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Innovative Foundry Technology and Material Using Fused Deposition Modeling and Polylactic Acid Material in Sand Casing

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Abstract

In sand casting, Fused Deposition Modeling (FDM) printing by using Poly Lactic Acid (PLA) filament is one of the innovative foundry technologies being adopted to substitute traditional pattern making. Several literatures have reported the influence of process parameters such as raster angle and print speed on some mechanical properties of FDM-printed, PLA-prototypes used in other applications. This study investigated the effects of interior fill, top solid layer, and layer height on the compressive strength of rapid patterns for sand casting application. Different values of the process parameters were used to print the pre-defined samples of the PLA-specimens and a compression test was performed on them. The coupled effects of the process parameters on compressive strength were investigated and the optimum values were determined. Interior fill of 36%, layer height of 0.21 mm and top solid layer of 4 were found to produce a FDM-printed, PLA-pattern that sustained a compaction pressure of 0.61 MPa. A simulation analysis with ANSYS® to compare failure modes of both experiment and model shows a similarity of buckling failure that occurred close to the base of each specimen.

Keywords: Fused deposition modeling, Rapid pattern, Sand casting pattern, FDM-printed, PLA-pattern, Mold cavity

1. Introduction

Sand casting is a process of producing metal parts which involves the use of sand as the mold material, pattern for creating the mold cavity and molten metal as the feedstock into the cavity. The molten metal is poured through a down-sprue into the cavity (die or mold) which is a replica of the desired geometry [1]. Physical patterns are usually required to produce the mold cavity in which metal castings are formed. For instance, a hybrid pattern for bevel gear was developed using Stereo-Lithography Apparatus (SLA) rapid prototyping technique for application in investment casting [2]. Therefore, pattern making is a central activity in many foundry processes including sand casting [3], [4].

For a casting process to be successful and to achieve the required specifications in the final cast article, the pattern used to prepare the mold cavity must be an exact replica of the final object [5]. Therefore, the dimensional accuracy, surface finish and shape of the final casting are influenced by the quality of the physical pattern used in mold preparation [6].

Before now, the production method for traditional pattern making usually employs either wood, polystyrene, resin [7] or a combination of the aforementioned. The common practice in many foundries in Nigeria is the use of wood. Wood is easily machined and salvaged. Non Computer Numerical Controlled (non-CNC) machines are often used for the pattern making process. However, the process of converting wood into pattern using non-CNC machines involves several intermediate steps including visualization of the model, drawing interpretation, model layout and wood machining [8]. Therefore, it is often difficult to create some complex and intricate geometries and to achieve specific contour in some patterns. Furthermore, the duration involved in producing some patterns with non-CNC machines is considerably high and sometimes the dimensional accuracy is compromised due to errors in interpreting drawings or those related to the working tools. Based on the aforementioned challenges, it is obvious that foundry men in Nigeria have been looking for a suitable replacement for traditional making pattern. One relief is the adoption of RP techniques to produce rapid pattern.

The RP techniques are generally believed to provide faster production time, higher dimensional accuracy and cost reduction for printed patterns with complex geometries [9]. Specifically, in precision casting, foundry men often use RP techniques to produce patterns [2], [10]–[12]. The RP involves a collection of manufacturing techniques that fabricates 3D physical parts layer-by-layer directly from a CAD model [13], [14]. It was originally developed for prototyping purposes and to enable designers easily realize their concepts in actual physical object [15], [16]. Thereafter, RP evolved into being used to produce patterns and sand molds directly from a 3D CAD model layer-by-layer [17].

The possibilities of producing hybrid patterns with SLA for gear casting in investment casting process have been investigated. It was determined that SLA made it possible to produce hybrid patterns from both resin and casting wax and this has led to a reduction in the volume of wax pattern and the duration and cost of pattern making [2]. This method may not be suitable sand casting because sand casting patterns subjected to high compaction pressure in the range of 0.60 – 1.0 MPa during molding operation.

Also, the use of Laminated Object Manufacturing (LOM) in pattern making for sand casting has been reported. It was stated that it reduced the necessary process steps and cycle times involved in sand casting process [18]. However, some process parameters of LOM such as print speed were reported to affected the bond structure of the printed patterns [19].

For Fused Deposition Modeling (FDM) technique, it has been reported that it provides a low-cost 3D printing alternative than other RPs and traditional methods [20]. This is, perhaps, the reason for its adoption for pattern making in sand casting. However, the numerous process parameters such as raster angle, layer height, interior fill, print speed that are required in some RP technologies including FDM usually affect the mechanical strength and surface quality of the final part [15], Figure 1. Some process parameter values of FDM that influence the mechanical properties, dimensional accuracy and build time of the final part have been identified [15]. Similarly, the effects of raster angle and print speed on the mechanical properties and surface quality of printed parts have been reported in previous studies [21]–[23]. This study is focused on the effect of top solid layer, layer height and interior fill on the mechanical strength of FDM-printed PLA-pattern for sand casting application.

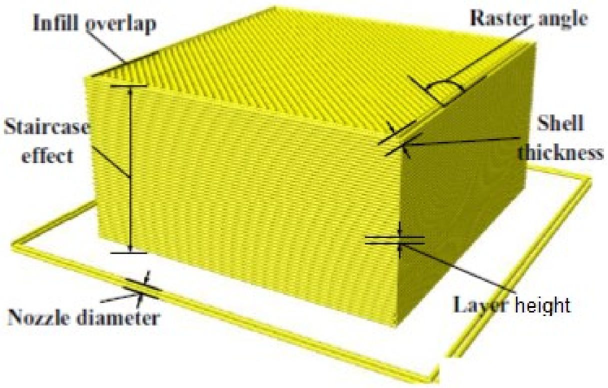


Fig. 1. Some process parameters used in FDM. Source: [24]

In FDM printing, material deposition is done successively on top of the previous layers and both conduction and force convection heat transfers are usually responsible for the part solidification [14]. In addition, FDM printing process also involves consecutive material deposition in the horizontal direction. It has been determined that side-by-side extruded paths (or consecutive horizontal layers) have better fusion because of their mutual high temperature while successive layers extruded on top of each other have weaker fusion due to their high temperature gradient [15]. Furthermore, the fusion between successive layers involves local re-melting of previously solidified layers [25], [26]. Consequently, the re-melting and cooling effects usually induces non-uniform thermal gradient that cause residual stress leading to warping, delamination and low mechanical strength [27]. However, this study was carried out to investigate the effect of varying other process parameters such as layer height in the vertical direction, top solid layer and interior fill on the compressive strength of FDM-printed PLA-patterns.

The effect of raster angle (or build orientation) on compressive strength of printed parts using ABS filament has been reported [21]. The experiment demonstrated that parts printed with transverse (vertical) orientation had 15% lower compressive strength than those printed with axial (horizontal) orientation [21]. In the experiment, a fixed raster angle of 45°/-45° was used and the air gap was set to zero. However, the test specimens were made of ABS filament material which is different from PLA filament which is being considered for printing PLA-patterns for sand casting. The sand mold commonly used in sand casting in Nigeria has a green compressive strength (GCS) of between 0.05133 MPa – 0.10314 MPa [28]. In the industry, the normal practice is to apply a molding pressure higher than the GCS to ensure good compaction of the sand mold. This pressure is within the range of 0.55 MPa – 1.0 MPa which is the gauge pressure commonly used in industrial facilities [29]. Therefore, any pattern (wooden or printed PLA type) in the sand mold is imparted by a pressure usually not less than the minimum compaction pressure of 0.6 MPa of the molding machine [30]. Therefore, a compression test for a model printed with a commercial PLA filament is been investigated in this current research by considering the most relevant process parameters including top solid layer, layer height and interior fill.

Similarly, parts printed with PLA filament have been investigated for tensile strength [23]. It was determined that PLA parts printed at 45° raster angle had the highest tensile strength and endurance limit while those printed at 90° raster angle had the least resistance to fatigue loading [23]. These findings may not be useful in sand casting application where compaction pressure is impacted on a printed pattern during molding operation. The effects of raster angle on tensile and compressive strength of FDM-printed parts for other applications have been extensively investigated by several researchers [21], [23]. In this current work, a raster angle of 45°/-45° is maintained while varying other process parameter values such as interior fill, layer height and top solid layer to determine their effects on the compressive strength of FDM-printed PLA-pattern.

2. Materials And Methods

2.1. FDM process parameters optimization for patterns used in sand casting

The interior fill describes how hollow or dense a printed part is, where 100% represents a solid part and zero percent indicates a part that is hollow [15]. To save on time and filament cost, models are mostly printed with low percent of interior fill. This is because printing a prototype using higher interior fill increases the duration of print and the mass of filament material used. But printed PLA prototypes using higher interior fill may have higher mechanical strength to withstand the molding pressure. Interior fill of 25, 30, 36, 40, and 50% were investigated to determine their effects on compressive strength of FDM-printed PLA-pattern.

The slice height (or layer height) describes the thickness of each layer measured in the vertical or Z-direction and this also affects the strength of printed pattern [15], [21] and its surface quality. Layer height refers to the margin the extruder moves up in the Z-direction as it deposits each layer of the model. To print a part that has fine details and high surface quality and resolution, a layer height of 0.1 mm has been suggested [31]. High resolution usually increases build time for the same print speed. Thus, the 0.1 mm layer height is used as the lower limit of boundary condition. Layer height is generally set lower than the nozzle diameter by 20% to allow successive layers to bond properly. This forms the upper limit value of layer height for FDM printing. Using a nozzle diameter of 0.4 mm, layer height of 0.10, 0.15, 0.20, 0.25, and 0.30 mm were investigated to determine their effects on compressive strength.

The solid layer allows separate horizontal shell printing for top and bottom of the interior fill. The product of solid layer and layer height is the thickness of the solid section printed on the bottom or top of the interior fill. Solid layer is unitless. It is used to vary the thickness of the solid section at the bottom and top layers and to ensure precise flatness and a complete solid surface. Solid layer provides control over the strength and flexibility of the printed parts. It has two different settings in some slicer software such as Simplify3D® used in Nigerian Foundries Ltd. These are the top solid layer and the bottom solid layer. The top solid layer is considered in relation to compressive strength because the pressure is exerted on top of the printed part in molding operation. The top solid layer ranging from 2 to 7 were used to print different specimens.

2.2. Experimental procedures

Test specimens were printed from PLA filament. The model was first created in Solidworks® and then converted to STL file format before being imported into the Simplify3D® slicer software. The process parameters (interior fill, layer height and top solid layer) were then varied for each specimen. After adjusting the process parameters, the model was sliced and saved to the desktop. The slicing process defines the tool path of the specimens in the form of G-code. The resulting G-code was filtered through mikk26.eu's Simplify3D® app in readiness for printing. The 3D printer (Titan Robotic Atlas®) is then prepared and calibrated for printing. The build direction for all the specimens was Z-axis, Figure 2. The layers were extruded at a raster angle of 45° to the X-Y plane. For each 40 mm cube specimen printed, different values for layer height, interior fill and top solid layer were used. A compression test based on BS EN 196-1:2016 standard was reported to have been used for 3D printed fibre reinforced material with specimen dimensions of 40 x 40 x 40 mm [32]. The current compression test was also based on BS EN 196-1:2016 standard and was performed on each specimen on a Universal Testing Machine (UTM) with a load cell of 100 kN, Figures 3 and 4.

Fig. 2. Printing of specimen in the Z direction. Source: [30]

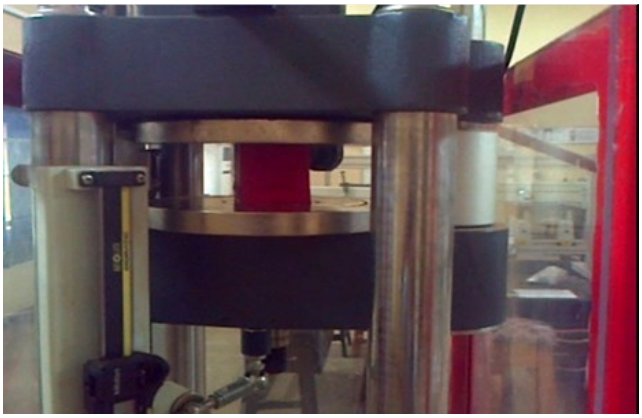


Fig. 3. Compression test using UTM Model No. SM1000

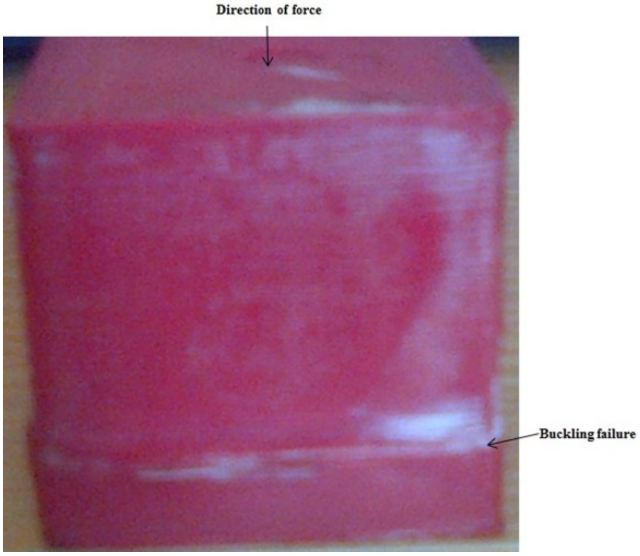


Fig. 4. Compression test and failure mode of 40 x 40 x 40 mm PLA specimen

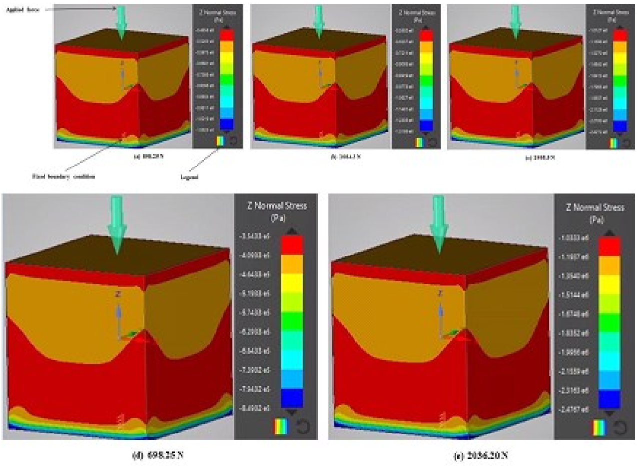
2.3. Simulation analysis

The properties of a commercial PLA were considered in modeling of the specimen. Table 2 shows the relevant mechanical properties used in the simulation analysis [33]. The simulated model assumes an isotropic structure and uniform properties through the layers.

Table 2.
Mechanical properties of a commercial PLA. Source: [33]

Properties	Value	Unit
Solid density	1252	kg/m^3
Viscosity	0	m/kg s
Young's modulus	1280	MPa
Poisson's ratio	0.360	
Thermal conductivity at 190°C	0.195	m kg / s^3 K
Specific heat at 190°C	2060	m^2 / s^2 K

In the ANSYS simulation, a fixed boundary condition was applied to the bottom side of the model in the Z-plane direction. An average of the forces of three related specimens, considering layer height and interior fill, were computed for five groups. The average distributed load of 898.25 N, 1084.26 N, 1995.48 N, 698.25 N, and 2036.20 N, as obtained from the compression tests, were applied on the opposite side of the model for simulation a – e respectively, Figure 5.



(a) 898.25 N

(d) 698.25 N

(e) 2036.20 N

Fig. 5. Z-normal stress simulation of a 40 x 40 x 40 mm PLA model

3. Results And Discussions

Different interior fills of 25%, 30%, 36%, 40% and 50% were used to print different samples of PLA cube of 40 mm for compression test. Compression test for the specimens printed with 35% interior fill was determined to be optimum for the minimum compaction pressure of 0.6 MPa from the moulding machine, Figure 6. But the compressive strength of the 25% interior fill specimens was found to be lower than the minimum compaction pressure from the moulding machine. However, there is a general increase in compressive strength when the interior fill is increased for each compression test, Figure 6. As interior fill increases, so is the filament material usage. Therefore, to achieve a balance between strength and material savings, an optimum interior fill of 36% that makes the experimental compressive strength higher than the minimum compaction pressure should be used in printing PLA-patterns.

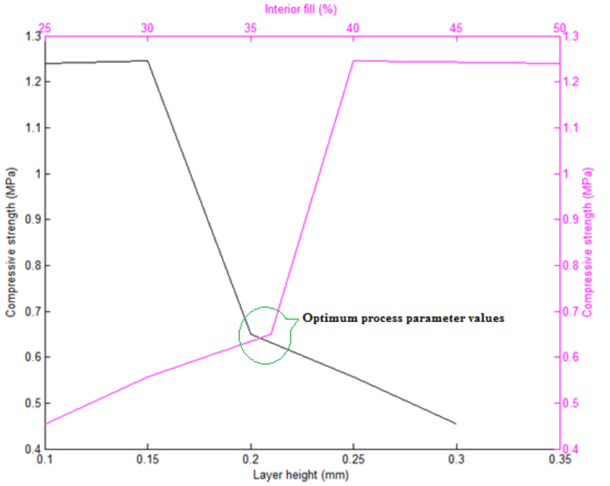


Fig. 6. Compressive strength against interior fill and layer height

Top solid layer was also varied from 2–7 for the printed PLA specimen. It was observed that compressive strength increases with increase in top solid layer, Figure 7. As stated, top solid layer determines the thickness of solid section at the top and this section provides an overlay and structural network for the interior fill. As defined, solid section is the product of layer height and top solid layer. In the present study, it was observed that solid section affects the strength of printed patterns. A low thickness of solid section reduces the strength of the printed specimens. For FDM-printed PLA-pattern, it was found that increasing top solid layer, thus, raising the thickness of solid section also increases the strength of the pattern. A top solid layer of 4 was found to be optimum for the minimum compaction pressure. Similarly, a layer height of 0.21 mm was determined as optimum for printing PLA pattern to withstand the minimum compaction pressure.

Contrary, layer heights with lower values were generally observed to increase compressive strength of PLA-pattern, Figure 6 and Figure 7. But the lower limit of layer height for the study was 0.1 mm. Below this limit, the extruded layers tend to discontinue. On the other hand, the upper limit of layer height for FDM printing is usually a function of nozzle diameter. It is normally set not more than 80% of nozzle diameter. This is because when PLA melts, it expands and becomes sticky creating an overlap of layers leading to poor surface finish. In the present study, a nozzle diameter of 0.4 mm was installed on the extruder. Therefore, a layer height of 0.30, 0.25, 0.20, 0.15 and 0.10 mm were investigated to determine their effects on compressive strength. Compressive strength was observed to decrease with an increase in layer height. A possible explanation is that for every extrusion of successive layer, there is a local re-melting and cooling of previous layers. This may induce non-uniform thermal gradient and low fusion between layers thereby leading to low mechanical strength of 3D printed parts. Higher layer heights induce larger thermal gradient between layers. Consequently, there is lower fusion between layers. On the other hand, lower layer heights easily re-melt, bond and solidify thereby ensuring high strength for printed part.

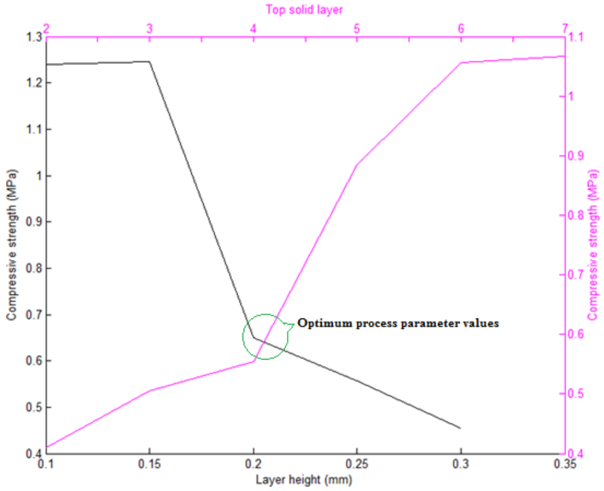


Fig. 7. Compressive strength against top solid layer and layer height

For the nozzle diameter of 0.4 mm, layer height of 0.30, 0.25, 0.20, 0.15 and 0.10 mm were investigated to determine their effects on compressive strength.

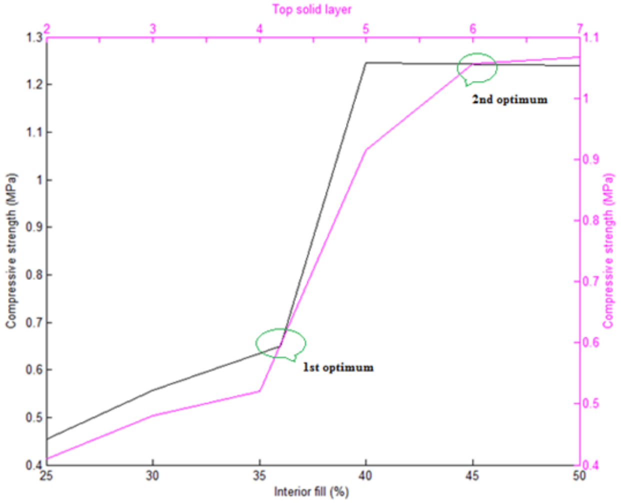


Fig. 8. Compressive strength versus top solid layer and interior fill

As determined, compressive strength generally increases with increase in interior fill and top solid layer, Figures 6 and 7. However, for the coupled effects of top solid layer and interior fill, the optimum value of interior fill was 36% while the top solid layer still maintained 4, Figure 6. In the present opinion of the author, the little increase in optimum interior fill from 35 to 36% resulted from the effect of balancing out the decreasing influence of higher values of layer height on compressive strength, Figure 16. However, higher values of interior fill usually require more filament materials.

The printing of PLA-patterns using FDM printer for sand casting has significantly reduced lead-time in pattern making for some selected shapes. It has also improved dimensional accuracy of PLA-patterns. Despite these advantages to the pattern making process, it is uncertain what values of interior fill, layer height and top solid layer can be combined to print a PLA-pattern that can withstand the compaction pressure of the molding machine. Likewise, the ease of withdrawal of a PLA-pattern from the mold without damaging the mold cavity also depends on the values of process parameters used in printing the pattern.

In the present work, compressive strength was observed to decrease with increase in layer height. However, when layer height is reduced for printing a PLA-pattern, the print duration is also increased because more number of layers must be printed to produce the complete model. But the benefits of reduced layer height are higher compressive strength and surface finish. On the other hand, to reduce print duration, higher interior fill is required. This also increases the compressive strength of the PLA-pattern. However, with high interior fill, the filament material used also increases. Therefore, optimum values for the coupled effects of layer height and interior fill have been determined to achieve a balance between filament consumption and strength of FDM-printed PLA-pattern used in sand casting.

The failure mode from the simulation analysis was observed to be buckling and it occurred closer to the fixed boundary condition, Figure 5. This is similar to the actual failure mode in the printed PLA specimen, Figure 4. It is observed that the specimens that failed under the smallest load have the greatest normal stress on the Z plane. Those that failed under the highest load have the smallest normal stress on the Z plane.

4. Conclusions

When FDM-printed PLA pattern is to be subjected to compaction pressure, as is the practice in sand casting, it is necessary to print the pattern with optimum values of interior fill, top solid layer and layer height to achieve a compressive strength that prevent its failure during molding operation. This paper identified the three process parameters (interior fill, layer height and top solid layer) that are critical to printing a pattern for molding operation using FDM 3D printer. Increasing the interior fill generally produced higher compressive strength. Nonetheless, interior fill of 36% was determined to produce strength that withstands compaction pressure from a typical molding machine commonly used in sand casting. However, the maximum pressure of such machine may require using interior fills higher than 36%. This will be at the expense of more filaments and higher material cost. Also, higher number of top solid layer increased compressive strength. Contrary, higher layer height reduces compressive strength. The optimum for savings on material cost and strength is 36% interior fill and 4 units for top solid layer.

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