Title:

Fused Deposition Modelling Design Rules for Building Large, Complex Components

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Introduction:

The Fused Deposition Modeling (FDM) process is a bead deposition process which builds a product from thin layers of molten thermoplastic filaments (i.e., acrylonitrile butadiene styrene (ABS), polycarbonates, polycaprolactone, polyphenylsulfones, and waxes). The wire is fed through a temperature-controlled head and the material extruded when it is in a semi-viscous state. The resulting bead is elliptical in shape.

The head is mounted on an x-y positioning system. The table is mounted on the z axis, which is indexed one layer thickness lower after each layer is deposited. The extrusion head has two outlets, one for the component material, and the other for the support material. The support material is required for overhanging features such as holes orthogonal to the build direction. The component and support materials are deposited in separate operations per layer. The beads for the perimeter and fill for the build material are deposited, and then the support material is extruded as appropriate (Figure 1). The support material must be removed afterwards. Depending on the feature location and the support material properties, this can be a time consuming process.

The process planning decisions are typically limited for the additive manufacturing process family, and minimal decision making is required by the designer to build a component via the FDM process. The process equipment, planning options available in the original equipment manufacturer (OEM) software, the build material, and the support material characteristics need to be studied when developing a process plan. The impact of orientation on the build time, material usage, and the surface finish has been investigated by many researchers, and is expanded upon with examples in this work. Researchers have presented multiple solution approaches to quickly determine an orientation that minimizes the support material, or maximizes the horizontal area to address time and surface finish concerns [2-3], [7], [9-10], [12-13]. Adaptive slicing is an interesting solution proposed to address both the time and finish concerns. In regions of high curvature or near horizontal slopes, thinner slices are employed to reduce the stair stepping effects [10-11]; however, this adaptive slicing is not option is available in the commercial systems at this time. Realistically, surface finish is an issue, especially at the support material-build material interfaces; hence, post processing strategies must be considered as part of the process planning strategy. The build times for the specialized spherical ball joint illustrated in Figure 1, for various slice thicknesses, is illustrated in Figure 2.

For designs related to rapid tooling, prior research has typically been directed on the Selective Laser Sintering (SLS), Stereolithography (SLA), or 3DP processes [5], [8]. Limited information is available focusing on general FDM design rules for large complex parts, and specific rules for rapid tooling development, which are both discussed in this research. For example, in lieu of a multiple core assembly, an intricate non-planar parting surface is utilized for a match plate pattern (one pattern used for both the cope and drag) for a rear upright casting. A modular assembly approach for a V-block 'slice' casting pattern set utilizes the FDM process for the complex intricate geometry, and machining is used for the gate, runners, and other large simple components.

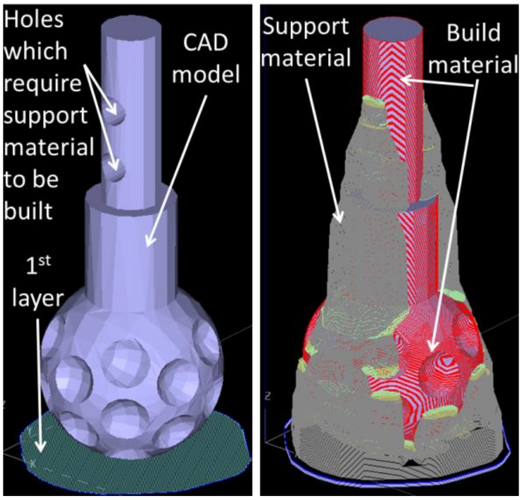

Fig. 1: The FDM fabrication for a specialized spherical ball joint. Note: the horizontal through holes require support material to be able to build the overhanging arches.

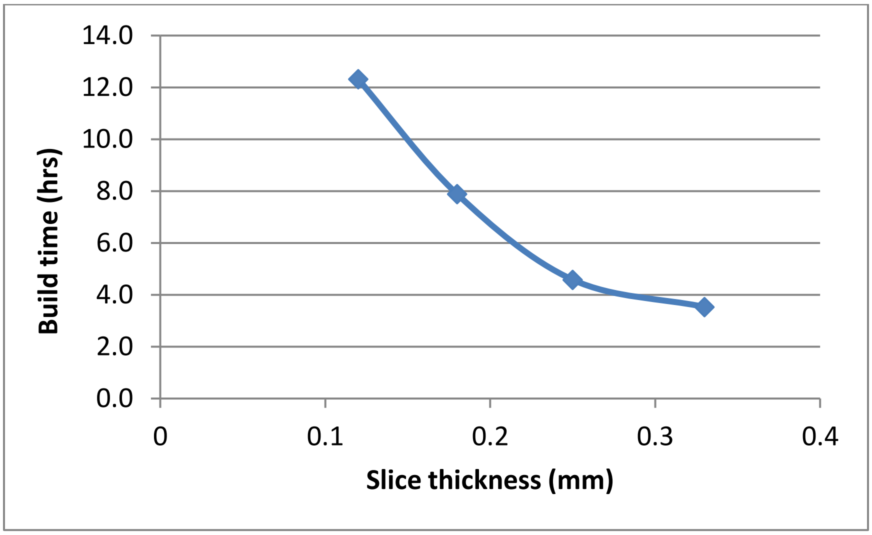

Fig. 2: Build time variations for a solid fill strategy, with sparse support material.

The long-term goal of this research program is to develop design and modeling tools to support material deposition processes, in particular the FDM process. This includes: (i) developing design rules to leverage the FDM advantages and overcome its limitations, (ii) reduction of the material costs (i.e., using internal structures as an intermediate fill strategy), (iii) optimal assembly methods to fabricate large components, which require segmentation, and (iv) improvement of the overall fabrication time (including the build, finishing and assembly tasks). The goal of this research is to leverage the advantages of the FDM process to allow designers to focus on functional design while reducing the complexity when fabricating the final component or assembly. Design rules have been developed to address the FDM process advantages and limitations. Many were determined when designing and fabricating large sand castings patterns. Complementing the design rules for large, thick, and rigid components (casting patterns) are unique segmentation, reinforcement, and build strategies for large thin walled parts. Many project examples are presented to show both the benefits and challenges related to applying the FDM process for large component fabrication.

Main Idea:

The FDM process introduces unique fabrication advantages and challenges. The 'design for manufacturing' aspects for FDM focus on: (i) large component segmentation (Figure 2), (ii) understanding the impact of the build orientation and its impact on surface finish, build time, and material usage considering the application and post processing tasks, (iii) building assemblies (Figure 3), and strength considerations. Along with introducing general FDM 'design for manufacturing' guidelines, specific design rules for rapid tooling are presented.

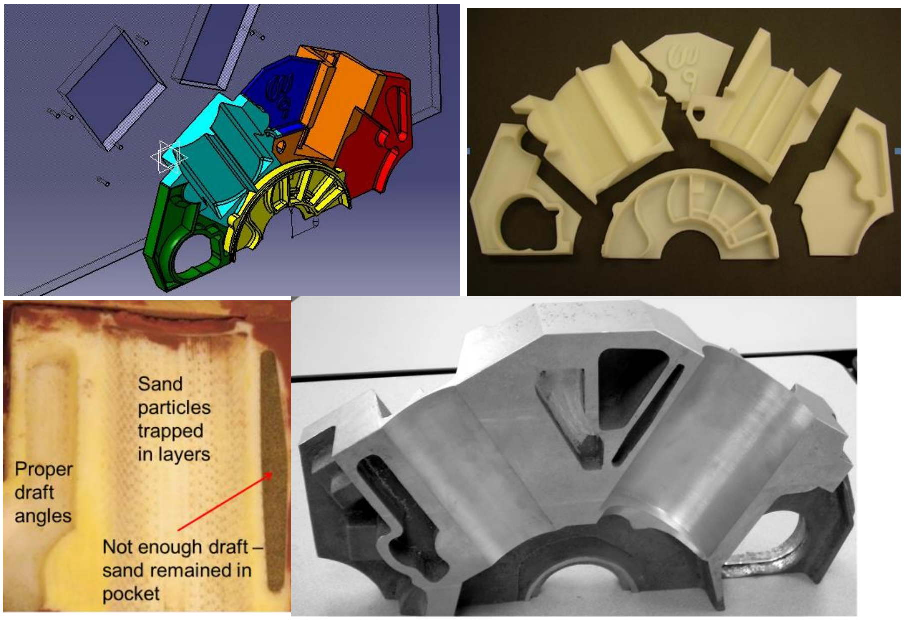

Fig. 2: V6 block section modules, assembly (cope – top, drag – center), sample module (orange cope module), and final cast part, adapted from [14].

Anisotropic properties for the FDM process have been reported by several researchers [1], [4], [6]. Depositing the material in fiber-like beads creates variable strength characteristics, which differ based on the build orientation of a component, and the raster fill strategy. Tension and compression tests are performed experimentally with ABS [43] and polycarbonate (PC) materials using the ASTM D638-10 and ASTM D695-10 standards and selected results are presented. Currently, contemporary anisotropic strength analyses consider the de-bonding between layers and not the bead placement within the layers (short fibers from disjointed tool paths) due to the tool path strategy (Figure 4). When comparing the theoretical volume of the CAD model to the build material usage, there is an 11.5% difference. No unexpected failures occurred when the void volume is less than 6%; hence, it is proposed to use a design threshold as follows:

$$\frac{Build\ material\ usage}{CAD\ model\ volume} \geq 95\% \qquad (1)$$

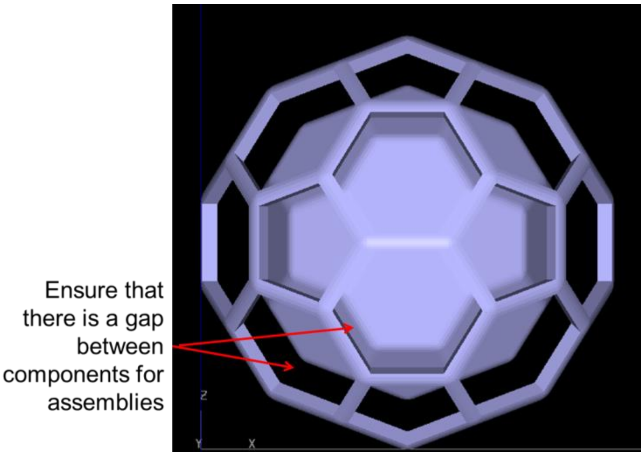

Fig. 3: A soccer ball within a soccer ball mesh assembly with a gap.

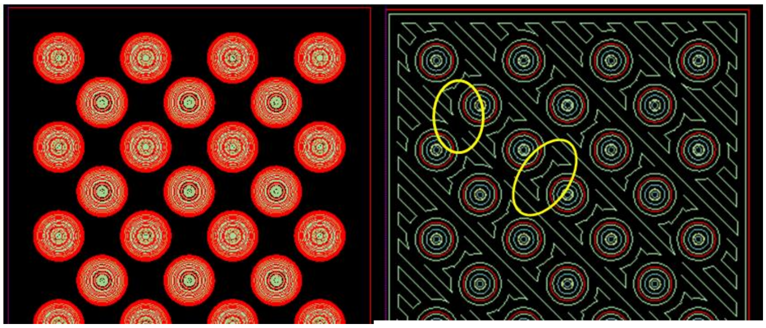

Fig. 4: Designed voids to reduce the material usage, and voids due to the tool path discontinuities.

Several case studies highlight the design and fabrication potential. Rapid tooling solutions for complex sand casting patterns are presented, as well as a smart phone charging station designed to showcase the FDM process.

Conclusions:

Additive manufacturing technologies allow for a great deal of product customization and optimization, as sophisticated process planning strategies, as well as tooling and fixtures requirements, are essentially eliminated. It is important to understand the potential and limitations of each AM process so that it can be appropriately leveraged. In this research, designs are optimized with respect to the final product usage. "Design for machining" aspects were not considered, as they would potentially compromise other design goals. Although complex components are readily fabricated using FDM processes, there are limitations with this technology with respect to the size, surface finish, and accuracy. As well, there may be no real advantage using the FDM process for components with simple geometry, such as components with simple contours, pockets, and holes. For these components, it may be more cost effective to use conventional machining processes [39]. Never the less, using this flexible manufacturing tool intelligently opens windows of opportunity. Limited technical resources are required and significant time savings can be realized for component fabrication, as illustrated in the above case studies. As improvements to the travel paths, materials, and other advancements are being made, the FDM has limitations experienced in this research are being addressed.

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