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POTENTIAL AND CHALLENGES OF FUSED GRANULAR FABRICATION IN PATTERNMAKING

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Abstract

Efficient manufacturing of tooling and patterns is an essential part of a good foundry process. Traditional patternmaking methods have been honed to almost perfection during the years. Additive manufacturing has been growing as an industry and presents many new possibilities for the foundry industry. However, many additive manufacturing technologies do not currently provide usable sizes and scales for foundries to properly use. Fused granular fabrication (FGF) in conjunction with finish machining might provide an answer to this issue, with printing volumes and speeds many times of those compared to filament-based fused deposition modeling printing. In this work, some traditional patternmaking materials are compared to a FGF manufactured one based on polylactic acid and cellulose blend, and their characteristics are discussed. 3D scanning of as-printed geometry shows variations inherent to material extrusion methods, while the final machined state shows comparable results to traditional polyurethane model material. The combination of high-volume material extrusion with machining to final dimensions might allow more utilization of additive manufacturing in patternmaking, especially when combined with high-performance polymer materials.

Keywords: *patternmaking, additive manufacturing, fused granular fabrication, large-scale additive manufacturing*

Introduction

Patterns, core boxes and other types of tooling are essential parts of any expendable mold foundry process. They are needed both in high and low volume production. Efficiency, processability, use properties and cost are some of the factors that matter when dealing with foundry tooling. These kinds of factors are emphasized especially when dealing with large-scale patterns. Traditional patternmaking utilizes various material removal methods on bulk materials and has grown to be very efficient in terms of production speed and utilization of computer-aided design (CAD)/computer-aided manufacturing (CAM).

Additive manufacturing (AM) has been growing fast as an industry and presents many new possibilities for foundries. Methods are available ranging from rapid prototyping to tooling, rapid manufacturing, and casting, each having their own niches and challenges.[1] However, many additive manufacturing technologies do not currently provide usable sizes and scales for foundries to properly use with regard to tooling, although the situation is in constant flux.

AM methods are usually categorized into solid-, liquid- and powder-based processes based on the raw material.[2,3] Material extrusion-based technologies are some of the most widely used processes overall, being accessible to consumers, prosumers as well as in many industries. The availability of print materials, general low cost and lack of limitations on overall build size due to the possibility to move the extruder in relation to build areas are some of the main advantages of these processes. For general manufacturing purposes and applications with requirements to

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high production speeds, material structural integrity and if high dimensional accuracy is required, extrusion technologies pose challenges. Extrusion-based technologies have limitations in general with overhangs, defined by a critical angle of a printed component,[2,3] making support structures necessary for more complex geometries. Fused deposition modeling/fused filament fabrication (FDM/FFF), a widely used material extrusion process both industrially and on a consumer level, is generally suitable for smaller scales. Filament-based methods often utilize sub-millimeter nozzles and layer heights,[2,3] although it should be mentioned that somewhat bigger ones are possible and available on the market. Potential material flow rates are thus not optimal for large-scale manufacturing in these processes, resulting in excessive print times and additional time loss risk potential with print failures. Fused granular fabrication (FGF) is an evolution of material extrusion 3D-printing, where feedstocks such as pellets are heated and extruded similarly through nozzles, but often much larger than those in filament-based methods. Bigger nozzles and flow rates allow larger volumes to be printed in hours rather than days, enabling scales relevant to most foundries. Accuracy in shape is naturally lost with the increase in nozzle sizes and layer heights,[4,5] but it should be noted that few additively manufactured parts are usable straight from the printer without any type or form of finishing. The possibility of attaching the extruder to gantries or robots makes it possible to print in almost any arbitrary volume, being mostly limited in the extruder material flows, thus print times. The resulting increase in production capacity for FGF in conjunction with finish machining might provide an answer to the issue of scale. It could be said that any additive manufacturing technology needs to be part of large-scale additive manufacturing (LSAM) or big area additive manufacturing (BAAM) methods to truly be widely usable in foundry patternmaking. FGF has the same inherent properties and challenges of materials extrusion additive manufacturing while additionally having extra ones due to combination of large scales and thermophysical properties of the extruded materials.[6] Liquid-based AM methods, some of such known as stereolithography and vat-photopolymerization, are capable of very high resolutions, accuracies and can achieve great material properties.[3] These methods are limited in certain situations due to liquid container size (vat), speed, hardened layers sticking to separation films, etc., although especially high increases in printing speed have been seen in recent times. Powder-based AM methods can produce components in a wide range of material types in great accuracies, ranging from polymers to metals,[3] and are not as limited in complex geometries due to self-supporting nature of processes like powder-bed AM.

Considering patternmaking and other foundry tooling, several factors that are challenging for general additive manufacturing do not apply to patterns. A reusable foundry pattern requires design factors like drafts for good pattern separation, leading to almost all pattern shapes, excluding specific complex geometries, having naturally no overhangs or undercuts. This makes applications like sand casting patterns a great end-use target for methods with challenges with material supporting. Any hollow feature, infill structure, print support or other internal structure will be irrelevant to the end-use, if the shape is strong enough to withstand the forces of the molding process. These points make FDM/FFF and FGF very interesting in the scope of patternmaking, if the additive process can compete with traditional patternmaking methods in terms of material cost, design time, worker time or use performance. Similar interesting use cases for foundry patternmaking exist with other AM technologies, like liquid resin and powder-based methods, and should be investigated further. One highly relevant and widely accepted use case of powder binder jetting is additive manufacturing of intricate sand molds and cores,[7] allowing ways of new approaches to design of castings. Although many AM methods have interesting properties in the case of patternmaking, the scope of the current work was chosen to compare FGF printing as a potential method to produce foundry tooling and compare one printed material's processability to some traditional ones.

Experimental Procedure

A single sided separate pattern (380 $\times$ 260 $\times$ 90 mm in dimension) was used as a baseline for all materials. Plywood was joined with adhesives and then machined into shape from block. The layers in the used plywood were roughly 1 mm in height. Medium-density polyurethane model board was machined into shape from block material. FGF robotic additive manufacturing was used to print a larger than final shape, with 5 mm of machining allowance (offset) in all surfaces, layer height of 1 mm and 8 mm diameter nozzle. The print was done with a honeycomb infill to reduce use of material, resulting in final internal infill ratio/density of 65% after machining. The print material was cellulose fiber filled plastic composite (20% fill) with a polylactic acid base (PLA), with advertised wood-like post-processing properties. Patterns were 3D-scanned and compared to design geometry (best fit) to analyze geometrical variations from the processes. Examples of manufactured patterns are shown in Figure 1. Industrially typical coatings were applied to the patterns to compare work needed and differences in material behavior. Some general properties of studied materials are listed in Table 1. The 3D-printed material is in the range of high-density tooling boards, while the final pattern weight is similar to the medium-density polyurethane pattern used in this study. Table 2 collects process related data for the different cases studied in this work. Cost of materials have been indexed to relate to the cheapest material, plywood. The raw material cost for the FGF process is based on granule price by weight and printed volume, while

Figure 1. Studied pattern materials: FGF lower left, polyurethane model board lower right, plywood top.

Table 1. General Properties of Studied Pattern Materials

Material	Density (g/cm^3)	Final pattern weight (kg)
Polylactic acid + cellulose fiber (20%)	1.20	2.84
Plywood	0.69	2.52
Polyurethane model board	0.70	2.44

Table 2. Material Costs and Processing Times

	FGF	FDM/FFF (estimate)	Plywood	Polyurethane
Materials cost, index=100	375	–	100	725
Print time, h	4	60	–	–
Machining design (CAM), h	2	–	2	2
Board/block blank preparation	–	–	0,5	0,5
Preparation and setup, h	2 (incl. bottom surfacing)	–	1	1
Machining time, h	1,5	–	1,5	1,5

plywood and polyurethane cases are calculated from the material volume before subtractive processes. Table 2 also contains an estimation print time taken from a slicing software for a PLA filament-based print run with 1 mm nozzle, 0.3 mm layer height, similar print material volume for comparison purposes. Table 3 lists the pattern machining and tool parameters for all the studied cases. The subtractive processes consisted of a roughing phase followed by a finishing step. Pattern coatings tested after machining: polyester resin, alkyd resin nitrocellulose paint.

Results

Print quality of the FGF process is shown in Figure 2. A large nozzle in conjunction with high layers results in rough surfaces. These factors highlight the importance of parameters like layer print start and stop, potentially concentrating defects in certain areas that will be machined later in the patternmaking process. Such areas can be seen on the right side in Figure 2. The general behaviors of the studied materials are listed as follows:

Fused Granular Fabrication

The following behaviors were seen processing the FGF-printed PLA and cellulose composite material:

- Printed dimensions were 1–2 mm sunken compared to design CAD model and some parts were horizontally bigger. 3D-scanned comparison of print size design geometry and print result is shown in Figure 3.
- Bottom side was warped/curled, requiring a 1–2 mm material removal for straightening before being mounted for the upper side machining processes
- Some air pockets were found during machining, shown in Figure 4
- The 5 mm machining allowance was sufficient to reach nominal/final design dimensions
- Some machined features were near horizontal layer/fusion lines (nozzle extrusion diameter), sometimes developing cracks, damage, chipping, etc., shown in Figure 5.

Table 3. Machining Parameters Used for All Materials

	Roughing	Finishing
Tool diameter, mm	20	16
Tool corner radius, mm	0	4
Spindle speed, r/min	8000	10,000
Cutting speed, m/min	503	503

Figure 2. FGF print before machining.

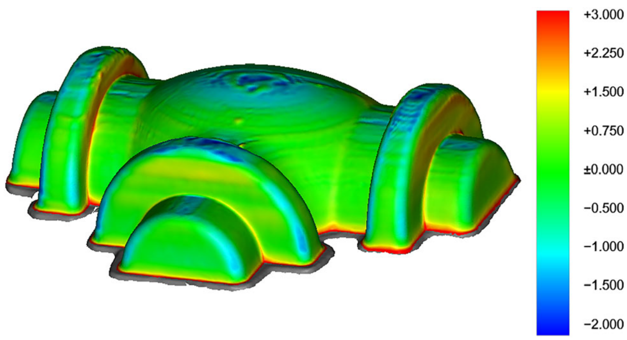

Figure 3. 3D scan-based dimensional differences between 3D-model and FGF print result (scale in mm).

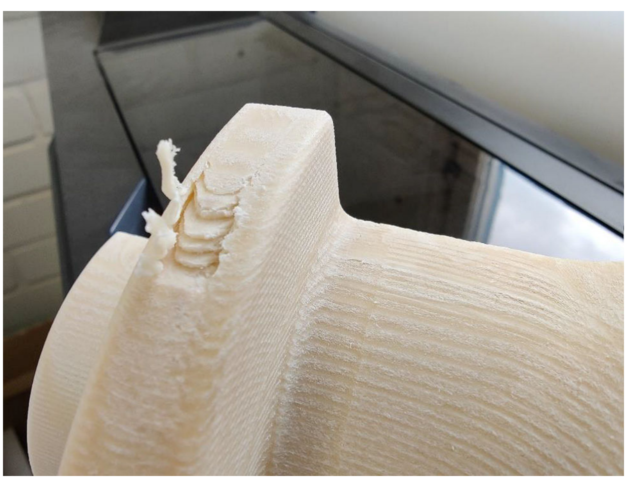

Figure 4. Incomplete fusion and air pockets in FGF print.

- Infill/hollow structures, shown in Figure 6, are a challenge when mounting is considered, e.g., addition of screws and inserts, requiring knowledge where internal structures are located
- The high density of the material in conjunction with the layered structure creates some challenges with surface finishing, especially in case of adhesion/extrusion defects, shown in Figure 7. It is advisable to design the material removal to not be near fusion zones, illustrated in Figure 8.

Figure 5. Chipping of FGF print material during machining.

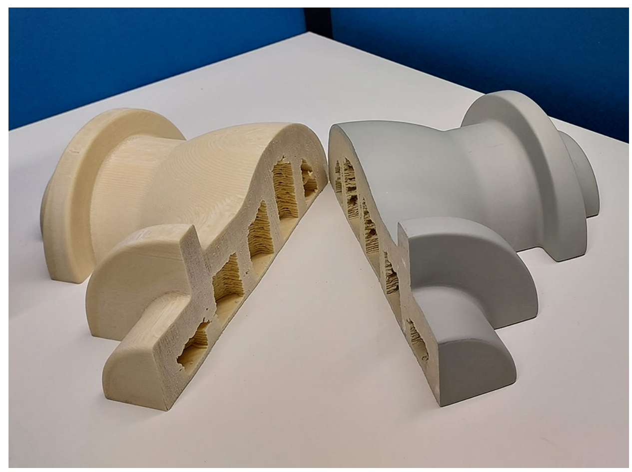

Figure 6. Cut-away view of FGF manufactured, machined (left), and coated (right) patterns.

Figure 7. Layer adhesion defect in FGF-printed material.

- Layer lines tended to create some difficulties in applying basecoats and processing said coatings, layer lines and associated defects, like shown in Figure 7., being visible even after several applied coats
- More work in preparation, setup and time required in CAD/CAM design compared to bulk/block materials. Times are listed in Table 2.

Traditional Pattern Materials

Plywood and polyurethane patterns were manufactured for comparison. These exhibit the following behavior compared to the FGF-printed material:

- Polyurethane model board is the most consistent of the studied materials to work with due to the homogeneous nature without layer-structures
- Plywood is naturally the most traditional “wood-like” regarding processability, as the FGF material is still a cellulose-plastic blend
- Plywood and FGF were similar with regard to the layer structure, but the softness of the wood makes processes like sanding easier

Comparisons made with 3D-scan results between final pattern design geometry (reference) and as-machined states (actual) are shown in Figure 9 (FGF), Figure 10 (plywood) and Figure 11 (polyurethane). Registration of scan results has been done with best-fit method. Most variation can be seen in the plywood pattern, while the FGF and polyurethane patterns are close to one-another. The polyurethane model board pattern is the most uniform in surface quality, while the FGF pattern is generally the closest to the design geometry based on these scan results. While the high-density FGF pattern is more challenging to machine, the material is dimensionally stable during the process based on these results.

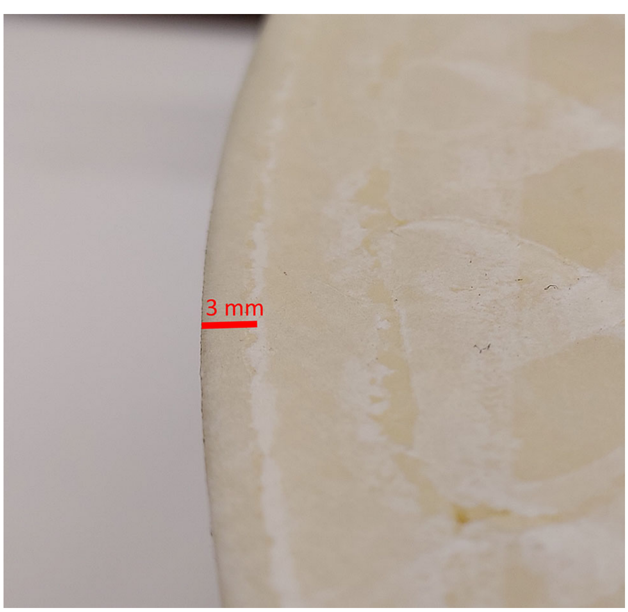

Figure 8. Distance from surface to nearest extrusion fusion zone, viewed from underside of pattern. 3 mm distance highlighted in red.

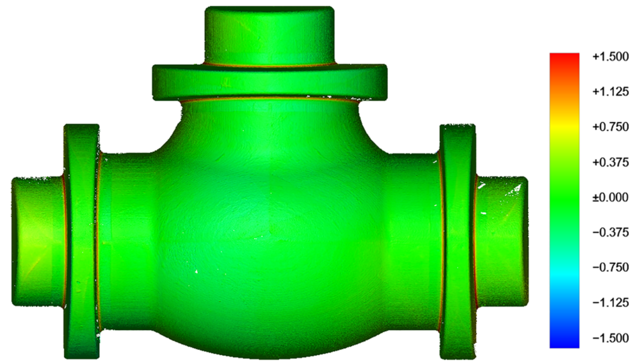

Figure 9. 3D scan-based dimensional differences between final pattern design geometry and FGF print after machining (scale in mm).

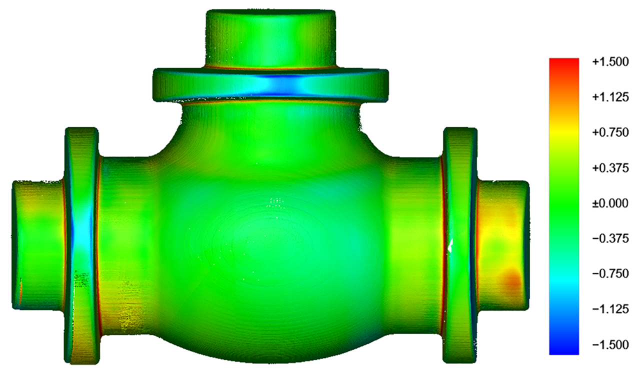

Figure 10. 3D scan-based dimensional differences between final pattern design geometry and plywood pattern after machining (scale in mm).

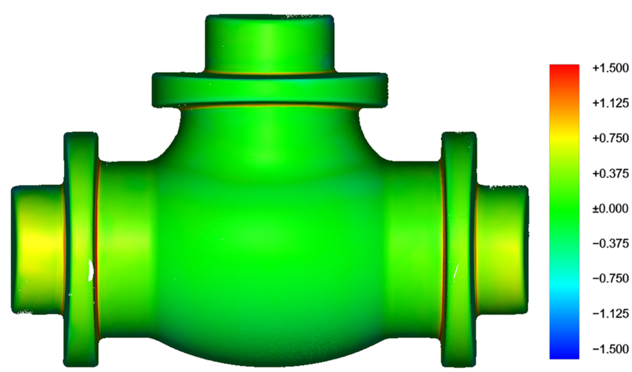

Figure 11. 3D scan-based dimensional differences between final pattern design geometry and polyurethane pattern after machining (scale in mm).

Discussion

From the experimental results, at least the following challenges can be postulated:

1. Layered structure ↔ layer adhesion ↔ extrusion flow
2. Material thermophysical behavior during the printing process ↔ deformation
3. Nozzle diameter ↔ wall thickness ↔ required machining allowance
4. Layer print start seam alignment

As a material extrusion process in a layered manner, those considering the FGF method should take material homogeneity into account. This relates to material printability, print parameters and accuracy of used machine control systems. The first point also relates to point two; the elevated temperature printing process, subsequent cooling and shrinking is not unlike what those working on metal castings need to consider. Elevated temperatures are needed to achieve proper material fusion, while the subsequent cooling imposes geometrical changes, necessitating addition of dimensional allowances to the design. The two first points lead to the third; material removal and the final surface should not be too near the layer fusion zones. Differences in layer adhesion might lead to inhomogeneous surfaces after machining, like illustrated in Fig 7. Even small areas of incomplete fusion, that otherwise would be left internal and be irrelevant, can lead to chipping of material under high cutting forces in machining, illustrated in Figure 5. This is especially important for materials with lower impact toughness, like unmodified PLA is known for.[3] Thus, material removal should end up more in the middle of a single extrusion zone, rather than near the edges to alleviate this problem, as seen in Figure 8. This should be considered while choosing printer nozzle sizes. Another considerable parameter affecting the potential of defect creation is layer print start seam alignment, the point where printing of each layer is started and stopped. If these points are not randomly distributed, or otherwise properly set up, multiple seams concentrating vertically might cause cracking during machining, as illustrated in Figure 5.

Considering foundry patterns, requirements for surface quality with regard to pattern release from molds are rather high. The economies of scale natural to serial castings are the result of good tooling. From small series to large series, the requirements for releasability, pattern wear, etc., increase. In patternmaking, compared to bulk materials, additive manufacturing has certain potential benefits, like material and cost saving with use of infill and lattice structures offsetting increased base material costs of high-performance materials. Henderson et. al. studied and compared various additive methods of making foundry patterns,[8] seeing several potential benefits of utilizing additive manufacturing. They postulated that materials and printing methods must balance increased print speed (Big Area Additive Manufacturing) with degradation in surface finish, since a rough finish will further complicate mold/pattern separation when producing sand molds. In their work, utilization of high-resolution FDM printing improved surface quality compared to BAAM, although some issues with surfaces were seen and breakage of patterns was found with low infill parts. Dimensional accuracy of FDM printing is dependent on multiple factors; like print material, nozzle temperature, print speed, part geometry[2–5] to name a few. Thus, there is a lot to consider when balancing print times and as-printed surface quality. Photopolymerization methods, where liquid resins are hardened in layers, are not exempt from variations and inaccuracies based on geometry orientation either.[9] More research is needed to find the niche and best available processing methods for any additively manufactured components, as raw material costs often favor the use of traditional subtractive processes.

Similar findings to the reference material are evident in the current study. The FGF process lowers print times to matter of hours (4h), compared to FDM where the similar geometries would have taken days to print (60h slicer estimate) with usual materials and nozzle sizes. Given that the studied pattern can be considered small as far as foundry patterns are concerned, these differences in print times become much bigger when the print scales are increased. The loss of surface quality with the FGF method can be mitigated with machining, as was done in this study. However, this type of a process necessitates some additional design factors. As is usual in design of a cast components, one needs to consider dimensional manufacturing tolerances and required machining allowances. Such matters are globally standardized for different molding methods when dealing with metal castings. Sagging, behavior of components with cavities and existence of higher thermal gradients are important design factors for LSAM/BAAM due to the larger scales.[4] All of these should be considered when designing material allowances for additively manufactured and machined patterns or other types of components. In the current study, the added 5 mm allowance was enough to reach nominal design dimensions of the final pattern. The sagging of the upper side of the print resulted in 1–2 mm of material loss compared to the print design geometry. Warping of the bottom side required roughly 1 mm of material removal. Although some challenges in processing the FGF-printed material existed, the process allows the use of higher density materials with lower final pattern weights due to the possibility of hollow structures. With the current materials and infill structures, rather similar pattern weights were achieved with a material having 70 % higher density compared to the traditional medium density ones. The material costs, listed in Table 2, placed the FGF manufactured PLA/cellulose blend roughly halfway between the cheapest, plywood, and the most expensive in the tested materials, polyurethane. The possibilities of using optimal infill patterns, with regard to strength and material use, will potentially enable the use of higher density, stronger and wear resistant materials, while keeping costs at a sane level by reducing the amount of printed material. One potentially positive aspect of thermoplastics with both filament and granule-based methods are repurposing and recycling of printed components back to printable raw materials. However, reuse of printed materials poses some technical, like material degradation, and regulatory issues, as outlined in review made by Sola.[10]

The studied process of printing and machining on different machines, necessitating remounting of printed parts for the subsequent processes is not the most optimal way one can imagine. Actual pattern shape machining times are similar between the different methods, although the need for preprocessing is a factor for a printed patterns. In this case, additional work time was required in the case of FGF pattern, shown in Table 2, owing to straightening the bottom side for the subsequent machining processes. One of the potential ways to overcome the showcased challenges is the utilization of hybrid manufacturing methods, where additive and subtractive processes are combined in the same machine. These kinds of machinery are starting to be available on the market, utilizing pellets/granules for high production rates, while machining is used to ensure dimensional accuracy. The possibility to use high performance and functionally graded materials,[11] allowing location-specific properties, should also be investigated also for the use of foundry patterns. Additionally, tools and functional components/patterns are possible with additive manufacturing. For example, Billah et al. investigated large-scale additive manufacturing in the production of self-heated molds[12] for composite production. Integrating heating wires into molds during the printing process allowed locally heated molds. Such systems could be beneficial for specific foundry tooling as well, considering inorganic and other relevant heat-cured binder systems. These additional possibilities especially have potential regarding core boxes and other tooling where one needs to consider input of gas, heat, distortion, etc.

Conclusion

- FGF poses some challenges usual to additive manufacturing which are not relevant in bulk material removal processes
- The layered cellulose-plastic blend behaves between a homogenous hard plastic and layered wood, requiring care in processing and knowledge of print parameters like fusion lines
- Additive manufacturing enables the use of infill structures, allowing the use of higher density materials with final pattern weights similar to lower density bulk materials, while decreasing material use and thus also cost
- Given that challenges like presented in this study are recognized and counteracted with design, the FGF method in conjunction with finish machining has potential regarding large-scale patterns

Ongoing work on the showcased pattern materials include dimensional stability during storage and use, binder reactions and manufacturing efficiency.

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