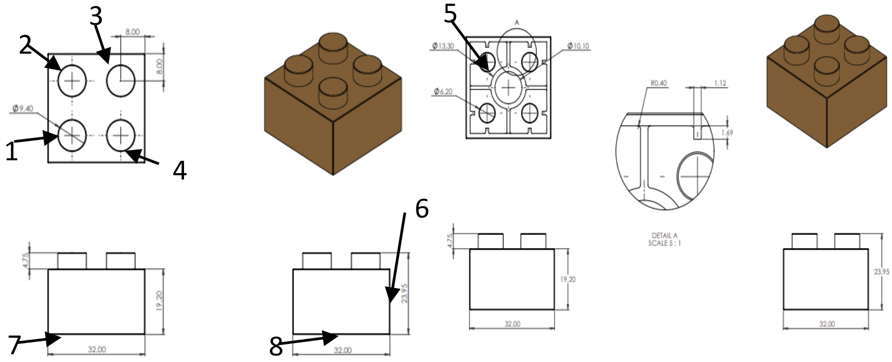


Figure 2: Drawing of kid's building blocks.

3.0 RESULTS AND DISCUSSION

3.1 The dimension measurement of CMM

The kids' building block was printed with two different materials, 100ABS polymer and 7.5KRABS composite, as shown in Figure 3. The printed parts were well connected and able to achieve the product function.

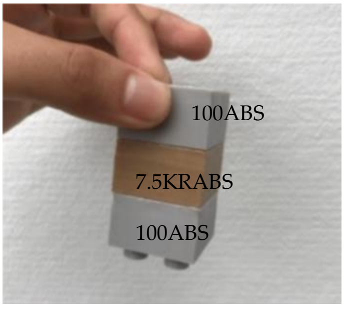


Figure 3: FDM 3D printed kids' building blocks.

In dimension measurement using CMM, the values were obtained in Table 3, where the measurement parts were identified in Figure 2. A comparison was made between the actual drawing dimension, 100ABS, and 7.5KRABS kids' building blocks. Eight dimensions were taken to evaluate the accuracy of the printed blocks. Relative error was used to measure the difference between the actual dimension from the drawing and the dimension of the printed part. The measurement of 100ABS had less error compared to 7.5KRABS. The minimum error was the height (H) measurement for 100ABS and 7.5KRABS, which were 0.051% and 0.16%, respectively. The maximum errors occurred on the dimension of circle 5 (D5), which were 1.667% and 1.902% for both 100ABS and 7.5KRABS, respectively. On average, the 3D printer had fabricated 100ABS kids' building blocks with 0.754% error and 7.5KRABS composite kids' building blocks with 0.879% error. Based on the results, the errors did not significantly affect the geometry and accuracy of the design. Therefore, the results also supported that the blocks were interconnected and reached their product function.

Table 3: Dimension measurement using CMM.

No. Item	Dimension	Drawing (mm)	100ABS (mm)	Error %	7.5KRABS (mm)	Error %
1	Diameter of circle 1	9.400	9.301	1.053	9.260	1.489
2	Diameter of circle 2		9.296	1.106	9.283	1.245
3	Diameter of circle 3		9.295	1.117	9.323	0.819
4	Diameter of circle 4		9.346	0.574	9.308	0.979
5	Diameter of circle 5	13.300	13.078	1.669	13.047	1.902
6	Height	23.750	23.762	0.051	23.788	0.160
7	Breadth	32.000	31.939	0.191	32.069	0.216
8	Length	32.000	31.913	0.272	31.928	0.225

3.2 Printing Defects

The 7.5KRABS composite blocks went through several times of printing processes to obtain the most accurate printed block. Several factors were identified to significantly affect the quality of the printed block. In this study, it was found that the composition of the filament material greatly affected the quality of the printed object. A temperature tower model was built to achieve a suitable melting temperature or nozzle temperature, as shown in Figure 5. A temperature tower is a structural design like a building with several floors or stages. It was used to evaluate the printing quality from layer to layer as the temperature varied on each floor. Based on Figure 5, the temperature started from the highest to the lowest. This temperature tower for 7.5KRABS started at 245 °C with a decrement of 5 °C until it reached 215 °C. Based on the visual inspection, the 7.5KRABS composite temperature tower at 245 to 230 °C showed poor surface quality with poor bridging and produced strings between the towers. Hence, higher nozzle temperature produced less viscous material and created more strings. This happened because the fiber separation occurred inside the composite where the bonding condition of the fibers and molecule of the polymer matrix was weaker with the increased temperature. Besides, a molten blob on the surface increased the surface roughness in high temperatures. It was suggested that the temperature be 225 °C and below for better printing quality. At 220 °C nozzle temperature, the "elephant foot" occurred at every edge of the block.

This problem happened due to improper printing temperature setting. Based on the findings from the temperature tower, 215 °C was chosen as the nozzle temperature; consequently, the molten filament flowed well without any clogging issues. Platform temperature also played a vital role in building this part. Warping can be defined as when the object starts to peel off or curl upward during the 3D printing process. Lower platform temperature would cause the part to shrink. Therefore, the platform temperature was varied to obtain the most suitable temperature for printing the 7.5KRABS composite. Table 4 shows the various platform temperatures against constant nozzle temperature and the result of the printed block. Based on the results, at a platform temperature of 105 °C, elephant foot occurred at the bottom of the block. Next, the platform temperature decreased to 100 °C, resulting in fine quality of the block and well stickiness on the platform. It showed that the platform temperature met the glass transition temperature of the composite.

To explore more, a 95 °C platform temperature was set up, and unfortunately, the brim curled upward and peeled off from the platform before the product reached 100% construction. Hence, the higher platform temperature produced elephant foot on the part, and the lower platform temperature warped the part.

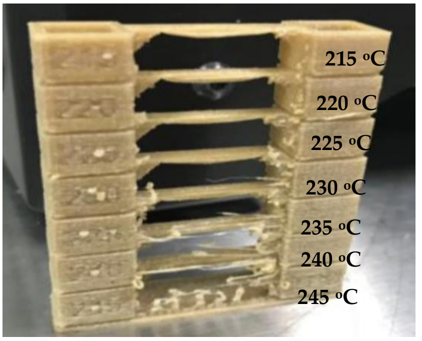
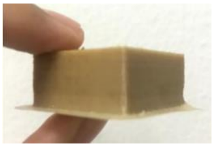


Figure 5: Temperature tower.

Table 4: Physical effect of platform temperature.

Description	Elephant Foot	No Major Defect	Warping
Physical Effect			
Platform Temperature (°C)	105	100	90
Nozzle Temperature (°C)	215		

The filament was placed inside the extruder and passed through the drive wheels. The drive wheels were a pair of rollers and gear that helped pull the filament downward. The gap between roller and gear for Flashforge Creator Pro was about one filament size of 1.75 mm. The gap between the roller and the gear was controlled by a stiff spring. Then, the filament was heated by the required temperature and put into a PTFE Teflon tube with an inner diameter of 2 mm. Finally, molten filament flowed through a 0.4 mm nozzle orifice onto the platform. As expected, nozzle clogging happened due to fibers agglomeration at the nozzle orifice during printing. This problem could not occur if the fibers and ABS matrix had strong interfacial bonding strength. A study suggested modifying the fibers before blending them with the ABS matrix [12]. Fiber modification can be performed using chemical, physical, or biological modification methods. Chemical modification is the most common method for natural fiber surface treatment, where alkaline and silane are used to remove impurities and clean the fiber's surface. A chemical solution like alkaline and silane can decrease the inherent hydrophilic behavior of the natural fiber and consequently improve the interfacial bonding condition of the matrix and fibers. In nature, natural fiber possesses hydrophilic behavior and polymer matrix possesses hydrophobic behavior, resulting in weak interfacial bonding conditions of the resultant composite. Consequently, poor mechanical properties were exhibited from the composite with weak interfacial bonding conditions of fibers and matrix. Ahmad et al. [13] showed a study that resulted in better mechanical properties of oil palm fiber/ABS composite as the fibers were treated with NaOH during the fiber preparation process for filament FDM. Huang et al. [14] also stated that modification of wood dust with the binding agent, maleic anhydride enhanced the mechanical properties of the thermoplastic polymers used for FDM.

4.0 CONCLUSION

In conclusion, this study found that printing temperature significantly affected 3D printed parts, indicating the need to carefully determine this parameter before printing. Additionally, the inclusion of kenaf fibers in FDM filament did not significantly affect the physical performance of the 3D-printed parts. Therefore, it can be assumed that natural fiber composites could serve as substitute materials for FDM filament, as they are compatible with the 3D printing process and comparable to traditional filament materials. Kids' building blocks printed from 100ABS filament and 7.5KRABS filament were used as a case study. The blocks from both materials showed good accuracy, were well interconnected, and achieved the product function. Based on the dimensional accuracy, on average, the 100ABS block obtained a 0.754% error, and the 7.5KRABS composite block obtained a 0.879% error. Neither error significantly affected the geometry of the printed blocks. Printing defects were found in the physical investigation of the effect of printing, temperature, and the presence of fibers in the filament material. A higher nozzle temperature (245 °C), above the composite's melt temperature, produced poor quality and a temperature (215 °C) that was slightly lower than the melt temperature (220.97 °C) produced better quality. Moreover, a lower platform temperature (95 °C) caused warping, and a higher platform temperature (105 °C) caused elephant foot at the edges of the printed block. Hence, printing defects and nozzle clogging could be avoided by proper characterization of the thermal properties of the material, as the presence of fibers significantly influenced the quality of the printed object. Further investigation should be conducted with different fiber loadings and sizes to study the influence of both parameters.

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AUTHOR CONTRIBUTIONS

C.H. Hazliza: Methodology, Software, Writing- Original Draft Preparation; M.T. Mastura: Validation, Supervision; M. Noryani: Data Verification; S.I. Abdul Kudus: Conceptualization, and editing; M. Farhan: Editing and Data Analysis

CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest on the manuscript.

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