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Fused Deposition Modeling Printed Patterns for Sand Casting in a Nigerian Foundry: A Review

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Abstract

There has been a gradual adoption of Three-Dimensional (3D) printing in pattern making for sand casting absolutely because of its reduced lead-time and higher dimensional accuracy. Pattern making is the most central activity in the production line of any casting operation. A delay in pattern making or a defect in pattern usually translates to increased production cost and time or poor quality castings respectively. Many foundry industries have been concerned with reducing the duration for pattern making and improving the dimensional accuracy of patterns. Adoption of Fused Deposition Modeling (FDM) based patterns have only provided a limited solution to the challenges of traditional pattern making for sand casting. Some patterns are not suitable for FDM printing due to their size volume which is not usually cost-effective to print. Also, the surface quality and mechanical properties of patterns produced with FDM are usually affected by process parameters thereby leading to post-manufacturing treatment before the patterns are suitable for moulding operation. This study investigated the problems of traditional pattern making and the challenges of FDM-printed PLA-patterns for sand casting and suggested solutions and areas for future research. Related researches on 3D printing in the foundry carried out around the worldwide are discussed.

Keywords: Foundry, Sand Casting, PLA-pattern, Pattern Making, Fused Deposition Modeling, Rapid Pattern

INTRODUCTION

Sand casting is the production of metal articles by pouring molten metal into mould, where upon solidification, the shape of the resulting casting is determined by the mould [1]. The mould commonly used in sand casting is the expendable type [2]. It is usually destroyed after each casting and re-prepared for subsequent castings [3]. The mould is prepared by compacting sand around a pattern placed in a mould box, and after the compaction, the pattern is withdrawn from the mould leaving a cavity the shape of the pattern. The common moulding sands include silica sand (SiO_2), zircon sand, olivine sand and chromites [4], [5]. But silica sand is mostly used in Nigeria because it occurs naturally in abundance, it is inexpensive and suitable for repeated use, and it can withstand high temperatures [2]. Therefore, many foundries producing metal articles from iron materials use silica sand and pattern to prepare the mould cavity.

A pattern is an object made as the replica of the shape to be cast. The most widely used material for pattern in traditional pattern making is wood because it is easily machined and salvaged [6]. Also, wood has inherent high compressive strength along its grains that makes it suitable for compaction moulding with little or no potential for failure during the moulding operation. However, wood must undergo several machining and tooling processes before the wooden pattern can be withdrawn from the mould after compaction. Likewise, when non Computer Numerical Control (non-CNC) machines are the only tools employed for the pattern making process, as is the current practice in many foundries in Nigeria, the lead-times usually run into several weeks and months depending on machine shop scheduling, experience and capabilities of the pattern makers.

The listed drawbacks of wooden patterns had led to the use of alternative materials for patterns in special casting requirements. This includes the use of polystyrene in Evaporative Pattern Casting (EPC) to increase dimensional accuracies and improve casting quality [4]. But polystyrene has little or no capacity for repeated use because it can be consumed or damaged in a single casting process.

PROBLEMS OF TRADITIONAL PATTERN MAKING

In sand casting, several activities are involved including pattern making, core making, mould flask and core box preparation, melting, metal handling and pouring, shake out, shot blasting and fettling [7]. However, pattern making is the most central activity just as is the case in every other foundry process [8]. It precedes many other casting activities. Therefore, an error in the pattern making process or pattern itself usually leads to a plurality of errors in every activity down the production line.

The traditional pattern making involves the use of non-CNC machines and manual labour to produce pattern. In this method, the most common material for pattern making is wood. In using wooden pattern for mould preparation, there is usually surface friction between sand and pattern walls [2]. This friction causes damage of the mould cavity on removal of the pattern from the mould. A method was, therefore, suggested to facilitate the withdrawal of wooden patterns from the mould and this includes coating with a protective material [1]. However, some of the protective materials are hazardous to health and the environment.

The non-CNC machines include diverse equipment and tools used for pattern making such as files, saws, hammers, try square, turning lathe, planners, abrasive disc machine, drilling machines, Vernier protractor, Vernier calipers and micrometer screw gauges. With many of these under the control and operation of a pattern maker (which is usually manual), it is often difficult to achieve precision and repeatability in dimension due to errors related to working tools and those arising from human drudgery. Likewise, traditional pattern making can be time consuming for some patterns with intricate designs and sometimes the patterns may be difficult to achieve with high precision. Besides, many of the equipment for wooden patterns especially those that are precision-based tools usually require periodic re-calibration to re-establish their precision grade. Poor re-calibration of some of the equipment usually makes it difficult to achieve precision and dimensional accuracy in wooden patterns.

Similarly, tooling costs for traditional pattern making in sand casting range from several thousands to tens of thousands of dollars depending on size and complexity. In addition, lead-times range between several weeks to months depending on machine shop scheduling, experience and capabilities of the pattern makers. Also, traditional pattern making thrives more on repeated removal of materials from a work piece to achieve the desired geometry of the wooden pattern. This is usually expensive and time-consuming to accommodate and an alternative method using Fused Deposition Modeling (FDM) is being investigated.

Furthermore, wood dust from pattern making operation is a common and serious health hazard. Pattern makers are continuously exposed to wood dust and chemical during wood machining and surface coating processes. The prolonged or repeated exposure to formaldehyde binders and styrene-based fillers used in forming fillet radius on wooden pattern is suspected to cause damage to fertility or the unborn.

Based on the aforementioned challenges, foundry men have been looking for a suitable replacement for traditional making pattern. One of these alternatives is Additive Manufacturing (AM).

ADDITIVE MANUFACTURING TECHNOLOGIES IN THE FOUNDRY

Pattern making and mould preparation are the two major activities that greatly affect the quality of castings. Without a good pattern or mould, the castings produced may not meet customer's requirements for quality and performance. Likewise, customers demand for more efficient and effective metal products are on the increase. Therefore, foundries have to adapt to the constantly increasing demand for high quality and performance casting products in order to maintain their position [5]. One important technology that has become relevant to the foundry industry for improved production efficiency is additive manufacturing.

There are several AM techniques currently used in different foundry applications. For rapid investment casting, three AM processes are commercially available for the production of wax patterns and they include Stereo-Lithography Apparatus (SLA), Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) [9]. The commonly used AM techniques in sand casting are Laminated-Object Manufacturing (LOM), SLS, FDM and binder jetting. But the most popular and widely used AM method in the world is FDM [10]. The FDM process is reported to provide low-cost alternative compared to other AM techniques [11]. This, perhaps, explain the reason for its adoption in printing rapid patterns in some Nigerian foundries.

Printing of Smart Moulds for Metal Casting

Printing of sand moulds is one important use of AM in the foundry [12]. Sand moulds have been produced with binder jetting technology for the casting of non-ferrous metals. It has several advantages over traditional moulds. It makes it easier to insert components within the casting and/or mould [12]. It provides the casting industry the opportunity to produce sand moulds that have complex cavities and good dimensional accuracies [12]. It also provides more flexibility in the design of metal delivery system including sprues, runners, ingates, and risers [12]. Binder jetting technology is normally used as sand printers to ink-jet a binder resin into a catalyst-mixed sand [12]. Printed sand moulds have helped to optimise castings in respect of strength-to-weight trade-off [12]. Similarly, complex moulds and cores that are required for casting a number of precision metal alloys can be produced with SLS [8].

Printing of Patterns for Investment Casting

The application of LOM in investment casting has made low-volume production runs economical because of the outstanding manufacturing capabilities of LOM [13]. Patterns printed with LOM technique for sand casting and investment casting has been reported to be advantageous over traditional pattern making because of LOM objects' robustness, wood-like properties and relative low material cost [14]. The LOM technique reduces the necessary process steps and cycle times involved in traditional pattern making [14]. In addition, silica sand patterns based on SLS has been investigated [15].

Printing of Patterns for Sand Casting

The FDM technique is gradually being adopted for pattern making in sand casting. It is believed that printing of patterns with FDM can reduce lead-time and poor dimensional accuracy that are associated with traditional pattern making. The technology builds a prototype by depositing molten filament according to the cross-sectional layers of the model [10], [16]. As shown in Figure 1, there is typically a pulley-drive system located in the extruder that pushes the filament into a nozzle at a controlled rate. The nozzle is also located in the extruder (or print head), Figure 1. The nozzle contains resistive heaters that keep the filament in appropriate melting point. The melting point is usually a little above the glass transition temperature of the filament. This allows the molten filament to be extruded in a semi-liquid state. It then flows easily through the nozzle onto a base plate sometimes called a build platform, bed or table, and return to solid state immediately after extrusion thereby forming the solid pattern. The process continues until the model is complete and it is removed from the build chamber and cleaned [17].

However, some challenges are usually identified with the printed patterns such as poor surface finish, different compressive strengths of PLA-pattern at different values of process parameters, delamination of PLA-pattern while in storage and high surface friction between the sand and the pattern wall leading to frequent mould damage on removal of the pattern from the mould. This requires further investigation and solution to encourage the adoption of FDM on a large scale for sand casting.

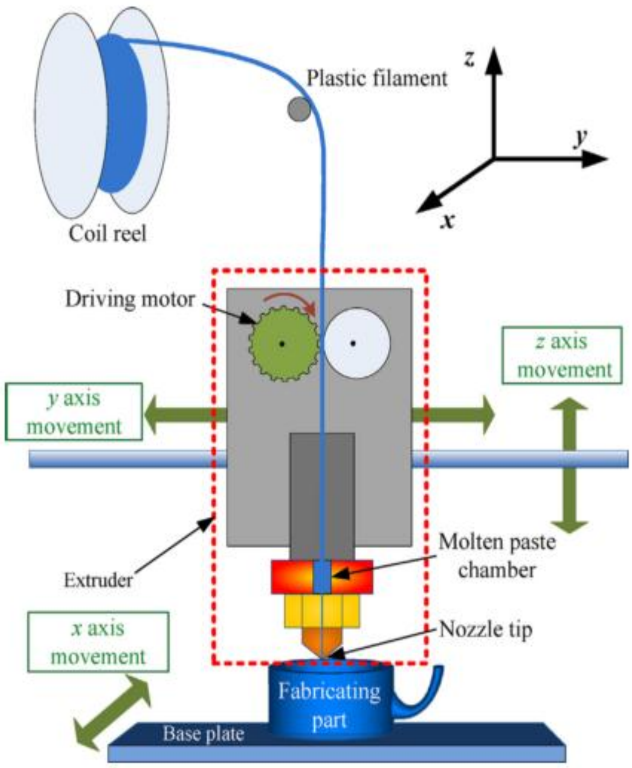

Figure 1. Schematic of fused deposition modeling process. Source: [18]

CHALLENGES OF FUSED DEPOSITION MODELING PRINTED PATTERNS

Some of the FDM process parameters that affect printed prototypes including PLA-patterns are print speed, layer height, raster angle, interior fill, and build temperature [19], [20]. Figure 2 shows the process parameters used in FDM for printing prototypes. These process parameters usually affect the mechanical properties, surface finish quality, print duration and filament consumption depending on their respective values.

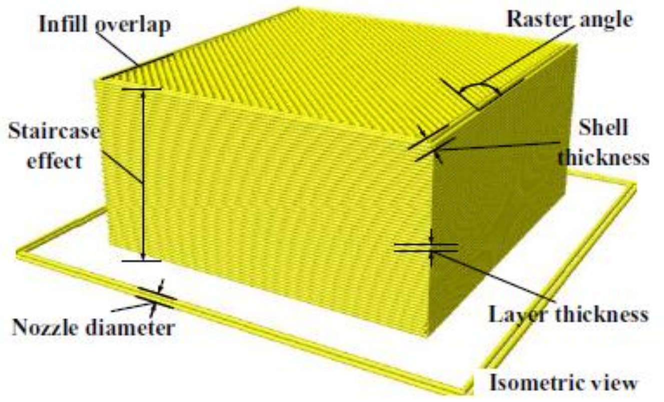

Figure 2. FDM process parameters. Source: [21]

Every pattern in sand casting is used to prepare a mould cavity by compacting sand around the pattern placed in a mould box. The green compressive strength (GCS) of sands used in many Nigerian foundries is 0.045 – 0.105 MPa to withstand the pressure of the molten metal during casting [22]. The normal practice when moulding the sand around the pattern is to apply a compaction pressure higher than the GCS to ensure good compaction of the sand mould and prevent the failure of the mould cavity either while removing the pattern or from pressure of the molten metal. Typical compaction pressure commonly used in many industrial facilities is usually within the range of gauge pressures of 0.55 – 1.0 MPa [23]. Obviously, any pattern (wooden or printed PLA type) in the sand mould must be subjected to this pressure. Wooden pattern has inherent high compressive strength along its grains that makes it withstands the compaction pressure. But for PLA-pattern, the compressive strength is not usually the same for all values of process parameters and this makes some PLA-patterns to fail during compaction. It is therefore, suggested that process parameters values for FDM-printed PLA-pattern be optimised to make it suitable for machine moulding.

Layer height (or the thickness of each layer measured in the Z-direction) and nozzle diameter have been identified as the process parameters that affect the surface finish quality of FDM printed prototypes [21]. In this study, PLA-patterns printed with FDM were found to be unsuitable for direct moulding operations because the pattern walls were serrated. Post-manufacturing treatments such as filling the pattern walls with resin, allowing it to cure and sanding out excess resin were often used to improve the surface finish quality before moulding the pattern, Figure 3.

Figure 3. Poor surface finish of a FDM printed pattern that required post-treatment before moulding operation Source: [24]

Prototypes printed with FDM are usually in their weakest state at the beginning of the process and in their strongest state at the end [25]. This makes it inevitable to use support structures in printing PLA-patterns especially those that have overhang and cavity [26]. The support structures provide stable form for the printed patterns during the print duration. However, the support structures often lead to increase filament usage, build time and surface roughness of sections of the build pattern that are in contact with the support structure. Consequently, different post-processing techniques such as chemical treatment [27], machining [28], heat treatment [29], support removal and cleaning [26] and mechanical sanding are being used to improve the surface finish of FDM-printed PLA-patterns as shown in Figure 4. The aggregate impact of the additional time and costs related to these post-manufacturing activities may be considerably high thereby making FDM printing in pattern production less cost-effective compared to traditional pattern making.

Figure 4. a) Printed channel grating undergoing post-treatment to improve the surface finish
b) After the moulding operation of the PLA-pattern but with the mould cavity damaged due to poor surface finish

Source: [24]

Printing of PLA-patterns with FDM technique does not usually reduce cost or time of pattern making for all types and sizes of pattern. For some patterns that do not have cavities or fillets, it may be suggested that traditional pattern making is more cost-effective. Figures 5 and 6 show a pattern printed with FDM and Table 1 presents the empirical data of producing the same pattern with both the traditional method and FDM technique. The duration of the FDM process was over two times more than the traditional method. The only advantage in using the FDM printer is that the printer was fairly autonomous for two days while the traditional method required 8 hours per day for 2 days with human involvement.

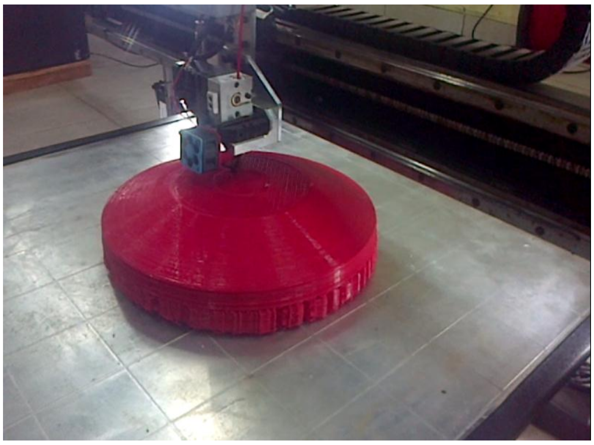

Figure 5. The printing of a PLA-pattern with FDM

Figure 6. FDM-printed PLA-pattern for sand casting

Table 1: Duration of pattern making with FDM and traditional methods

Particulars	Production Lead Time (hr)	
	FDM Method	Conventional Method
CAD model	4	4
Solid PLA pattern / wooden pattern	46	16
Total time	76	20
Manpower (Nos)	1	2

AREAS OF FURTHER RESEARCH

It is stated that FDM-printed PLA-patterns do not usually have the same compressive strength and surface finish quality for all values of process parameters. The compressive strength and surface finish quality are the major factors that determine the success of a PLA-pattern in sand casting. The three process parameters that are critical to the compressive strength of PLA-patterns are layer height, interior fill and top solid layer.

The interior fill describes how hollow or dense a PLA-pattern is, where 100% represents a solid pattern and lower percent indicates a pattern that is hollow [30]. Therefore, to save on time and filament cost, lower interior fills are usually conceived for printing PLA-pattern. However, some values of interior fill may not produce the required compressive strength to withstand compaction pressure. Although, printing a PLA-pattern with higher interior fill may have higher compressive strength to withstand the compaction pressure, it is suggested that the optimum interior fill be investigated to achieve a balance amongst material cost, build time and compressive strength. Research is already being carried out in this regard. This is in line with the first goal of AM processes in optimising the density of printed part to reduce the deterioration of their mechanical properties [31]

CONCLUSIONS

Despite the challenges of FDM-printed PLA-patterns in sand casting, patterns printed with other AM processes for sand casting and investment casting have been reported to create savings in terms of lead-time and cost for new product trial and low-volume production runs [13]. It is necessary to improve FDM technique for pattern making to exploit its full benefits in sand casting operation.

In many moulding operations involving the use of PLA-patterns, surface friction of pattern walls with the mould is a common occurrence. The sand cohesion is especially around the grooves, corners and fillets. These defects in the mould cavity as a result of the withdrawal of stuck PLA-pattern often lead to casting failure thereby causing a repetition of the whole process. One possible solution is to optimise layer height. Layer height determines the surface finish quality of PLA-pattern. This will reduce the grooves or serrations on the PLA-pattern walls but they cannot be totally eliminated. Because of the difficulty in eliminating serrations on PLA-pattern by controlling layer height, post-manufacturing treatment is suggested to improve the surface quality of patterns to reduce the cohesiveness of sand with the pattern wall. This treatment is depended on the type of filament material used for the printed patterns. Chemical treatments as well as coating of pattern walls using polyurethane and mechanical polishing are recommended for improving the surface finish quality of PLA-patterns.

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