© Universiti Tun Hussein Onn Malaysia Publisher's Office

JAMEA

http://penerbit.uthm.edu.my/ojs/index.php/jamea

e-ISSN : 2716-6201

Journal of Advanced Mechanical Engineering Applications

A Brief Review of Factors Affecting the Mechanical Properties of Fused Deposition Modelling Part

M. N Sudin[1,2*], S. A Shamsuddin[1,2], F. R Ramli[1,2], N. Md Daud[1,2]

[1]Faculty of Mechanical Engineering,
Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, Durian Tunggal, 76100, Melaka, MALAYSIA

[2]Centre for Advanced Research on Energy (CARe),
Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, Durian Tunggal, 76100, Melaka, MALAYSIA

*Corresponding Author

DOI: https://doi.org/10.30880/jamea.2022.03.02.001
Received 02 September 2021; Accepted 17 October 2022; Available online 13 December 2022

Abstract: The mechanical properties of fused deposition modelling (FDM) parts are the most common indicator in defining their potential for a specific application. The reason for the low strength of FDM printed parts is that they are not as strong as their conventionally manufactured counterparts. It is an anisotropic characteristic due to the voids between the deposition lines and the low strength of the thermoplastic material. This paper reviews the factors influencing the mechanical properties of FDM parts from various aspects, including the development of new materials such as FDM filament, process parameter optimization, process parameter adjustment, and other methods for achieving better mechanical properties of FDM parts. The results pointed out that the FDM applications are limited by the material available for filament feedstock and the nature of the FDM process that introduces voids between lines. In addition, the review showed that most research conducted on FDM parameters is about the cause-and-effect relationship but lacks research to relate this effect to the microstructure and mesostructure of FDM parts as well as the mechanism that controls the bonding strength of the part.

Keywords: Fused deposition modelling (FDM), additive manufacturing

1. Introduction

Additive manufacturing (AM) technologies have been developed to fabricate products in a short amount of time. Desktop 3D printing, also known as additive layer manufacturing technology, is a popular method for fabricating three-dimensional (3D) objects. The technique of 3D printing allows rapid prototyping of complex digital design models. Technically, this method converts 3D digital CAD data into a physical product without any intermediate steps.

Fused deposition modelling (FDM) is an AM technique that layers semi-molten plastic filament onto a platform from the bottom up. It is among the most widely adopted and applied AM techniques for producing plastic parts due to its low cost, low waste, and ease of material change [1]. Parts can be produced quickly using FDM by depositing fused layers of material through an extrusion head with a specific toolpath and a numerically defined cross-sectional geometry. Thermal fusion is the process by which a material is bonded to an adjacent material and solidified.

Unfortunately, because of the anisotropic nature of layer-by-layer deposition, FDM-printed parts are weaker than molded parts [2]. Acrylonitrile butadiene styrene (ABS), Polycarbonate (PC), Polylactic acid (PLA), Polyamide (PA), and mixtures of two thermoplastic materials are among the most common thermoplastic materials used as FDM filaments [3-4]. Various process parameters contribute to the low strength of FDM printed parts. The parameters, in this case, are the raster angle, part raster width, and the air gap [5].

*Corresponding author: nizamsudin@utem.edu.my
2022 UTHM Publisher. All right reserved.

FDM is a promising manufacturing technique that has the potential to produce complex parts quickly and efficiently. On the other hand, FDM prototypes lack the isotropic and robust mechanical properties required for mass production. To overcome this limitation, FDM-fabricated parts must be strengthened. This paper aims to examine the relationship between FDM process parameters, material, temperature, and the mechanical properties of FDM parts. Furthermore, this study also examines the current state of FDM research and identifies areas that require further investigation.

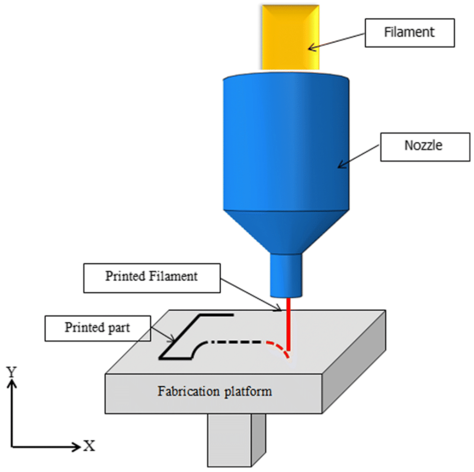

Fig. 1 - A schematic drawing of FDM printing

1.1 Regular FDM Process Parameters and Definition

Popescu et al. [6] classified FDM process parameters into three categories, namely slicing parameters, building orientation and temperature conditions (Table 1).

Table 1 - Category of FDM process parameters

Category	Parameter
Slicing parameters	Layer thickness/height, nozzle diameter/bead/road width, flow rate, deposition speed, infill rate, infill pattern, raster orientation/angle, raster pattern, raster gap, air gaps (raster to raster, perimeter to raster), number of contours/perimeters (contour width), top thickness, bottom thickness.
Building orientation	Horizontally, vertically, or laterally, but other orientations can also be used.
Temperature conditions	Environment (or envelope) temperature, extrusion temperature, bed, or platform temperature.

The quality and performance of the printed parts depend on the choice of these process parameters and the definition of process parameters are given as follows:

i. Raster/bead/road/layer/fiber orientation or angle (Fig. 2): Refer to the angle between the track of the filament and the x-axis (typically load direction) of the platform.

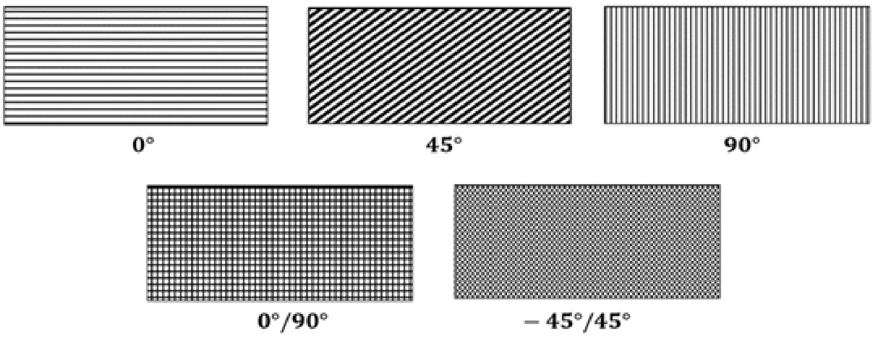

Fig. 2 - Raster orientation [7]

ii. Orientation/part build orientation (Fig. 3): Refers to the direction of the part built on the platform concerning the X, Y, and Z axis, where the X and Y-axis are considered parallel to the build platform, and the Z-axis is along the direction of the part build [7].

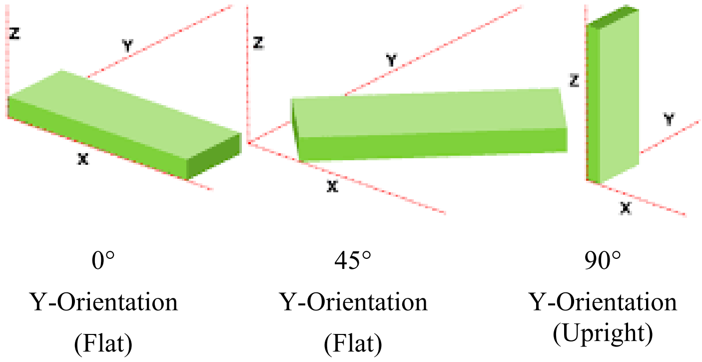

Fig. 3 - Build orientation [8]

iii. Layer thickness/layer height (Fig. 4): Refer to the thickness of the layer deposited by the nozzle and depends upon the type of nozzle used [7].

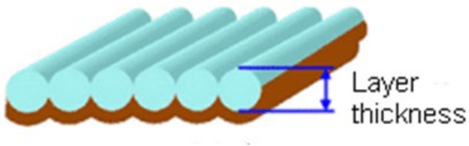

Fig. 4 - Layer thickness [9]

iv. The number of contours/outlines/external perimeters/shell (Fig. 5): This refers to the number of closed rasters deposited along the edge of the part. [7].

v. Part raster width/raster width (Fig. 5): Refers to the width of the bead/road for rasters that rely on the nozzle size. [7].

vi. Raster to raster gap (air gap) (Fig. 5): Refers to the distance between adjacent rasters on the same layer [7].

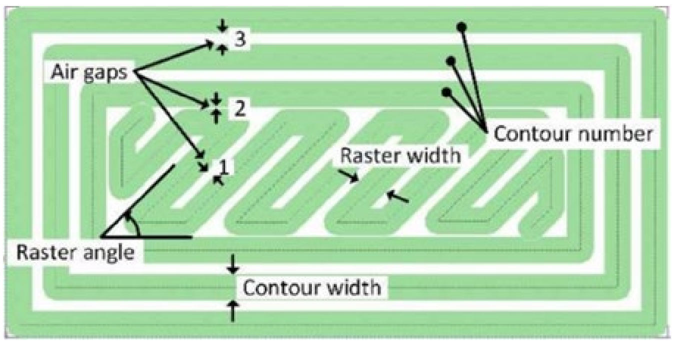

Fig. 5 - Slicing parameters [10]

vii. Infill pattern/print pattern (Fig. 6): Refers to how the filament fills the printed area. Different infill patterns are used in parts to produce a strong and durable internal structure. Hexagonal, diamond, and linear are commonly used infill patterns [7].

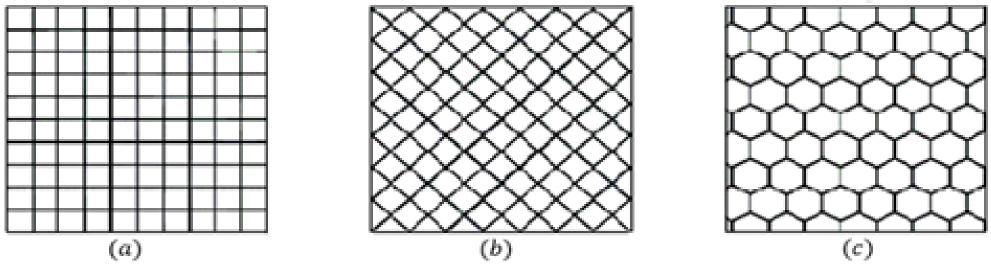

Fig. 6 - Infill pattern [11]

viii. Infill density/percentage/ratio (Fig. 7): The amount of material is filled in the part or product. It shows the degree of solidness and is also related to the strength of the part or product manufactured by the 3D printing process [7].

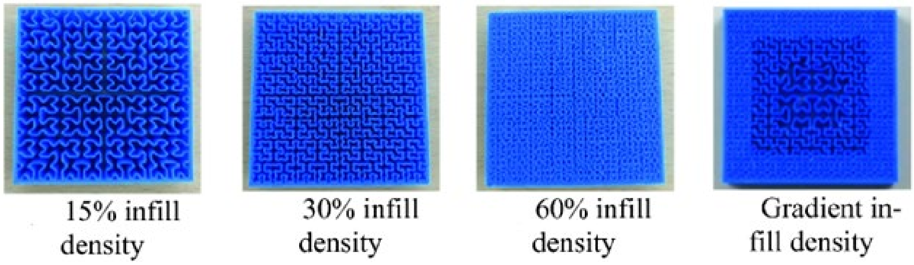

Fig. 7 - Infill density [12]

ix. Extrusion temperature: The temperature at which the filament of material is heated during the FDM process. Extrusion temperature depends on various aspects, for example, the type of material or print speed [7].
x. Print speed: The distance travelled by the extruder along the XY plane per unit of time while extruding. Printing time depends on print speed measured in mm/s [7].

2. Mechanical Properties of FDM Printed Part

It is crucial to determine the mechanical properties of the FDM part to ensure it can be used to produce functional components. Amongst the key mechanical properties evaluated concerning the influence of the FDM process parameters are tensile, compressive, bend and impact strength. The mechanical properties of FDM plastic parts should meet service loading and operational requirements and be comparable to parts produced using the molding technique. Compared to conventional manufacturing processes, the mechanical properties of the FDM part are dependent on structural and process parameters rather than solely on material properties [13]. Therefore, an investigation into the effect of FDM process parameters on FDM mechanical properties is one of the key research focuses in the FDM study.

2.1 Effect of Process Parameters on Mechanical Properties

Today, the application of material extrusion processes, such as FDM, in aerospace, biomedical science, and other industries has become common. This application is due to the ease of access to production-grade thermoplastic polymer materials and their potential to produce complex shaped parts without tooling requirements or human interface [5]. This demand has increased the concern about its mechanical properties, particularly for functional parts. In practice, a functional part is subjected to different types of loads. Therefore, mutual responses of process parameters need to be optimized synchronously. To address this issue, the influence of process parameters viz., layer thickness, orientation, raster angle, raster width, and air gap for multiple responses; tensile, bending, and impact strength was investigated by Sood et al. [14]. They observed that all these factors significantly influence the responses.

As compared to some conventional manufacturing processes, AM part properties rely on both structural and process parameters rather than only on material properties [13]. Dudescu and Racz [13] assessed the influence of the process parameters on mechanical properties (i.e. tensile stress, tensile strain and Young's Modulus) of printed specimens by considering different raster orientations, infill rates and infill patterns. The influence of raster orientation was tested through specimens with different transverse planes. The specimens were printed by placing them at different angles such as 0°, 30°, 45°, and 90°. In addition, specimens with an infill rate varying from 20% to 100% and six different infill patterns were also tested. Dudescu and Racz [13] found that all three investigated process parameters significantly influenced the mechanical properties of ABS specimens. In another study, Wu et al. [15] investigated the influence of layer thickness and raster angle on the mechanical properties of 3D-printed polyether-ether-ketone (PEEK). Samples with three different layer thicknesses (i.e., 200, 300 and 400 μm) and raster angles (i.e., 0°, 30°, and 45°) were built using a 3D printing system. These samples were tested for their tensile, compressive, and bending strengths. The optimal mechanical properties of PEEK samples were found at a layer thickness of 300 μm and a raster angle of 0°.

2.2 Effect of Process Parameters on Tensile Strength

The selection of proper parameters is crucial to improve manufacturing solutions for the FDM process. Durgun and Ertan [16] examined the tensile strength and flexural strength of FDM parts for different build orientations and raster angles. They discovered that build orientation influenced surface roughness and mechanical behavior more than raster angle [16] or, in particular, on the tensile and flexural strength [17] and the tensile and compressive strength [18]. The tensile and compressive strengths decreased with increasing build orientation from 0° to 90°. In both cases, the 0° orientation gave the maximum strength, while the strength achieved from 90° orientations was the minimum. Nevertheless, the results of Savvakis et al. [19] on how build orientation affects tensile strength are contradicted by those from other studies [16-18]. The authors found that the build orientation does not significantly influence the tensile strength of the parts, although the FDM part is anisotropic in nature. In addition, these authors also found an inverse relationship between layer thickness and tensile strength. According to Afrose et al. [20], the maximum tensile stress is exhibited by parts printed in X orientation. It was in the range of 60-64% of the injection molded part compared to the part built in Y and 45° orientations.

The mechanical properties of FDM specimens are influenced by raster orientation, which is directly related to build orientation [21]. Letcher et al. [22] studied the mechanical properties of ABS-printed parts for various layer numbers, thicknesses, and raster orientations. Specimens were printed at raster orientation angles of 0°, 45°, and 90°. A layer thickness of 0.2 mm was chosen to print specimens from a single layer up to 35 layers. Samples were tested using an MTS Universal Testing Machine with an extensometer to determine mechanical strength characteristics such as modulus of elasticity, ultimate tensile strength, maximum force, and maximum elongation as the number of layers increased. Results showed that 0° raster orientation yields the highest mechanical properties compared to 45° and 90° at each individual layer. A linear relationship was found between the number of layers and the maximum force for all three orientations. In other words, the maximum force required to break specimens linearly increased as the number of layers increased. Meanwhile, the elastic modulus and maximum stress increased as the number of layers increased, up to almost 12 layers. However, for samples with more than 12 layers, the elastic modulus and maximum stress are still increased, but at a slower rate. This result is in line with Christiyan et al. [23] and Savvakis et al. [19] in their research studies about the correlation between layer thickness and tensile strength.

The mechanical properties can be improved by studying the various FDM parameters and using new materials [24]. Camargo et al. [24] studied the mechanical properties, tensile strength, flexural strength, and impact energy of PLA-graphene parts fabricated with FDM technology. The infill pattern and layer thickness were varied, while the build orientation (flat) and infill pattern (honeycomb) were maintained. They found that the mechanical properties increased as the layer thickness increased. The tensile strength and flexural strength increased as the infill density increased, while impact energy decreased. According to Dawoud et al. [25], an adequate selection of FDM parameters can achieve mechanical properties comparable to injection molded parts for both static and dynamic loading. Thus, Dawoud et al. [25] investigated the effects of raster angle and raster gap on the mechanical behavior of ABS printed parts. They found a negative raster gap is more significant in enhancing mechanical behavior, and a raster angle of 45°/+45° (Fig. 7) produced the maximum tensile and impact strength. The highest flexural strength was recorded for a 0/90° raster angle. In contrast, a positive gap drastically reduces performance.

Rajpurohit and Dave [26] experimentally investigated the tensile properties of polylactic acid (PLA) parts fabricated using the FDM process. The raster angle was varied from 0° to 90° to study the effect on tensile strength. Further, a part with a crisscross raster angle was also fabricated and compared with the part fabricated with a unidirectional raster angle. The result showed that tensile strength is significantly affected by raster angle. Higher tensile strength is observed at 0° raster angle, and lower tensile strength is observed at 90° raster angle.

Subramaniam et al. [27] investigated the tensile properties of PLA and found the optimum printing parameter combination using a low-cost fused filament printer. Varying values for the two parameters, i.e., raster angle (20°, 40°, 60°) and infill density (20%, 50%, and 80%), have been used. In this study, tensile specimens that combine these two parameters were printed according to the ASTM D638 type 1 standard, with a layer height of 0.1 mm as a constant. Tensile tests on the PLA specimens were conducted to determine the best-suited parameter combination that would result in optimum mechanical properties. Three mechanical properties were analyzed: ultimate tensile strength, elastic modulus, and yield strength. They found that the optimum combination of parameters is 0.1 mm layer height, 40° raster angle, and 80% infill density. The optimum mechanical properties of PLA are 32.93754 MPa for ultimate tensile strength, 807.48931 MPa for elastic modulus, and 26.08234 MPa for yield strength.

An existing FDM system cannot fabricate flexible parts made of soft elastomers due to the filament feed extrusion mechanism restriction. Instead of filament shape, the material in pellet form has a broad range for 3D printing of flexible parts. For instance, ethylene vinyl acetate (EVA) material is widely used to fabricate flexible objects. However, its potential has yet to be explored using the FDM process [28]. Kumar et al. [28] investigated the effect of process parameters on the tensile behavior of flexible specimens of EVA material that had been printed using a customized pellet based FDM system. The effect of process parameters, including barrel temperature, platform temperature, build orientation, raster angle, and the number of contours, was studied on the ultimate tensile strength and percent elongation at break. They found that raster angle affects the tensile behavior of EVA specimens significantly, with the maximum values of ultimate tensile strength and elongation at the break being 8.83 MPa and 522.34%, respectively.

Galeta et al. [29] determined the impact of structure and building orientation on the tensile strength of 3D printed parts and determined the best combination that yields the highest strength. Test samples were prepared with variations of i) internal geometrical structure, ii) longitudinal orientation, and iii) base alignment. The tensile test results revealed that the highest strength was attained when the honeycomb-structured parts were built by orienting them along the Y-axis and aligning them over their thinner bases inside the printer building box. Additionally, analysis of variance revealed that only the main individual factors (structure, orientation, and base) and the interaction of all three are significant, as well.

Fernandez-Vicente et al. [30] evaluated the influence of two variables, i.e., pattern and infill density, on the tensile behavior of 3D printed parts. A series of test pieces with different density characteristics and infill patterns were produced using an open-source 3D printer. The results show that the different printing patterns cause less than 5% variation in maximum tensile strength, although the behavior is similar. The change in infill density determines mainly the tensile strength. The combination of a rectilinear pattern in a 100% infill has higher tensile strength, with a value of 36.4 MPa, which is less than 1% higher than the raw ABS material. Alvarez et al. [31] analyzed the influence of the infill percentage on the mechanical properties of ABS-printed parts. Various infill percentages of tensile strength and Charpy test specimens were printed to characterize this influence, while the other printing parameters were kept constant. Three different results were analyzed for these tests, namely tensile strength, impact resistance, and effective printing time. Based on the findings, the maximum tensile force of 1438 N and tensile stress of 34,57 MPa were obtained by using 100% infill. Besides, the maximum impact resistance of 1,55 J was also achieved with 100% infill. When considering the effective printing time, the data did not recommend printing with an infill range between 50% and 98% because the effective printing time was higher than that with a 100% infill. Also, the tensile strength and impact resistance is smaller.

Setting a suitable combination of FDM process parameters is critical to improving its quality. For instance, the combination of 75% infill density and linear pattern gives the highest tensile strength [32]. In response to this demand, Griffiths et al. [33] optimized the tensile and notched bending properties of the materials used in the FDM process while considering production time and material efficiency. They found that the layer height was insignificant to the mechanical properties of both specimens, but it was critical to the cost control concerning build time and material usage. Thus, the maximum layer height could be used for cost control of the design without affecting its final performance. Using the design of the experiment (DOE), Rayegani and Onwubolu [34] investigated the effect of five important process parameters on the tensile strength of the test specimen: layer thickness, part orientation, raster angle, raster width, and air gap. Using the group method of data handling (GMDH), mathematical models relating the response to the process parameters have been developed. Using differential evolution (DE), optimal process parameters have been found to achieve good strength simultaneously for the response [34].

2.3 Effect of Process Parameters on Flexural Strength

Flexural strength is an important property of every material as it measures the ability to resist deformation under load. Lužanin et al. [35] studied the influence of layer thickness, deposition angle, and infill on the flexural force of FDM specimens of PLA material. The results indicate that layer thickness had a dominant and statistically significant influence on the flexural force [35], in which low layer thickness exhibits maximum flexural strength [23]. In addition, a significant interaction between deposition angle and infill was also found [35]. In more detail, Wu et al. [15] studied the flexural strengths of PEEK samples for various layer thicknesses (i.e., 200, 300 and 400 µm) and raster angles (i.e. 0°, 30° and 45°). They found the optimal mechanical properties, including flexural strength, of PEEK samples, were at a layer thickness of 300 m and a raster angle of 0° [15]. In addition, Christiyan et al. [23] also studied the effect of printing speed on flexural strength. The results indicated that low printing speeds exhibit high flexural strength. Meanwhile, according to Abdullah et al. [36], layer thickness and raster angle affect the flexural strength more than the tensile strength of the test specimen. Camargo et al. [24] found that the flexural strength increased as the infill density increased. In a recent study on the effect of infill patterns on flexural strength, Rajukumar [37] discovered that cubic infill patterns tend to exhibit the highest maximum flexural strength, followed by concentric infill patterns, and zigzag infill patterns tend to have the lowest maximum flexural strength. This research analyzed and compared six distinct infill patterns.

2.4 Effect of Process Parameters on Fatigue Strength

There is very little data presented on the fatigue performance of FDM-processed parts. Afrose et al. [38] investigated the influence of build orientations on the fatigue behavior of FDM parts made of PLA material. Test specimens' three different build orientations (i.e., X, Y, and 45°) were prepared based on the ASTM D638 standard. Later, using a universal testing machine, these parts were cyclically tested at 80, 70, 60, and 50% of their nominal values of ultimate tensile stress. Higher tensile stress is displayed by parts printed in X orientation for static loading. It was in the range of 60-64% of that of its injection molded counterpart as compared to the part built in Y and 45° orientations. In contrast, the results under tensile cyclic loading conditions are different as the parts in 45° build orientation have higher fatigue life than the parts built in X and Y orientations for the same percentage of applied static loads.

Domingo-Espin et al. [39] studied the fatigue response of ABS parts manufactured using FDM. According to a design of experiments (DOE) using the Taguchi methodology, the influence of different building parameters (i.e., layer height, nozzle diameter, infill density, and printing speed) on the lifespan of cylindrical specimens was studied. The same DOE was applied to two sets of specimens using two different infill patterns, rectilinear and honeycomb. The results show that infill density is the most important parameter for both studied patterns. The specimens manufactured with the honeycomb pattern show longer lifespans. According to Padzi et al. [40], 3D-printed parts have a lower fatigue life, which may not be suitable for industrial applications but can be improved by parameter manipulation for low-strength applications. The investigation into fatigue life as measured as a function of the raster angle showed that samples printed at 0°/45°/45° raster angles had a fatigue life of 18,505 cycles, which was longer than the fatigue life seen for samples made at 0° and 0°/90° raster direction angles [41].

2.5 Effect of Temperature on Mechanical Properties

FDM fabricates prototypes by extruding a semi-molten polymer filament through a heated nozzle in a set pattern onto a platform. Once the material is deposited, it cools, solidifies, and bonds with the surrounding materials. The temperature distribution among polymer filaments in the FDM process determines the bonding quality between adjacent tracks and layers, which influences the mechanical properties of the resultant prototypes [42]. During the FDM process, coalescence of the interconnection is achieved through the thermal energy of the deposited material. The achieved coalescence is strongly dependent on the temperature of the material, which is influenced by many factors related to the production process. However, the process parameters influencing this thermal history are often not monitored. Moreover, knowledge of the influence of thermal history on the coalescence of the interconnection between adjacent tracks is still lacking 42].

Gurrala and Regalla [42] investigated the contribution of bonding between the filaments to the strength of the parts manufactured by FDM. A mathematical model for neck growth between cylindrical filaments was derived based on viscous sintering for cylindrical filaments. The theoretical ultimate tensile load was determined from the layer thickness information, and the average final neck size between filaments was predicted. The experimental ultimate tensile load was obtained by a tension test for two different build directions. An agreement of results between theoretical and experimental ultimate tensile load and scanning electron microscope (SEM) photomicrographs of the fracture surface indicated that the strength of the FDM part was primarily due to intra-layer bonding, inter-layer bonding, and neck growth between filaments. They also found that the total time and heat available to the filaments are sufficient to grow necks but not enough to coalesce fully.

In response to Gurrala and Regalla's [42] outcomes, Faes et al. [43] further investigated the influence of inter-layer cooling time on the quasi-static properties of ABS components produced via the FDM process. Uniaxial test samples were built to control inter-layer cooling time by considering the build orientation and the number of parts in the envelope. Tensile tests were executed, and the fracture surfaces were investigated using digital microscopy. An opposite relationship was found for tensile samples constructed in the vertical direction between the inter-layer cooling time and the ultimate tensile strength/elongation at break. Furthermore, they found that the lengthy cooling of the deposited material results in weaker inter-layer bonding. This work proves the impact of inter-layer cooling time on the quasi-static properties of vertically built FDM-ABS components, though a true link with the thermal history is still lacking.

According to Sun et al. [44], the integrity and mechanical properties of the FDM part are ultimately determined by the strength of the filament bonding, which is thermally driven. Thus, Sun et al. [44] investigated the mechanisms that control the bond formation between extruded polymer filaments in the FDM process. The bond quality was assessed by measuring and analyzing changes in the mesostructure and the degree of fusion achieved at the interfaces between the adjection filaments. In addition, they observed the effects of temperature profiles on mesostructures, and mechanical properties of the specimens produced under different processing conditions. In parallel to this experimental work, predictions on the degree of bonding achieved during the filament deposition process were made, where the predictions are based on the thermal analysis of extruded polymer filaments. Experimental results showed that the envelope temperature and variations in the convection coefficient had strong effects on the cooling temperature profile and, subsequently, on the mesostructure and overall quality of the bond strength between adjacent filaments. In addition, they found that the sintering phenomenon had a significant effect on bond formation. However, this phenomenon only occurs for a very short duration, i.e., when the filament's temperature is above the critical sintering temperature. Otherwise, creep deformation was found to dominate changes in the mesostructure [44].

Benwood et al. [45] investigated the possibility of improving the mechanical properties of poly (lactic acid) by modifying or optimizing the thermal conditions of the printing process. Sample models were prepared for a wide range of printing parameters, including bed temperature, melt temperature, and raster angle. The results indicated that, at increased bed temperature, highly beneficial effects were attained. The best results were achieved at 105 °C compared to the reference samples printed at a bed temperature of 60 °C. This is around an 80% improvement in the impact strength, and a significant increase in strength and modulus is also found. In addition, scanning electron microscopy observations confirmed the increased diffusion level between the individual layers of the printed filament, leading to mechanical property improvement.

To enhance the thermal conductivity of FDM filament, Rostom and Dadmun [46] developed graphene-filled PLA as a new polymeric material for FDM filament and linked these changes to thermal evolution during printing, inter-filament voids and mechanical properties of the fabricated samples. The results showed that the graphene filler had improved the thermal conductivity of the filament, thus improving the inter-filament bonding, where the thermal transport improvement led to longer times at elevated temperatures. This results in more inter-filament diffusion of the polymers that manifests as stronger filament-filament interfaces, more robust and isotropic samples, and fewer inter-filament voids. However, the improvement is limited at lower graphene loadings (0.5%) because, at higher loadings, any increase in inter-filament polymer diffusion appears to be slowed by the presence of the graphene sheets. Nevertheless, the results showed that using fillers with high thermal conductivity provides pathways to tailor the thermal transport and thermal profile during printing. Also, it effectively controls heat transfer and offers a rational method to optimize the inter-filament interfaces and structural and mechanical properties of printed structures.

2.6 Effect of FDM Advanced Material on Mechanical Properties

There has been a demanding need to develop cost-effective filaments in FDM machines. Despite its commercial importance, very little work has been reported in developing an alternate solution to ABS-based wire presently used in most FDM machines. Singh and Singh [47] developed a nylon-based wire as an alternative to ABS wire (used as feedstock filament on FDM) without changing any hardware or software of the machines. Aluminium oxide (Al_2O_3) was added to nylon fiber in various proportions as an additive. However, the mechanical properties of the fabricated filament were not better than those of the original equipment manufacturer (OEM) filament. Many researchers have attempted to identify the potential materials for FDM to widen its application. Wu et al. [15] evaluated and compared the mechanical performance of 3D-printed polyether-ether-ketone (PEEK) and ABS parts. The results showed that the average tensile, compressive, and bending strength of PEEK parts were 108%, 114%, and 115% higher than those of ABS parts. However, the modulus of elasticity for both materials was similar. These results indicate that the mechanical properties of PEEK are superior to ABS.

Ning et al. [48] studied the effect of FDM process parameters on the tensile properties of FDM-fabricated carbon fiber-reinforced plastic composite parts. In addition, the fracture interfaces of the parts after tensile testing are observed by a scanning electron microscope to explain material failure modes and reasons. The conclusions were drawn as follows; raster angle of 0/90 exhibited significantly larger tensile strength, Young's modulus, and yield strength than the raster angle of 45/45 since the tensile load was more effectively transferred from outside to carbon fibers by the matrix, as indicated from the fracture interfaces of the CFRP composite parts built at 0/90 raster angle. The potential of polypropylene (PP) as a candidate for the FDM-based 3D printing technique was evaluated by Carneiro et al. [49]. The entire filament production chain was evaluated, starting with the PP pellets, filament production by extrusion, and test sample printing. The main conclusions of this study were: i) given the results obtained with different printing orientations, the adhesion between adjacent filaments is evident but, as expected, the samples are stiffer in the filament direction; ii) the use of fibers as reinforcement is also effective in 3D printing; and (iii) the use of enhanced (fiber reinforced) grades enables the cancellation of the decline in properties.

Meng et al. [50] evaluated the effects of the nanoparticles on the mechanical strength, anisotropy, and thermal properties of the ABS specimens. The authors found that the addition of nanofillers significantly reduced the mechanical anisotropy and improved the mechanical strength and thermostability of the ABS samples fabricated by FDM technology. With the introduction of nano montmorillonite, the tensile and flexural strength of the ABS samples increased by 25.7 and 17.1%, respectively. However, the addition of nano calcium carbonate lowered the mechanical anisotropy of ABS from 42.1 to 23.9% [50]. In addition, the FDM of wood fiber-reinforced biocomposites is linked to mechanical properties that are strongly dependent on printing orientation (0 or 90°) due to fiber anisotropy [51]. Plymill et al. [52] developed an improved and sustainable feedstock material for FDM by reinforcing polylactic acid with graphene and multi-walled carbon nanotubes (MWCNT). Composites with different loadings (i.e., 0.5, 0.2, and 0.1 wt%) of each reinforcement were extruded to generate filament feedstock for FDM. In this study, reinforcements have caused a moderate increase in mechanical properties. Particularly, 0.2 wt% loading of graphene showed a 47% increase in tensile strength, a 17% increase in modulus, and a 12% increase in energy absorbed upon fracture. On the other hand, the 0.1 wt% loading of MWCNT had respective increases of 41%, 16%, and 9% for tensile strength, modulus and energy absorbed upon fracture, with all reinforcement loadings leading to no statistically significant change in the thermal properties or fracture behavior [52].

ABS nanocomposites with organically modified montmorillonite (OMMT) filaments were produced for the FDM 3D printer. Then, the 3D printed samples were evaluated by tensile, flexural, thermal expansion and dynamic mechanical tests. Results have proven that adding 5 wt% OMMT has improved the tensile strength of 3D-printed ABS samples by 43%. The study also found that the addition of OMMT significantly increased the tensile modulus, flexural strength, flexural modulus, and dynamic mechanical storage modulus but decreased the linear thermal expansion ratio [53].

Kuo et al. 54] have successfully prepared thermoplastic starches (TPS) with high processability with a twin-screw extruder. Finally, white, and black filaments of TPS/ABS biomass alloys, with diameters of 1.75 mm, for additive manufacturing (AM) were prepared by a single-screw extruder, and feasibility evaluation for 3D printing applications has been conducted. Experimental results revealed that the physical properties of white and black filaments (i.e. mechanical properties, thermal resistance, flowability, and emissions of volatile organic compounds (VOCs)) are better than commercial ABS filaments. Furthermore, the shaping samples for 3D printing have also been successfully fabricated, and the preliminary result shows the potential of biomass polymeric materials with excellent physical properties and high processability for 3D printing utilization.

Tian et al. [55] proposed a novel 3D printing-based fabrication process of Continuous Fiber Reinforced Thermoplastic Composites (CFRTPCs). Continuous carbon fiber and PLA filament were utilized as reinforcing phase and matrix, respectively. They were simultaneously fed into the FDM 3D printing process to realize the integrated preparation and forming of CFRTPCs. The interfaces and performance of printed composites were systematically studied by analyzing the influence of process parameters on the process temperature and pressure. The multiple interfaces forming mechanism was proposed and used to explain the correlations between process and performance. The content of the printed specimens was controlled by changing the process parameters. When the fiber content reached 27%, the flexural strength of 335 MPa and modulus of 30 GPA were obtained for the printed composite specimens.

3. Summary of the Influence of FDM Parameter on Mechanical Properties

Factor	Studied parameter	Studied output	Effect of parameter on response	References
Slicing parameter/build orientation/temperature condition	Build orientations and raster angles	Tensile and flexural strength	Significant	Durgun and Ertan [16]
	Build orientation	Tensile strength	Insignificant	Savvakis et al. [19]
	Layer number, thickness, and raster orientation	Modulus of elasticity, ultimate tensile strength, maximum force and maximum elongation	Significant	Letcher et al. [22]
	Infill pattern and layer thickness	Tensile strength, flexural strength, and impact energy	Significant	Camargo et al. [24]
	Raster angle and raster gap	Tensile, impact and flexural strength	Significant	Dawoud et al. [25]
	Raster angle	Tensile strength	Significant	Rajpurohit and Dave [26]
	Raster angle and infill density	Tensile properties	Significant	Subramaniam et al. [27]
	Barrel temperature, platform temperature, build orientation, raster angle and number of contours	Tensile behavior	Significant	Kumar et al. [28]
	Infill pattern and build orientation	Tensile strength	Significant	Galeta et al. [29]
	Infill pattern and infill density	Tensile behavior	Significant	Fernandez-Vicente et al. [30]
	Infill percentage	Tensile strength	Significant	Alvarez et al. [31]
	Layer height	Tensile and bending properties	Insignificant	Griffiths et al. [33]
	Layer thickness, part orientation, raster angle, raster width, and air gap	Tensile strength	Significant	Rayegani and Onwubolu [34]

	Layer thickness, deposition angle, and infill on the	Flexural force	Significant	Lužanin et al. [35]
	Layer thickness and raster angle affect the	Flexural strength	Significant	Abdullah et al. [36]
	Build orientations	Fatigue behavior	Significant	Afrose et al. [38]
	Bed temperature, melt temperature, and raster angle	Mechanical properties	Significant	Benwood et al. [45]
Advance material	Carbon fiber-reinforced plastic composite (CFRP)	Tensile strength, Young's modulus, and yield strength	Significant	Ning et al. [48]
	Nanofillers + ABS	mechanical properties	Significant	Meng et al. [50]
	Reinforcement of polylactic acid with graphene and multi-walled carbon nanotubes (MWCNT)	Tensile, flexural, thermal expansion and dynamic mechanical tests	Significant	Plymill et al. [52]
	Continuous Fiber Reinforced Thermoplastic Composites (CFRTPCs).	Flexural strength	Significant	Tian et al. [55]

4. Conclusions

Optimization of process parameters and the development of polymer composite materials are the two primary methods for enhancing the mechanical and tribological properties of FDM-printed parts. As a result of the part orientation, the surface roughness, and mechanical properties of the FDM component were enhanced. The built-up orientation has a substantial effect on the tensile and flexural properties of FDM parts, while reducing manufacturing costs. The thickness of the layer was the most important and statistically significant factor in determining the flexural force. Components with a greater layer thickness exhibited a lower tensile strength, and the raster gap was identified as the most important factor in improving the mechanical behavior of the components. By selecting the proper FDM parameters, it is possible to achieve mechanical properties comparable to injection-molded parts, and these properties can be achieved in either a static or dynamic loading mode. The sintering phenomenon was discovered to have a significant effect on bond formation. However, this influence was only exerted for a very brief time whenever the filament temperature exceeded the critical sintering temperature. The temperature settings are the primary and most direct factor in determining the variation in temperature across a field. The process parameters utilized have a significant impact on the mechanical strength, wear resistance, and surface roughness of FDM-fabricated parts. (1) The tensile strength was significantly greater for the angle [0, 90] than for any other angle. When nanofillers and other filler materials were added to samples of FDM-fabricated ABS, the material's natural mechanical anisotropy was drastically reduced, and the material's mechanical strength and thermostability also improved.

Acknowledgement

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) and the Ministry of Higher Education (Malaysia) for sponsoring this research under the Fundamental Research Grant Scheme-FRGS/2018/FKM-CARE/F00369.

References

[1] S. A. Bill, C. K. Chua, K. F. Leong, and C. S. Lim, "Rapid Prototyping: Principles and Applications (With Companion CD-ROM)", World Scientific Publishing Company. 2010.

[2] O. Ivanova, C.Williams, and T. Campbell, "Additive Manufacturing (AM) and Nanotechnology: Promises and Challenges", Rapid Prototyping Journal, vol. 19, no. 5, pp. 353-364, 2013.

[3] P. F. D. M. Dudek, "FDM 3D Printing Technology in Manufacturing Composite Elements," Archives of Metallurgy and Materials, vol. 58, no. 4, pp. 1415-1418. 2013.

[4] L. Novakova-Marcincinova, J. Novak-Marcincin, J. Barna, and J. Torok, "Special Materials used in FDM Rapid Prototyping Technology Application", In 2012 IEEE 16th International Conference on Intelligent Engineering Systems (INES), pp. 73-76, IEEE, June 2012.

[5] A. K. Sood, A. Equbal, V. Toppo, R. K. Ohdar, and S. S. Mahapatra, "An Investigation on Sliding Wear of FDM

Built Parts", CIRP Journal of Manufacturing Science and Technology, vol. 5, no. 1, pp. 48-54, 2012.

[6] D. Popescu, A. Zapciu, C. Amza, F. Baciu, and R. Marinescu, "FDM Process Parameters Influence over the Mechanical Properties of Polymer Specimens: A review", Polymer Testing, vol. 69, pp. 157-166, 2018.

[7] A. Dey, and N. Yodo, "A Systematic Survey of FDM Process Parameter Optimization and their Influence on Part Characteristics", Journal of Manufacturing and Materials Processing, vol. 3, no. 3, pp. 64, 2019.

[8] S. N. Kamoona, S. H. Masood, and O. A. Mohamed, "Experimental Investigation on Flexural Properties of FDM Processed Nylon 12 Parts Using RSM, In IOP Conference Series: Materials Science and Engineering, vol. 377, no. 1, p. 012137, IOP Publishing, June 2018.

[9] O. A. Mohamed, S. H. Masood, and J. L. Bhowmik, "Experimental Investigations of Process Parameters Influence on Rheological Behavior and Dynamic Mechanical Properties of FDM Manufactured Parts", Materials and Manufacturing Processes, vol. 31, no. 15, pp. 1983-1994, 2016.

[10] A. W. Gebisa, and H. G. Lemu, "Investigating Effects of Fused-Deposition Modeling (FDM) Processing Parameters on Flexural Properties of ULTEM 9085 Using Designed Experiment", Materials, vol. 11, no. 4, pp. 500, 2018.

[11] I. Hamza, and O. M. El Gharad Abdellah, "Experimental optimization of fused deposition modeling process parameters: a Taguchi process approach for dimension and tolerance control", Proceedings of the International Conference on Industrial Engineering and Operations Management, pp. 1-11, 2018.

[12] S. R. Mohan, and S. Simhambhatla, "Fabrication of Gradient Density Components through Extrusion-Based Additive Manufacturing", In Advances in Additive Manufacturing and Joining, Springer, Singapore, pp. 87-101, 2020.

[13] C. Dudescu, and L. Racz, "Effects of Raster Orientation, Infill Rate and Infill Pattern on the Mechanical Properties of 3D Printed Materials", ACTA Universitatis Cibiniensis, vol. 69, no. 1, pp. 23-30. 2017.

[14] A. K. Sood, V. Chaturvedi, S. Datta, and S. S. Mahapatra, "Optimization of Process Parameters in Fused Deposition Modeling using Weighted Principal Component Analysis", Journal of Advanced Manufacturing Systems, vol. 10, no. 02, pp. 241-259, 2011.

[15] W. Wu, P. Geng, G. Li, D. Zhao, H. Zhang, and J. Zhao, "Influence of Layer Thickness and Raster Angle on the Mechanical Properties of 3D-printed PEEK and A Comparative Mechanical Study between PEEK and ABS. Materials, vol. 8, no. 9, pp. 5834-5846, 2015.

[16] I. Durgun, and R. Ertan, "Experimental Investigation of FDM Process for Improvement of Mechanical Properties and Production Cost", Rapid Prototyping Journal, pp. 228-235, 2014.

[17] S. Raut, V. S. Jatti, N. K. Khedkar, and T. P. Singh, "Investigation of the Effect of Built Orientation on Mechanical Properties and Total Cost of FDM Parts" Procedia Materials Science, vol. 6, pp. 1625-1630, 2014.

[18] K. M. Ashtankar, A. M. Kuthe, and B. S. Rathour, "Effect of Build Orientation on Mechanical Properties of Rapid Prototyping (Fused Deposition Modelling) Made Acrylonitrile Butadiene Styrene (ABS) Parts," In ASME 2013 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers Digital Collection, 2013.

[19] K. Savvakis, M. Petousis, A. Vairis, N. Vidakis, and A. T. Bikmeyev, "Experimental Determination of the Tensile Strength of Fused Deposition Modeling Parts," In ASME 2014 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers Digital Collection, November 2014.

[20] M. F. Afrose, S. H. Masood, M. Nikzad, and P. Iovenitti, "Effects of Build Orientations on Tensile Properties of PLA Material Processed by FDM," In Advanced Materials Research, Trans Tech Publications Ltd, vol. 1044, pp. 31-34, 2014.

[21] Ö. Keleş, C. W, Blevins, and K. J. Bowman, "Effect of Build Orientation on the Mechanical Reliability of 3D Printed ABS," Rapid Prototyping Journal, vol. 23, no. 2, pp. 320-328. 2017.

[22] T. Letcher, B. Rankouhi, and S. Javadpour, "Experimental Study of Mechanical Properties of Additively Manufactured ABS Plastic as A Function of Layer Parameters," In ASME 2015 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers Digital Collection, November 2015.

[23] K. J. Christiyan, U. Chandrasekhar, and K. Venkateswarlu, "A Study on the Influence of Process Parameters on the Mechanical Properties of 3D Printed ABS Composite, "In IOP Conference Series: Materials Science and Engineering, IOP Publishing, vol. 114, no. 1, pp. 012109, February 2016.

[24] J. C. Camargo, Á. R. Machado, E. C. Almeida, and E. F. M. S. Silva, "Mechanical Properties of PLA-Graphene Filament for FDM 3D Printing," The International Journal of Advanced Manufacturing Technology, vol. 103, vol. 5-8, pp. 2423-2443, 2019.

[25] M. Dawoud, I. Taha, and S. J. Ebeid, "Mechanical Behaviour of ABS: An experimental Study using FDM and Injection Moulding Techniques," Journal of Manufacturing Processes, vol. 21, pp. 39-45, 2016.

[26] S. R. Rajpurohit, and H. K. Dave, "Effect of Raster Angle on Tensile Properties of PLA Part Fabricated Using Fused Deposition Modeling Process," In Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering, Chennai, India, IIT Madras, pp. 103-106, 2017.

[27] S. R. Subramaniam, M. Samykano, S. K. Selvamani, W. K. Ngui, K. Kadirgama, K, Sudhakar, and M. S. Idris,

"Preliminary Investigations of Polylactic Acid (PLA) Properties," In AIP Conference Proceedings, vol. 2059, no. 1, pp. 020038, AIP Publishing LLC, January 2019.
[28] N. Kumar, P. K. Jain, P. Tandon, and P. M. Pandey, "The Effect of Process Parameters on Tensile Behavior of 3D Printed Flexible Parts of Ethylene Vinyl Acetate (EVA)," Journal of Manufacturing Processes, vol. 35, pp. 317-326, 2018.
[29] T. Galeta, P. Raos, and M. Somolanji, "Impact of Structure and Building Orientation on Strentgh of 3D Printed Models," KGK-Kautschuk Gummi Kunststoffe, vol. 65, no. 10, pp. 36, 2012.
[30] M. Fernandez-Vicente, W. Calle, S. Ferrandiz, and A. Conejero, "Effect of Infill Parameters on Tensile Mechanical Behavior in Desktop 3D Printing," 3D Printing and Additive Manufacturing, vol. 3, no. 3, pp. 183-192, 2016.
[31] C. Alvarez, L. Kenny, C. Lagos, F. Rodrigo, and M. Aizpun, "Investigating the Influence of Infill Percentage on the Mechanical Properties of Fused Deposition Modelled ABS Parts," Ingeniería e Investigación, vol. 36, no. 3, pp. 110-116, 2016.
[33] C. A. Griffiths, J. Howarth, G. De Almeida-Rowbotham, and A. Rees, "A Design of Experiments Approach to Optimise Tensile and Notched Bending Properties of Fused Deposition Modelling Parts," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 230, no. 8, pp. 1502-1512, 2016.
[34] F. Rayegani, and G. C. Onwubolu, "Fused Deposition Modelling (FDM) Process Parameter Prediction and Optimization using Group Method for Data Handling (GMDH) and Differential Evolution (DE)," The International Journal of Advanced Manufacturing Technology, vol. 73, no. 1-4, pp. 509-519, 2014.
[35] O. Lužanin, D. Movrin, and M. Plančak, "Effect of Layer Thickness, Deposition Angle, and Infill on Maximum Flexural Force in FDM-Built Specimens," Journal for Technology of Plasticity, vol. 39, no. 1, pp. 49-58, 2014.
[36] Z. Abdullah, H. Y. Ting, M. A. M. Ali, M. H. F. M. Fauadi, M. S. Kasim, A. Hambali, and F. Handoko, "The Effect of Layer Thickness and Raster Angles on Tensile Strength and Flexural Strength for Fused Deposition Modeling (FDM) Parts," Journal of Advanced Manufacturing Technology (JAMT), vol. 12, no. 1 (4), pp. 147-158, 2018.
[37] Rajkumar, Santosh. "Effect of infill pattern and build orientation on mechanical properties of FDM printed parts: An experimental modal analysis approach." arXiv preprint arXiv:2202.05692 (2022).
[38] M. F. Afrose, S. H. Masood, P. Iovenitti, M. Nikzad, and I. Sbarski, "Effects of Part Build Orientations on Fatigue Behaviour of FDM-Processed PLA Material,. Progress in Additive Manufacturing, vol.1, no. 1-2, pp. 21-28, 2016.
[39] M. Domingo-Espin, J. A.Travieso-Rodriguez, R. Jerez-Mesa, and J. Lluma-Fuentes, "Fatigue Performance of ABS Specimens Obtained by Fused Filament Fabrication, Materials, vol. 11, no. 12, pp. 2521, 2018.
[40] M. M. Padzi, M. M. Bazin, and W. M. W. Muhamad, "Fatigue Characteristics of 3D Printed Acrylonitrile Butadiene Styrene (ABS)," In Materials Science and Engineering Conference Series, vol. 269, no. 1, pp. 012060, Nov. 2017.
[41] L. Safai, J.S. Cuellar, G. Smit, and A.A. Zadpoor, "A review of the fatigue behavior of 3D printed polymers." Additive manufacturing, vol. 28, pp.87-97, 2019.
[42] P. K Gurrala, and S. P. Regalla, "Part Strength Evolution with Bonding Between Filaments in Fused Deposition Modelling: This Paper Studies How Coalescence of Filaments Contributes to the Strength of Final FDM Part," Virtual and Physical Prototyping, vol. 9, no. 3, pp. 141-149, 2014.
[43] M. Faes, E. Ferraris, and D. Moens, "Influence of Inter-Layer Cooling Time on the Quasi-Static Properties of ABS Components Produced via Fused Deposition Modelling," Procedia CIRP, vol. 42, pp.748-753, 2016.
[44] Q. Sun, G. M. Rizvi, C. T. Bellehumeur, and P. Gu, "Effect of Processing Conditions on the Bonding Quality of FDM Polymer Filaments," Rapid Prototyping Journal, vol. 14, no. 2, pp.72-80, 2008.
[45] C. Benwood, A. Anstey, J. Andrzejewski, M. Misra, and A. K. Mohanty, "Improving the Impact Strength and Heat Resistance of 3D Printed Models: Structure, Property, and Processing Correlationships During Fused Deposition Modeling (FDM) of Poly (Lactic Acid)," ACS Omega, vol. 3, no. 4, pp. 4400-4411, 2018.
[46] S. Rostom, and M. D. Dadmun, "Improving Heat Transfer in Fused Deposition Modeling with Graphene Enhances Inter Filament Bonding," Polymer Chemistry, vol. 10, no. 44, pp. 5967-5978, 2019.
[47] R. Singh, and S. Singh, "Development of Nylon Based FDM Filament for Rapid Tooling Application," Journal of the Institution of Engineers (India): Series C, vol. 95, no. 2, pp. 103-108, 2014.
[48] F.Ning, W. Cong, Y. Hu and H.Wang, "Additive Manufacturing of Carbon Fiber-Reinforced Plastic Composites using Fused Deposition Modeling: Effects of Process Parameters on Tensile Properties," Journal of Composite Materials, vol. 5, no. 4, pp. 451-462. 2017.
[49] O. S. Carneiro, A. F. Silva, and R. Gomes, "Fused Deposition Modeling with Polypropylene," Materials & Design, vol. 83, pp. 768-776, 2015.
[50] S.Meng, H. He, Y. Jia, P. Yu, B.,Huang, and J. Chen, "Effect of Nanoparticles on the Mechanical Properties of Acrylonitrile–Butadiene–Styrene Specimens Fabricated by Fused Deposition Modeling," Journal of Applied Polymer Science, vol. 134, no. 7, 2017.

[51] A. Le Duigou, M. Castro, R. Bevan, and N. Martin, "3D Printing of Wood Fibre Biocomposites: From Mechanical to Actuation Functionality," Materials & Design, vol. 96, pp.106-114, 2016.
[52] A. Plymill, R. Minneci, D. A. Greeley, and J. Gritton, "Graphene and Carbon Nanotube PLA Composite Feedstock Development for Fused Deposition Modeling," Thesis Projects, University of Tennessee Honors, 2016.
[53] Z. Weng, J. Wang, T. Senthil, and L. Wu, "Mechanical and Thermal Properties of ABS/Montmorillonite Nanocomposites for Fused Deposition Modeling 3D Printing," Materials & Design, vol. 102, pp. 276-283, 2016.
[54] C. C. Kuo, L. C. Liu, W. F. Teng, H. Y. Chang, F. M. Chien, S. J. Liao, ... and C. M. Chen, "Preparation of Starch/Acrylonitrile-Butadiene-Styrene Copolymers (ABS) Biomass Alloys and their Feasible Evaluation for 3D Printing Applications," Composites Part B: Engineering, vol. 86, pp. 36-39, 2016.
[55] X. Tian, T. Liu, C. Yang, Q. Wang, and D. Li, "Interface and Performance of 3D Printed Continuous Carbon Fiber Reinforced PLA", Composites Part A: Applied Science and Manufacturing," vol. 88, pp.198-205, 2016.