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Fused Deposition Modeling Design Rules for Building Large, Complex Components

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ABSTRACT
The Fused Deposition Modeling (FDM) process is a bead deposition based additive manufacturing (AM) process that builds a product from thin layers of molten thermoplastic filaments. The ongoing goal of this research is to develop methodologies for designing and fabricating large complex parts such as complex beta testing prototypes, or sand casting patterns. The unique capabilities of the FDM process are leveraged when designing components and assemblies. Complex geometry can be readily manufactured allowing designers to incorporate non-standard component features, and consider unique solutions; however, there are size, surface finish, and accuracy limitations. Rules are developed to leverage the process characteristics and address the observed limitations. Case studies are presented to highlight the benefits and challenges when using the FDM process.

KEYWORDS
Fused deposition modeling; design rules; limitations; rapid tooling

1. Introduction to the Fused Deposition Modeling Process

Additive manufacturing (AM) or layer manufacturing (LM) refers to material deposition processes which produce a three dimensional part directly from computer aided design (CAD) geometry by stacking two dimensional (2D) slices to create a three dimensional (3D) component or assembly. Each 2D slice is built via boundary travel paths and a raster-based fill strategy. This technology family allows designers to fabricate complex designs (Fig. 1) with minimal effort.

Several layer manufacturing technologies are available, and are utilized in a variety of applications (Fig. 2). Many applications focus on patterns and tooling applications [25]. Several rapid tooling (RT) processes are commercially available – some produce the tool directly such as selective laser sintering of molds; however, the majority of RT technologies use the model created by the AM process as an intermediate step within the tool development process [12, 15]. The fused deposition modeling (FDM) process is the AM process utilized for this research and the case studies include sand casting patterns.

The (FDM) process is a bead deposition process that 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 is 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 the holes orthogonal to the build direction, the sphere base, and some indentations illustrated in Fig. 3). 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. The support material must be removed afterwards. Depending on the feature location and the support material properties, this can be a time consuming process.

Unlike welding where the base and filler material are mixed in the weld pool, the bonding between individual roads and layers for the FDM process is done by molecular diffusion. This bonding is enhanced by the thermal energy of the extruded fiber in molten state [33]. The side-to-side beads do not necessarily overlap (standard for the 'shell' or sparse build strategy and some support build strategies) and there may be a significant air gap.

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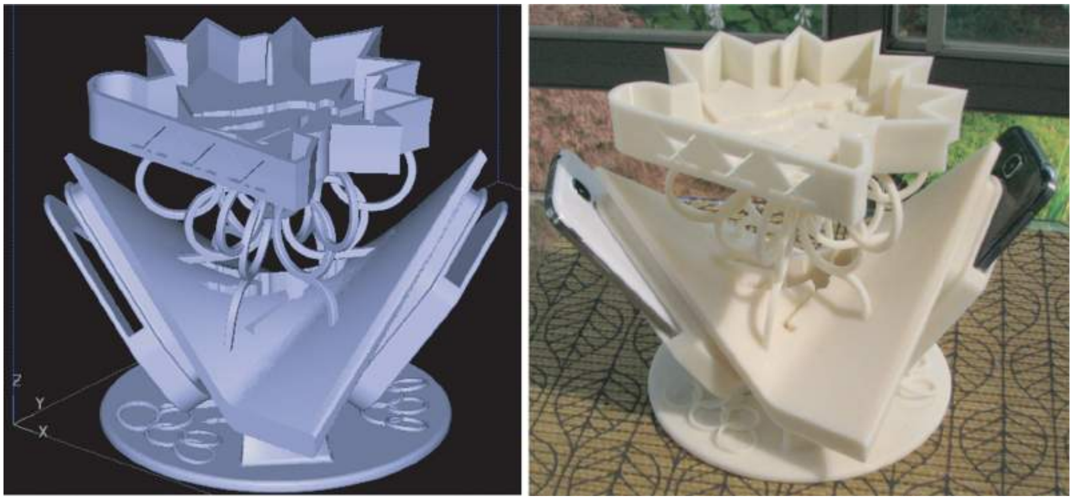


Figure 1. Cell phone charger stand model and built component, illustrating intricate interlocking structures and recessed features.

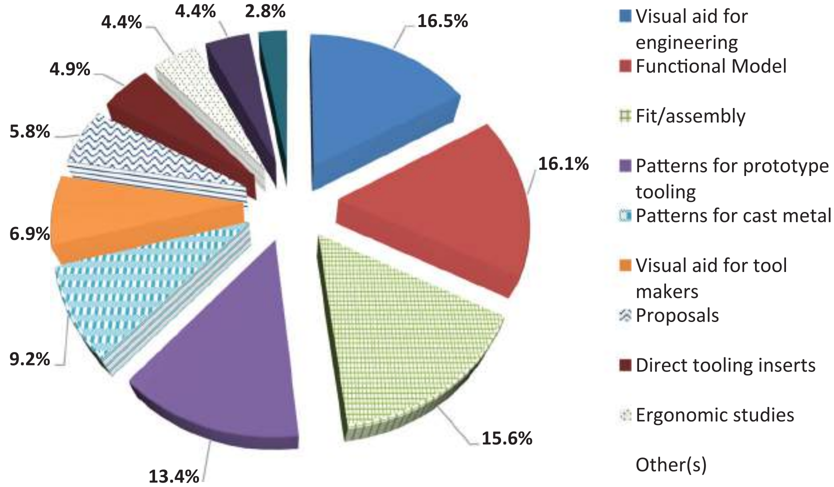


Figure 2. AM applications adapted from [1].

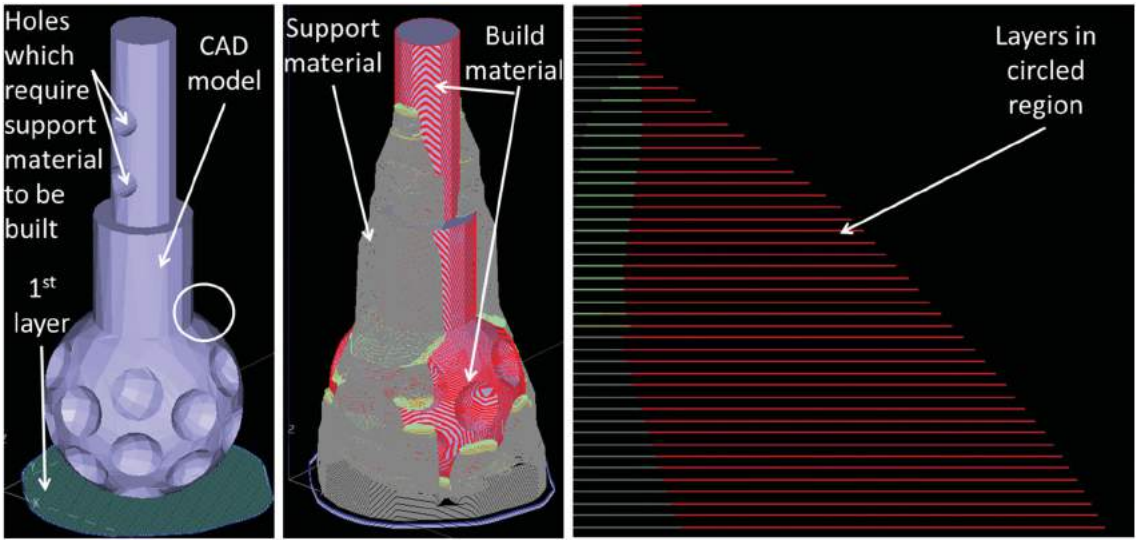
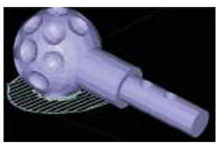


Figure 3. The FDM fabrication for a specialized spherical ball joint.

Table 1. Time and material requirements for the specialized spherical ball joint built in the upright position, varying the fill and support build strategies.

90° UP	Solid (T12 tip) 0.18 mm slice height Basic support	Solid (T12 tip) 0.18 mm slice height *Sparse* support	Sparse (T12 tip) 0.18 mm slice height Basic support	Sparse (T12 tip) 0.18 mm slice height *Sparse* support
Time	*8 hr 2 min*	*7 hr 53 min*	*7 hr 59 min*	*7 hr 51 min*
Build Material	48.630 cm^3	48.589 cm^3	30.355 cm^3	30.331 cm^3
Support Material	39.563 cm^3	36.415 cm^3	39.563 cm^3	36.432 cm^3

Table 2. Time and material requirements for the specialized spherical ball joint built in the 'material optimized' position, varying the fill and support build strategies.



	Solid (T12 tip) 0.18 mm slice height Basic support	Solid (T12 tip) 0.18 mm slice height *Sparse* support	Sparse (T12 tip) 0.18 mm slice height Basic support	Sparse (T12 tip) 0.18 mm slice height *Sparse* support
Time	*3 hr 19 min*	*3 hr 20 min*	*3 hr 11 min*	*3 hr 13 min*
Build Material	37.594 cm^3	37.585 cm^3	19.035 cm^3	19.030 cm^3
Support Material	13.977 cm^3	12.199 cm^3	13.977 cm^3	12.308 cm^3

When a sparse build strategy is employed, a loosely woven interior is generated with the bead (0.34–0.66 mm wide) spread apart 3–4 mm. The basic boundary thickness is three beads for the sparse build option, but there may be regions where additional material is utilized.

Parts are quickly built when a sparse build option is specified. FDM parts built in the 'solid' mode are dense, but not void free. For all build conditions, the resulting fabricated component has anisotropic properties [2], [7], [18], [19], [29], and [43]. Typically, the component built by the FDM process is stronger in compression than in tension [2], [7], [18], [43].

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. Consider the specialized spherical ball joint in Fig. 3. The build orientation, fill strategy, and layer thickness is modified and the time and material usage compared. Varying the orientation significantly impacts the build time (Tab. 1 and 2). Interestingly for this example, the build time is almost constant for the various fill strategies per orientation. Some limited material savings can be realized; however, as strength (discussed in section 4.2) is a key consideration for this component, this factor is not exploited.

The surface finish for the cylindrical features will have significant gaps when the unit surface normal approaches (0,0,1) as the gaps between the layers is large (Fig. 4). If the build options result in this, additional finishing may be required, depending on the final application. Changing the slice thickness impacts the build time significantly (Fig. 5), as well as the amount of material used (Fig. 6). The longest build time is 12 hr 19 min for the 0.12 mm slice thickness. Increasing the thickness by approximately a factor of 3 reduces the build time to 3 hr 32 min. As there are voids in the component interior, a finer slice thickness results in a denser final part as approximately 25% more material is used for the finest slice thickness compared to the coarsest slice thickness. Although the FDM process planning is limited, this example shows the planning considerations need to include evaluating the part shape, the functional requirements related to strength and surface finish with respect to: (i) the build material, (ii) the part orientation, (iii) the layer thickness, (iv) support material, and (v) post processing requirements. The optimal orientation may not be evident as it depends on the part complexity, the nature of the support structures, and downstream post processing requirements.

For the Prodigy 100® or Fortus 400 MC® FDM machine used in this work (Tab. 3), various build layer thicknesses can be selected within the software package (Catalyst® for the Prodigy 100 and Insight® for the Fortus 400 MC). For this work, 0.178 mm, 0.254 mm and

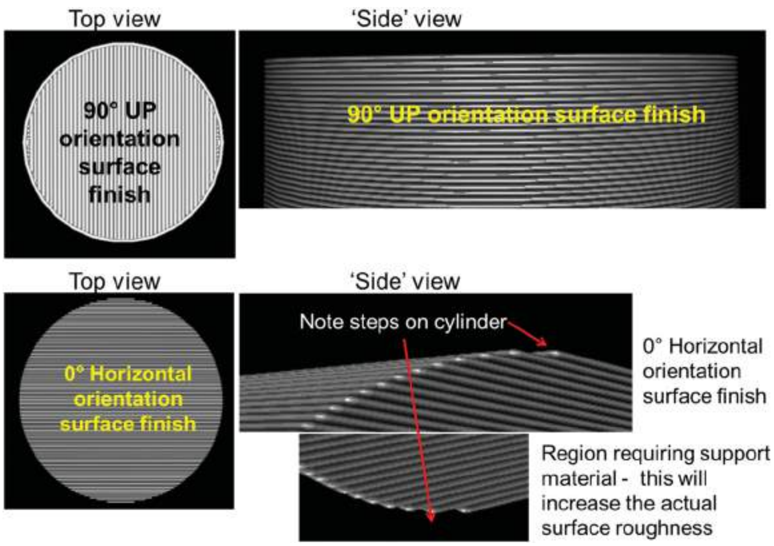


Figure 4. The surface finish for the cylindrical body for the two presented build orientations.

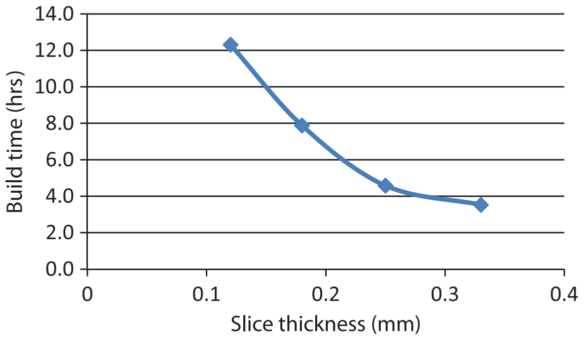


Figure 5. Build time variations for a solid fill strategy, with sparse support material, 90° UP build orientation. Note: the trend line has an $R^2 = 1$ for a polynomial fit, and a trend line fit of an $R^2 = .99$ for an exponential fit.

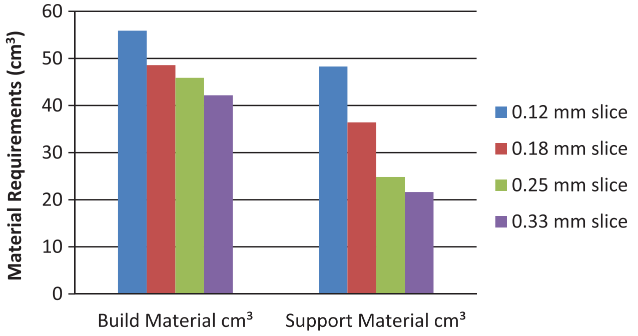


Figure 6. Material use variations for a solid fill strategy, with sparse support material, 90° UP build orientation. Note: ∼ 25% more material is required for the 0.12 mm slice thickness compared to the 0.33 mm slice thickness.

0.330 mm slice thicknesses are used. The bead width and height have a 2:1 ratio; therefore, the bead width is limited to 0.356, 0.508, and 0.660 mm although other options are available on the Fortus 400 MC.

The material is ABS for both the build and support materials, although the support material is more brittle. Water soluble support material is utilized for the parts built on the Fortus 400 MC. The layer thickness is constant throughout the part. A raster scan deposition strategy is utilized; however, the spacing is different for the support and build material travel paths. The user selects the fill strategy, the support type, and the component location and orientation within the build envelope.

An overview comparing machining to additive manufacturing is presented in Tab. 4. Clearly, the strengths associated with AM processes are related to limited process planning time, hard tooling costs, and skill sets required to manufacture a component. For intricate low volume applications such as prototype tooling, there may be significant cost benefits utilizing this technology.

If there are sharp internal corners in the original model, the FDM built part will also have sharp corners. To achieve sharp internal corners is challenging in material removal processes. Specialty cutting tools, tool paths, or processes (i.e., sink EDM) must be utilized. In many instances, a process designer is provided a limit with respect to the allowable fillets. Cutting tools and tool paths are optimized based on the application and environment. For certain applications such as molding patterns, proper, complete filleting must be incorporated in the model, and is critical for both product and process robustness. Special consideration must be taken when applying fillets to the model to ensure they are large enough to model using the desired layer thickness. For a part built by the FDM process (and AM processes in general), the surface finish is a resultant output characteristic influenced by the layer thickness and the component geometry. The surface finish may also be impacted by

Table 3. FDM machine characteristics.

Machine Type	X (mm)	Y (mm)	Z (mm)	Software	Build Material	Support Material	Width to Height Ratio
Prodigy 100	203.2	203.2	254.0	Catalyst	ABS	Breakaway	2:1
Fortus 400 MC (large)	406.4	355.6	406.4	Insight	ABS	Soluble	2:1

Table 4. Machining and additive manufacturing comparison summary, adapted from [41].

	Machining		Additive Manufacturing	
Feature	Advantages	Disadvantages	Advantages	Disadvantages
Material versatility	'Any' material can be machined, but there are optimal material-process-tool combinations which must be considered	Optimal material-process-tool combinations must be considered due to the material ductility, friability, etc.	Unique material combinations can be utilized for powder-infiltrate systems, multi-material sets can be used for laser cladding type systems	Limited materials are available (tend to be non-metallic and expensive) Anisotropic material prosperities, potential for generating voids and gaps during the build process
Process planning	Control of each operation element	Specialty fixtures and tools may be necessary, high level of interaction is required Many operations, tool paths, tools and fixtures are required to fabricate components with complex geometry	Simple process planning, minimal material waste, Unlimited geometrical complexity, component can be optimized for product usage Requires no special fixturing or tools	Limited modifications are possible
Accuracy and surface finish	High levels of accuracy possible Ability to control the surface finish through speed, feed rates, number of axes, step over, tool geometry, coolant and so forth			Limited accuracy: influenced by the layer thickness, orientation, geometry, thick wall – thin wall conditions, support structures or final processing requirements Surface finish is a resultant impacted by layer thickness, orientation, support structures (may require extra processing)
Part Size	Machines with large build envelopes are available			Limited build sizes
Personnel and support		Need to be proficient with manufacturing tools and processes Coolant and chips need to be controlled and disposed of	Minimal levels of supervision are required for fabrication	Time consuming to fabricate simple components with simple geometry, and perform post processing operations
Volumes	Efficient for mass production		Efficient for small quantities of complex unique components	

the support material. Regions that have support material are generally rougher. Removing the support material may also mark or damage the surface. These issues need to be taken into consideration, as additional fillet modeling and post processing for surface smoothing may be a requirement, depending on the application, layer thickness, and the form curvature.

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 focus 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 are being developed to address the FDM process advantages and limitations. Many were determined when designing and fabricating large sand castings patterns. These examples are presented, along with additional examples to show the benefits and challenges related to FDM.

2. Design for X – Casting, Pattern, and Additive Manufacturing Design Review

2.1. CAD Model considerations

In the CAD model, whether it is a surface or solid model, each component must be constructed from manifold geometry; otherwise, there will be processing errors during the build process. When generating the Stereolithography Tessellation Language (STL) file from the CAD model, the chord tolerance must be selected such that the model is as small as possible to minimize travel path generation time, but has also no undesirable facets on curved surfaces.

2.2. Pattern design overview

Casting patterns may be fabricated from wood urethane or metal, depending on the required volumes. Each material has its own manufacturing and durability issues such as susceptibility to corrosion or high wear. The design considerations related to pattern design focus on the final casting / molding process as well as considering machining capabilities and limitations. Heat control is a fundamental concern for robust castings. Utilization of chills, incorporating uniform wall thicknesses or graduated blending, minimizing sharp angles and corners (using rounded junctions), minimizing the number of sections / ribs together at one point (i.e., staggering junctions), properly proportioning inner walls, and filleting all sharp corners will balance heat flow, and are common design practice. The goal is to have homogenous cooling to prevent distortion, warpage, shrinkage voids, or cracking. Large fillets (equal to the wall thickness or greater) reduce stress concentrations and a draft angle is applied to all walls, ribs, and bosses parallel to the parting direction (preferably 2° - 3°) to facilitate part removal from the mold [8], [14]. Integrating the product requirements in tandem with good design practice for casting may result in complex models, which are challenging to machine.

Pattern segmentation is typically required for casting / molding processes. Parting lines, internal, and external core assemblies may be required as well incorporating a feeding system (gates, runners, sprues, vents, etc.). Cores add complexity; consequently, reducing or eliminating the need for cores is a design goal. Rapid tooling is a growth area due to the shape complexity typically associated with patterns, and is not a mature area of research. Researchers have explored different AM processes to manufacture patterns or molds [6], [15–17], [21–23]. However, comprehensive guidelines are not established, as the capabilities and limitations of AM processes, such as the FDM process, are evolving.

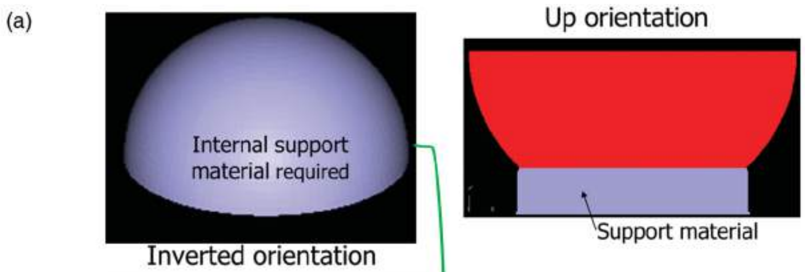
2.3. Large component segmentation

Unique fabrication challenges occur when building complex components larger than the machine build envelope. If the part cannot be rotated in 3D space to fit the envelope, the component needs to be segmented. Decisions need to be made related to the sub-division and assembly tasks. This is an issue with all AM type processes, as the build chambers tend to be enclosed, and systems have not been designed to be extendable. When sub-dividing a component, one does not want to introduce manufacturing and assembly issues that will influence the integrity of the final component. Nevertheless, segmentation introduces both unique challenges and opportunities for components manufactured by the FDM process.

Some overhang conditions (45° or less from the vertical axis) do not require support material, which introduces a potential material savings with appropriate segmentation strategies. When dividing the shelled hemisphere into segments (Fig. 7) the amount of material requirements is reduced, as less support material is required. Therefore a segmentation strategy that leverages this process feature and the introduction of 'Design for Assembly; (DfA) considerations provides additional criteria that can be explored related to process planning and potential optimization strategies for building FDM components.

Tang *et al.* develop an algorithm, which combines the flat planar parting methods and a feature-based volume decomposition methodology. The segmented components can be built in an orientation that optimized the surface finish; however, assembly features are not incorporated, nor are minimum feature size limits stated. Their solution approaches were tested with the 3D printing (3DP) and selective laser sintering (SLS) processes [37]. Dimitrov *et al.* investigated incorporating 3DP with conventional casting processes to develop economically and technologically acceptable process chains for manufacturing of functional prototypes for low volume applications. The issues associated with splitting a large master pattern are recognized as impacting the process flow. Unfortunately no working guidelines are presented in this work [15]. A structured reduction process is presented by Medellin et *al.* [28], where the base CAD model (cylinder head model) is decomposed into a set of 'grid-based' building blocks, each with unique assembly interface features. Chan and Tan [10] also propose a volume decomposition process to segment the model, while considering the degrees of freedom related to the assembly features. Unfortunately, several practical elements not considered for either of these solutions, such as the build limitations related to accuracy and

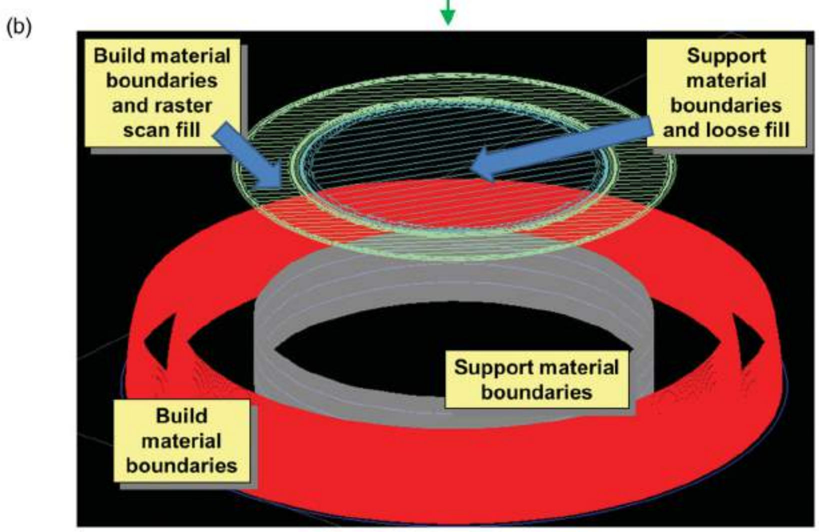
(a)



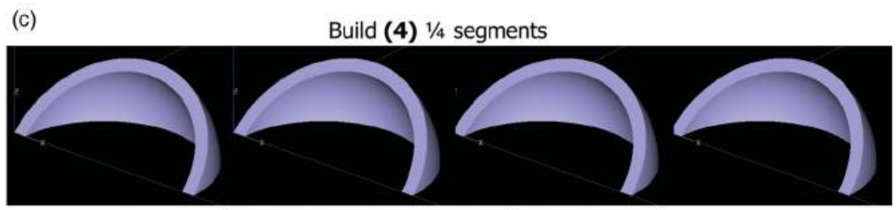
	Solid, Basic Supports	Shell Build, Basic Support
Time	41h 1m	32h 59m
Build (cm³)	715.7	287.7
Support (cm³)	321.4	321.4

	Solid, Basic Supports	Shell Build, Basic Support
Time	24h 31m	17h 55m
Build (cm³)	685.8	286.6
Support (cm³)	68.9	68.9

(b)



(c)



	Solid, Basic Supports	Shell Build, Basic Support
Time	11h 24 m	6h 56m
Build (cm³)	691.2	333.2
Support (cm³)	4.8	4.8

Figure 7. The build time and material requirements for 200 mm hemispherical shell with a 12.5 mm wall thickness, built with a 0.18 mm bead height, and a 2:1 ratio of bead width to build height: (a), (b) non-segmented and (c) segmented (all other considerations are constant). Note the minimal amount of support material required for option (c).

achievable build tolerances, the support structure fabrication and its subsequent removal. In Urbanic and Hedrick [40], design and assembly methodologies to subdivide a part to enable manufacturing while minimizing material costs are presented for FDM. An overarching approach needs to be developed. Strategies are presented here have been developed and refined for a variety of projects.

2.4. FDM Design considerations

The impact of orientation on the build time, material usage, and the surface finish has been investigated by many researchers. Multiple solution approaches have been presented to quickly determine an orientation that minimizes the support material, or maximizes the horizontal area to address time and surface finish concerns

[3,4], [20], [24], [27], [31], and [36]. This research targets the issues raised with the spherical ball joint example. 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 [24], [30] to reduce the stair stepping effects. However, this is not a feature commercially available at this time. As designers may have difficulty evaluating the surface roughness, other researchers have modeled surface roughness experimentally [33], or developed visualization tools [40].

For designs related to rapid tooling, case studies are presented typically for the Selective Laser Sintering (SLS), Stereolithography (SLA), or 3DP processes [15–17], [21, 22]. Ingole *et al.* present solutions based on the FDM process illustrating time and materials savings when using this process for patterns and tools [23]. Limited information is available focusing on general FDM design rules, and specific rules for rapid tooling development, which are both discussed in the next section.

3. Design Rules for Fused Deposition Modeling

3.1. General design rules for fused deposition modeling

AM technologies produce free-form geometry as easily as prismatic and symmetrical geometry; consequently, designers are not limited to standard linear or circular shapes when designing functional geometry and interface features. Organic shapes, variable radius fillets, supporting ribs and bosses, indentations, and other functional geometry should be integrated to create the optimal structure for that component or assembly. Rules to leverage the FDM process are listed next. Specific rules related to casting / molding patterns are presented in section 3.2.

- Optimize the component design based on functional requirements for the final application. If variable fillets are required to maximize strength and minimize material, or intricate ribbing or weight saver features are required, implement this in the design. Use asymmetrical geometry or recessed features as appropriate. The designers should not be constrained by 'Design for Machining' limitations. However, if the component is to be used as a pattern (as an intermediate step for another process), conventions related to the casting/molding process must be respected.
- The machine – process related minimum wall thickness and path length criteria cannot be violated for any feature. Unexpected gaps or feature fill in may occur.

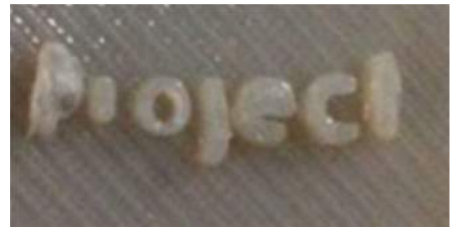


Figure 8. 'Project' lettering which is blurry and indistinct due to its size.

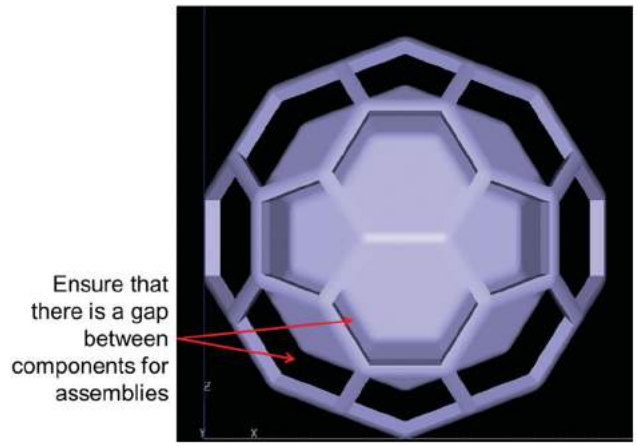


Figure 9. A soccer ball within a soccer ball mesh assembly, with a gap.

Fabrication fine features may also be problematic even if the path length criteria is met (Fig. 8).
- Analyze the build orientation impact on surface finish, build time, and material usage considering the application and post processing tasks. Special attention must be paid where thin or closely spaced features occur, as these may be damaged when removing breakaway support material.
- For building assemblies, ensure that there is a gap greater than one bead height between components to be filled with the support material (Fig. 9). The gap distance will vary due to the support material being used, (breakaway versus dissolvable), and the complexity of the shapes. Larger gaps are required for difficult to reach areas.
- If there are holes which are not orthogonal to the build direction, and dissolvable support material is not being utilized, consider designing a chamfered indentation incorporating an angle that will not require support material (45° or less from the vertical). This indented chamfer is a locating point for subsequent machining operations. This solution approach is appropriate for small diameter holes, especially if the depth does not allow the support material to be readily removed.

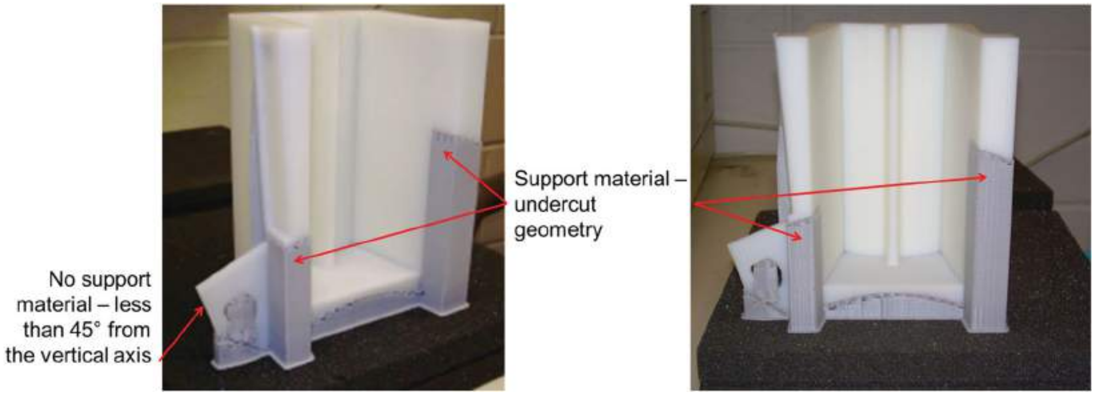


Figure 10. The build orientation and the part design influence the amount of support material utilized.

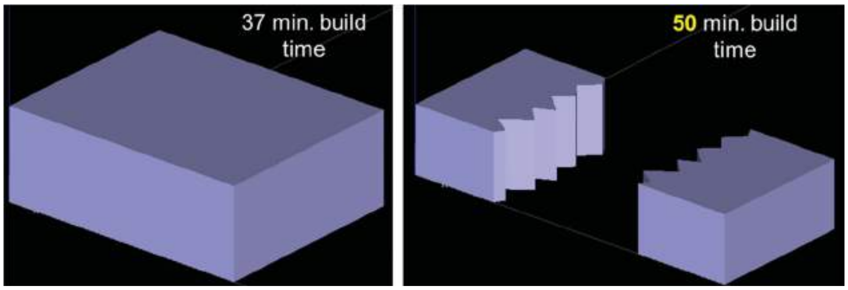


Figure 11. The build time for a 25 × 25 × 15 mm block (0.18 mm slice thickness and solid fill) – one-piece, and the same part with an intricate self-locating interface.

- If there are cavities or overhangs in the component, and support material is required, consider dividing the component into subsections to eliminate support material requirements even if the part fits within the build envelope. Support material may be difficult to remove for deep undercuts. Dividing the component and adding assembly features [11, 40, 42] can reduce the build time, material usage and final finishing times, as areas in contact with support material tend to have a rougher surface finish. This is discussed further in section 4.1.
- Any overhanging geometry should have a maximum angle of 45 degrees from the vertical faces to reduce support material usage, which impacts the resulting build time and costs (Fig. 10).
- Riffler files are recommended for removing support material and final finishing for undercuts and difficult to reach features.
- The bounding box of the sub-component must be compared to the 3D build envelope of the machine. A 3D variant of the 'rotating caliper' method may be used to find the corners of the minimum bounding box for the sub-component. The orientation and position can be refined based on the actual shape. If the component is rotated in 3D within the build envelope, this will increase the build time by introducing additional support material.
- Avoid sectioning through ribs, bosses, pockets and so forth. Focus sectioning on continuous planar surfaces if possible. If there is an offset on the mating planes, filler material and/or sanding may be required to eliminate the discontinuity.
- When partitioning the component, (i) introduce a self-locating interface or (ii) key type assembly features with the parting surface. Note: for the FDM process the build time is directly related to the perimeter travel distances as well as the volume of the component being built. The travel speed of the outer delimiting contour is slower than that of the raster fill; therefore, the introduction of intricate interface surfaces will increase the build time (Fig. 11).
- After determining the 'side to side' partition faces (which do not have to be planar), assembly features may need to be added to locate and or align the sub-components appropriately without introducing inference conditions. Asymmetry to ease assembly in the proper orientation and a hybrid of a key and hole/pin strategies can be readily incorporated. The holes do not have to be round. The feature geometry dictates the degrees of freedom (DOF) [10], [40], [42]. Fillets

and chamfers need to be incorporated to facilitate the assembly and prevent interference conditions. The minimum segment length constraint for the FDM process must be respected. Corner breaks or small fillet geometry may not be built.

- Clearances between mating component fillets must be incorporated in the design. Allow for tolerance clearances of at least 1 bead thickness for mating slot or hole-pin pairs. Establish points of contact, and introduce gaps for adhesive fill [5].
- If necessary, (i.e., many similarly shaped subcomponents) incorporate assembly markers for component identification.
- Thin wall – thick wall conditions may cause distortion in the built component [35]. This is a common design constraint for castings, as discussed in section 2.1. As the thermoplastics are heated, and the component is built in an enclosed chamber, large massive sections will cool at a different rate than the thin wall sections. Curl or warping can result. Thick massive sections should be shelled if the part is being built using the 'solid fill' mode.
- Springs should not be built using the FDM process for functional use. Unpredictable results will occur due to the anisotropic properties related to the process.
- If the component mechanical strength is a concern, analyze the theoretical volume of the CAD model and compare this to the build volume. If the void volume is greater than 5%, select a thinner slice height or vary the build orientation to minimize the void volume (section 4.2).

3.2. Design rules for rapid tooling

The above rules are applicable for pattern making; however, there are some additional considerations for effective tooling design and manufacture, as follow.

- All required fillets must be incorporated in the base product design and blended properly at the junctions. Otherwise, hand finishing will be required. Fillets avoid issues with potential stress concentrations in the final part, and facilitate the ease of the pattern removal for tooling applications; hence, they are critical design features.
- All draft angles must be incorporated in the base product design. No post processing step can effectively add draft angles without significantly compromising the complete part design.
- Review core making and parting line strategies focusing on the opportunities related to the FDM process. Many practical present day conventions are related to machining related time and resource issues.
- If features are to be incorporated at the base of a deep pocket, include this in the base design - separate inserts are not required.
- Assess the strength function requirements required for the casting/molding being utilized: a fine slice thickness with a solid fill will provide a component with the maximum amount of material. A sparse fill may not have the strength characteristics to withstand the compression forces from the sand packing. For, molding soft polymers, this is not a relevant concern.
- Final smoothing operations (sanding, using filler and then sanding) are required for preparing the pattern for a mold. The pattern may stick or ruin the mold when it is being extracted if the surfaces are not smooth.
- Large simple shapes (such as ancillary pattern components: gates, runners, core box, and so forth) should be machined using conventional processes and materials. Machining simple shapes is more cost effective with respect to both time and materials.

4. Optimization Considerations

4.1. Design for assembly

Large components must be decomposed into subcomponents due to the build envelope size limitations (Tab. 3). Manual assembly operations are utilized when assembling a component larger than the available build envelope or to reduce the required build time and materials; consequently, basic design for assembly (DFA) rules that pertain to this manual assembly operation

Table 5. Manual 'Design for Assembly' rules, and FDM processing planning considerations.

Design for Assembly Rule	FDM Process Planning Comments
The number of parts should be reduced. Alignment operations should be reduced.	Consider the build envelope X, Y, Z limits Consider the support material requirements to evaluate the segmentation and related assembly operations
Use chamfers and fillets to ease mating of parts.	Standard design approaches should be used.
Locating and aligning features should be used. Add orientation features so that parts can only be assembled in the correct orientations. Add orientation features to simplify orientation identification.	Unique locating and alignment features can be introduced, as the FDM process can fabricate oval bosses and holes as easily as round bosses and holes For segmenting components due to the build envelope constraints, consider non-planar parting faces for ease of location

Table 6. Summary of the locator and alignment features (adapted from [40]).

Degrees of Freedom	Location / Alignment Type		Key Parameters	Comments
	Male	Female		
1	Keyed type slot	Keyed type recess	1 critical angle > 90°	Dove tail geometry is a standard machining approach
1	Boss on face	Depression	Shape not round	Simple for FDM process
1	Round boss A + Diamond boss B	Round hole A + Round hole B	Diamond boss has only 2 contact points in mating hole	Standard approach – more flexibility for unique solutions using the FDM process
1	Round boss A + Round boss B	Round hole A + Slot B	Major axis of the slot to allow for assembly flexibility	
2	Keyed type slot	Keyed type recess	1 critical angle < = 90°	Standard approach
2	Round boss on face	Depression	Cylindrical, tapered or hemispherical boss / depression	

from (Boothroyd et al. [9] are considered, and are presented with comments relating to using the FDM process (Tab. 5). Typically, with manual assembly operations, snap fits are preferred to incorporating adhesives, but as a component is being broken down into sub-components to facilitate manufacturing, this rule is not considered for this work.

It is assumed that adhesives may be required to ensure the integrity of the component's strength [5]. The rules listed in Tab. 6 should be taken into consideration when introducing the component's parting lines, planes or other interface geometry in addition to locating, alignment and connecting features. The degrees of freedom (DOF), the contact area and the associated tolerances must also be considered when determining the form-feature assembly type, joining methods, and its associated geometry [11]. The locating and alignment feature types and their associated parameters are presented in Tab. 6 and Fig. 12.

When partitioning the component, the amount of segments, the overhang geometry conditions, and the location, type, and number of assembly features need to be considered. The interface form-feature type, the key design parameters, and the tolerances must be determined. For example, pin-hole location features should be separated as far as possible to minimize rotational errors, as well as introducing a clearance (i.e. one bead width) between the hole-pin to assure assemblability. To avoid assembly issues, only a limited set of connectivity features should be included. However, if a unique hemispherical boss / depression pair is incorporated at every interface, such as Medelin et al., [28], additional clearances need to be introduced for non-locating features (i.e. minimum +/- 0.5 bead thickness) to ensure tolerance stack up issues are not generated.

Chamfers must be applied for ease of assembly. As the FDM process produces free-form geometry as easily as prismatic and symmetrical geometry, the design is not limited to standard linear or circular shapes. Asymmetrical geometry, which would be difficult to achieve using standard metal removal processes, can be easily incorporated. Assembly locking connection features can also be utilized by taking advantage of the freeform fabrication abilities, such as incorporating a

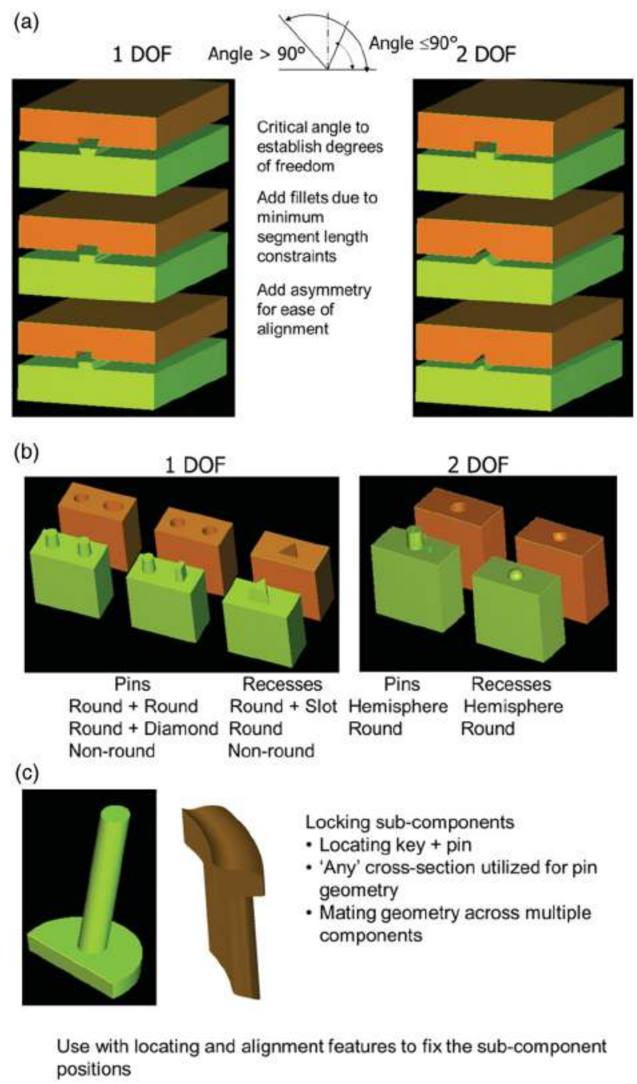


Figure 12. (a) Slot geometry with 1 and 2 DOF, (b) boss-hole pair geometry with 1 and 2 DOF, (c) locking pin example (adapted from [40]).

multiple angle locking pin. An example of this is presented in the case study in the next section. Variable shapes can be utilized for the locator-lock pin, and the base can be designed to conform to the components' surface.

4.2. Strength considerations

Anisotropic properties for the FDM process have been reported by several researchers [2], [7], [18], [19], [29], and [43]. 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 for tensile and compressive tests respectively. The force per unit volume of material is reported, as both hollow and solid samples are tensile and compressive tested using an MTS Criterion Model 43 (Fig. 13 (a)). For both materials, the measured compressive strength is much higher than the measured tensile strength. The average values are reported for specimens, although a full factorial design of experiments was performed, with specimens built with a 0/90° and -45/45° raster angle, and the XY, XZ build planes. The variations due build depended on the mechanical property being assessed, and the fill strategy (Fig. 13 (b)).

During the experimentation for light weighting strategies, it was observed that the specimens did not fail as expected. A compressive specimen with a face centered cubic based spacing of voids had a compressive strength 10% less than a hollow specimen, but had approximately 11% more material. Upon analyzing the tool paths, many unexpected voids and disjointed tool paths are observed (Fig. 14). Presently, 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. 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:

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

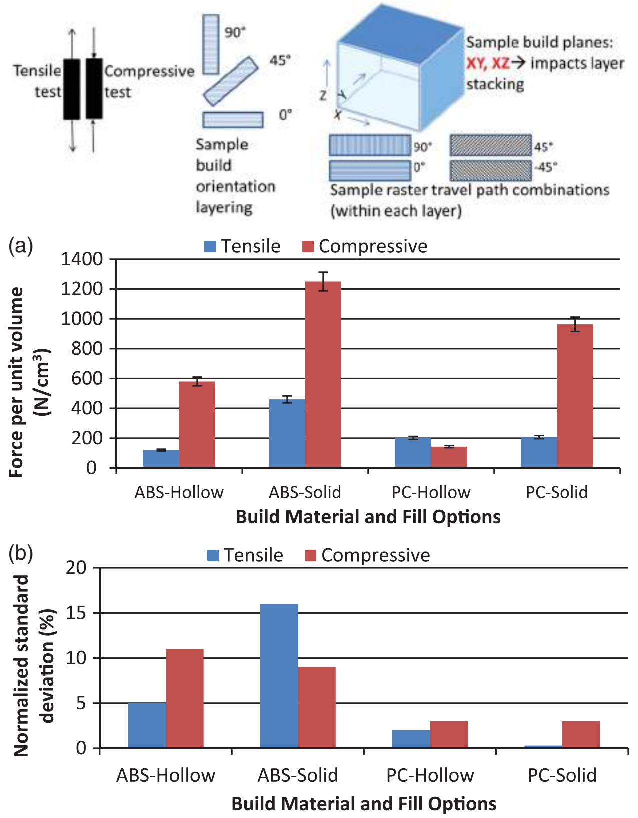


Figure 13. (a) The load force per unit volume for solid and hollow test samples for ABS and PC (polycarbonate) materials, and (b) the normalized observed experimental standard deviation.

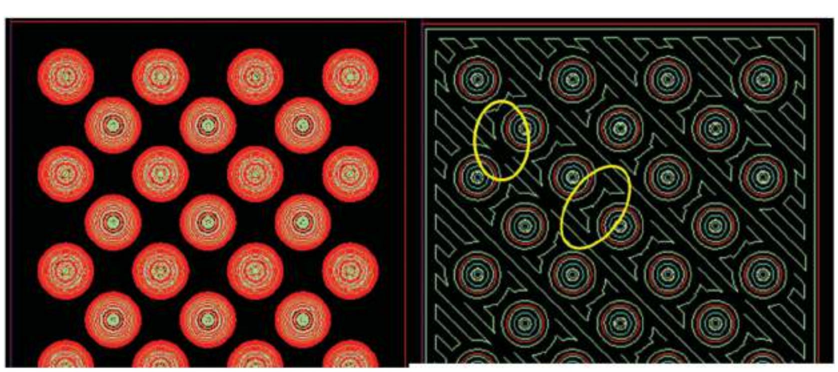


Figure 14. Designed voids to reduce the material usage, and voids due to the tool path discontinuities.

5. Case Studies

All case study components are designed for optimal performance for their specific application using advanced modeling and simulation tools to refine the designs. All would be challenging to fabricate using conventional manufacturing methods. Four case studies are presented: two related to rapid tooling, and two are complex functional models.

5.1. Match plate patterns: rear upright and gear box sand casting patterns [41]

The rear upright component illustrated in Fig. 15 is 200×200 mm square and approximately 200 mm in height, and was designed to be part of the suspension system for the University of Windsor Society of Automotive Engineers Mini-Baja competition vehicle. This component was designed to maximize the strength to weight ratio, which resulted in deeply recessed fillets and variable radii being incorporated. The mounting surfaces are planar. There are no “small” undercuts, but the bottom face geometry is concave, and the draft angles are at least 4°.

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). Leveraging the unique capabilities of AM processes eliminated the necessity of designing and manufacturing cores, and developing pattern assembly strategies. Typically, match plate patterns have planar surfaces, such as the gear box patterns illustrated in Fig. 17.

The upright parting surface contains a curvilinear section that follows the contours of the upright. The parting plane is offset 3 mm for this pattern, as compared to the gear box patterns, which have a 25 mm offset. The upright was built in one piece using the Prodigy 100 using a solid fill, and a 0.254 mm slice thickness. The build time was ∼ 29 hr 2 min. There were issues with the post processing due to the difficulty of removing the support material, and final sanding of the surfaces in contact with the support material.

The gear box patterns did not have the shape complexity of the upright; however, these patterns are large, and significant amounts of support material are required for the cavity ‘up’ or ‘down’ orientations. Both patterns required sectioning to facilitate them being built in the Prodigy 100. Gear box pattern 1 is 370×270×80 mm, and pattern 2 is 370×270×140 mm (Fig. 16 (a)). Gear box 1 was sectioned into four components, assembled using dowels and adhesives, and finish sanded after filler was applied on the surfaces. The build time was approximately 72 hours for these four parts, and the support material removal time was approximately 10 hours. Great care was required in regions where there was recessed geometry.

Pattern 2 is larger and more complex. When initially segmenting the component into 3 segments to reduce the perimeter distances, and hollowing sections to balance the wall thickness and reduce the build material requirements, the projected build time was approximately 78 hours. Additional segmentation is introduced to target reducing the support material. The base subcomponent is spilt into 3 regions with self-locating interfaces. Specific contact points are designed, with a 0.25 mm clearance provided for the application of adhesives, and to compensate for fabrication variations. Specialty keys, 1 DOF locator pins, and grooves are utilized for ease of assembly (Fig. 16 (b)). The wall thickness is modified to 3 mm on average; however, reinforcement structures are included within the raised boss regions, and key regions remain solid. The mounting tabs are unaltered. Using this design strategy, the

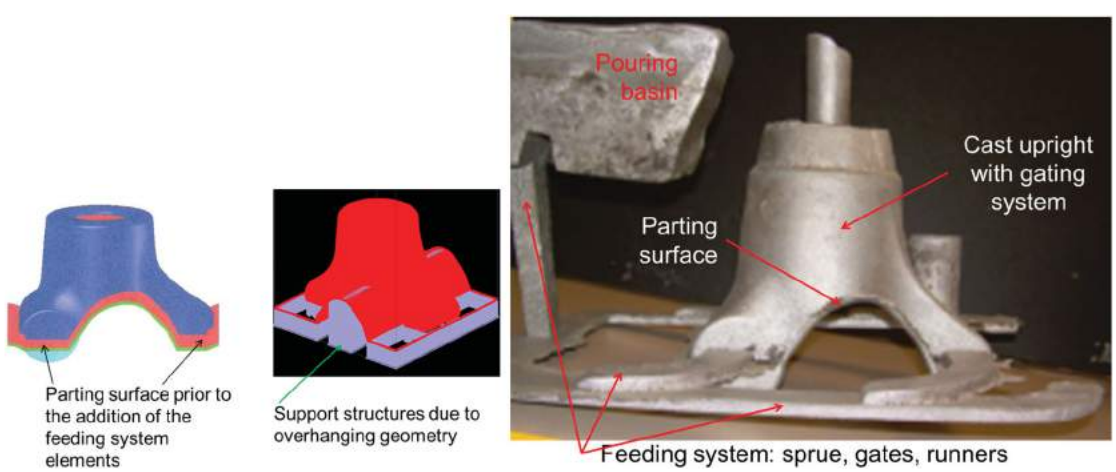


Figure 15. The upright casting model, and unfinished casting, adapted from [41].

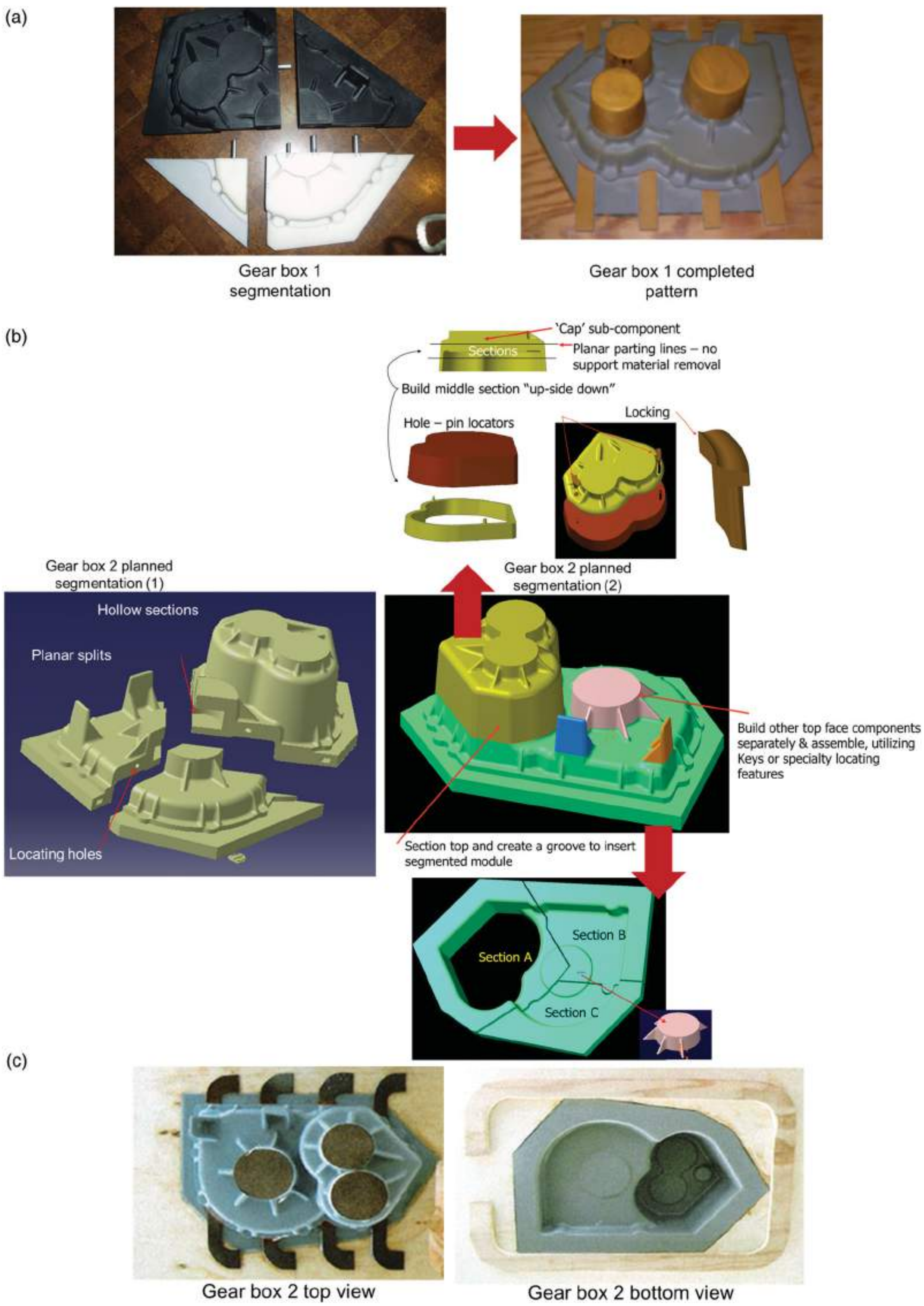


Figure 16. (a) Gear box 1 segmentation, (b) Gear box 2 segmentation options, and (c) Gear box 2 final pattern adapted from [40, 41].

build time is reduced by 23 hrs 52 min. Over 30% less build material and 18% less support material is required (Tab. 7).

Similar to gear box 1, much finishing work would have to be performed. This alternative was not chosen. Instead, an FDM Maxum machine was used to fabricate the part as the build envelope is $600 \times 500 \times 600$ mm (Fig. 16 (c)), and water soluble support material could be utilized. This eliminated the process segmenting and assembly time; however, the greatest time saving was related to the post processing. The water soluble support material utilized by the FDM Maxum machine reduced the labor

Table 7. Design for Assembly time and material improvements for gear box 2.

Case	# of Parts	Orientation	Build Time	Build Mat'l (cm^3)	Support Mat'l (cm^3)	Support Material Removal Effort
1	3	Top surface down	77 hr 49 min	2031.2	385.6	High
2	10	Best	53 hrs 57 min	1378.3	314.3	Low-Medium
		% Improvement	***30.6***	***32.1***	***18.5***	

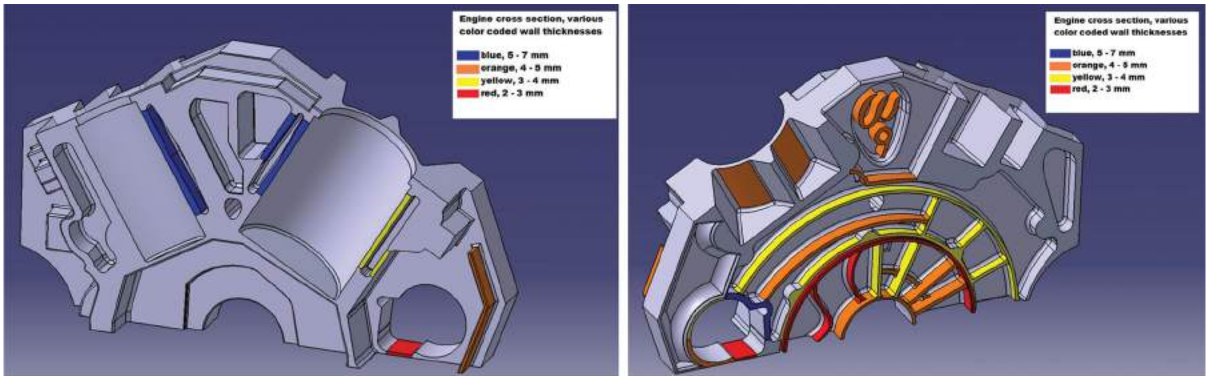


Figure 17. Thin wall sections for the V6 block section cope (top) and drag (bottom) – dark blue areas 5–7 mm thick, orange 4–5 mm thick, yellow 3–4 mm thick, red 2–3 mm thick.

associated with the support material removal (internal cavity) by an estimated 20 hours (based on the amount of material to be removed from pattern 1).

5.2. V-Engine block slice

A high feature V6 engine section geometric pattern is designed to be able to evaluate challenging geometry and casting characteristics such as: flow-ability, shrinkage, etc. The pattern design includes complex geometry, thin walls (Fig. 17), and draft on all features. There are three critical areas susceptible to future design changes: both cylinders and the bulkhead. Therefore, including modular sections that can be 'quick-changed' to create another mold is a key fabrication consideration. The part volume is low i.e., approximately 6–10 castings, and batches would be made from each pattern configuration.

Due to the complex pattern geometry, multiple set ups or 5 axis machining is required, as well as a significant lead time to accommodate for the tool path and process planning development. FDM fabrication on the Prodigy 100 is used for the pattern itself, but the feeder system and core box is machined using wood, as the features are simple, and some sizes large (i.e., the core box length ∼800 mm) [38]. The pattern design includes complex pockets and ribs, deep pockets, draft, and fillet radii between faces. The parting line is planar between the cope and drag is planar, and curvilinear self-locating segmentation is employed for the individual modules (Fig. 18). Assembly holes are included on the back face for location on the back plate; consequently, after removing the support material, these modules are assembly ready. Each module fit within the FDM machine build envelope. Some modules were clustered in the same build to reduce the setup time.

The back plate of the cope and drag pattern is considered a reference datum, and assembly holes were added via machining. Dowels are used to connect the FDM positional holes with the back plate (reference datum) positional holes for positional alignment. After positional alignment, the modules are assembled using screws from the back plate through the modules. When modules need to be changed, all screws can be removed from the back of the pattern or back of the back plate, which makes changing the pattern faster than if they were referenced from different areas. Standard and consistent screw sizes are used so that only one tool is required for maintenance and changing of the pattern [38].

The total build time for these modules is 161.83 build hours; however, they were built within 12 days. Post processing related to smoothing the surfaces and final assembly is additional, but due to the module based build strategy, parallel processing in tandem with the fabrication process is possible. Some 3D fillet blends could not be readily added to the model; hence, putty was added to the pattern to provide the necessary smooth junctions. The build orientation was optimized to minimize support material, not surface finish variations. The estimated cost for machining these molds was $5000.00; whereas, the cost was $1500.00 using ABS plastic, the Prodigy FDM machine, wood, and conventional CNC machines.

5.3. Flexible robot end effector coupling

The goal of this project is to design a resettable failsafe module between the end effector (i.e., body framing

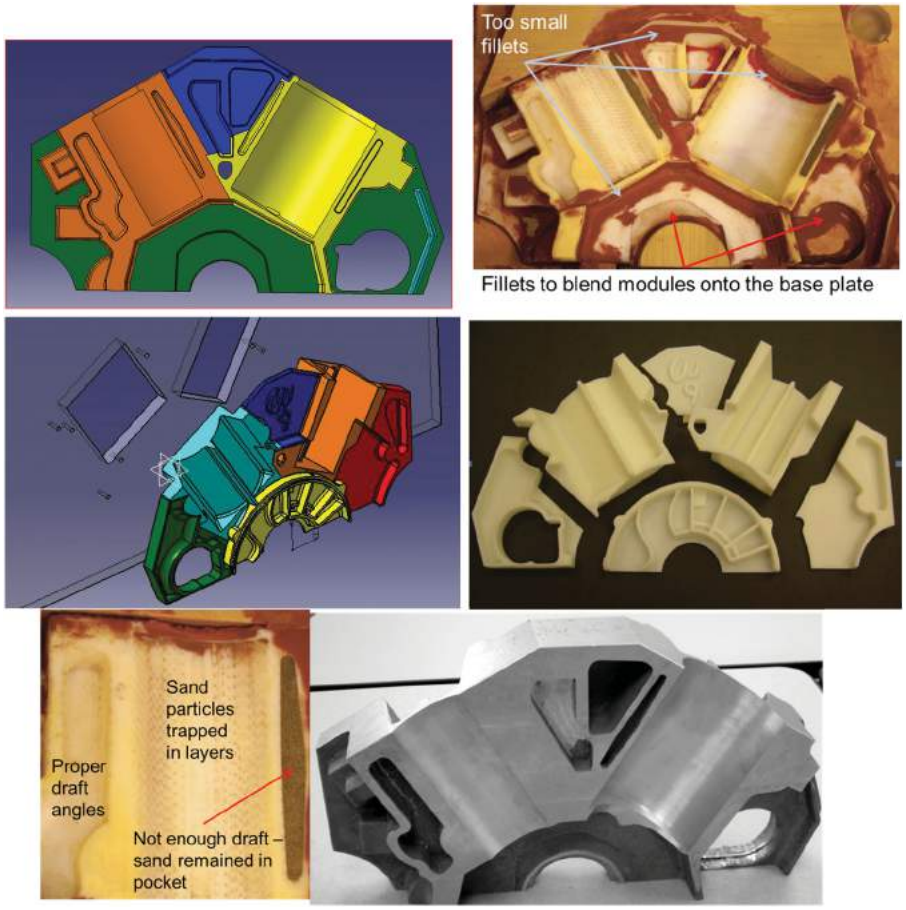


Figure 18. V6 block section modules, assembly (cope – top, drag – center), sample module (orange cope module), and final cast part, adapted from [38].

application where the end effector is a large frame) and the robot to minimize the damage done to the end effector structure during an accidental collision with external tooling. A spring loaded ball- mechanism is proposed which is capable of reacting to bending as well as torsional impact forces from any direction when there is a collision. The system must be rigid during normal operation (including e-stops), and resettable after a collision. Radial ball detent indentations are evenly distributed throughout (using an icosahedron as the reference pattern). There are six major components to this assembly, along with the balls and springs. The six main components are illustrated in Fig. 19.

To machine the specialized spherical ball joint, multiple machines (milling and turning) and setups are required (there are 20 concave spherical indentations on the spherical face), or the utilization of a twin spindle lathe with live tooling and X, Y, Z and C axes. The process sequence follows for the multi-spindle lathe configuration:

- Clamp the bar stock using a standard 3 jaw chuck, face, rough and finish the exterior cylindrical surfaces with rough and finish boring tools.
- Face the flat end face.
- Orient the component & drill the two orthogonal through holes.
- Grip the part in the sub-spindle and cut off the body (standard parting operation) to be able to work on the ball features.
- Rough and finish the rotationally symmetric portion of the OD using rough and finish boring tools.
- Orient, rough and finish the spherical indentations using a ball nosed end mill.

For the machining either a pattern set or the final components, all components require multiple machines and setups, and a wide selection of cutting tools. Three components have multiple complex surfaces. The process planning would be extensive. For casting patterns, draft and fillets would need to be applied, and cores made and

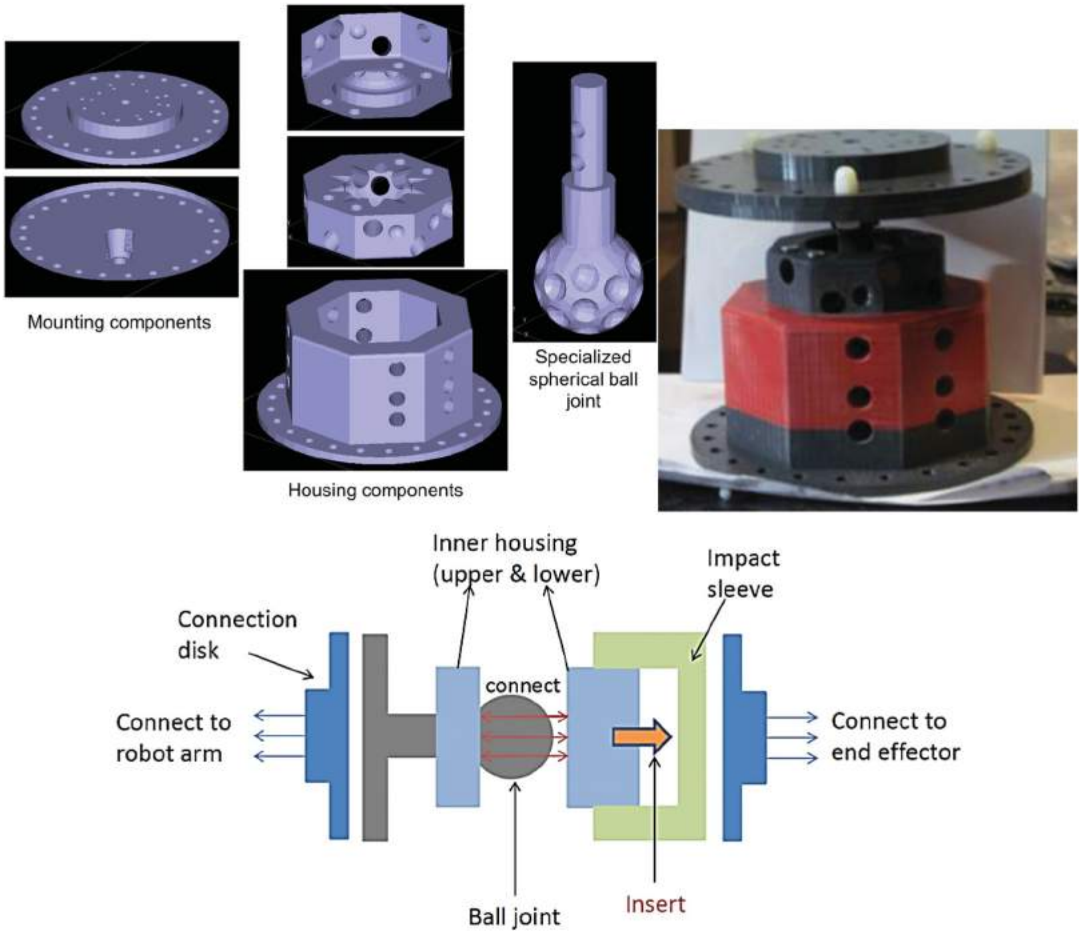


Figure 19. Flexible robot end effector coupling components, final FDM model, and the assembly diagram.

assembled in the mold for the holes. Post process finish machining would also be required.

To manufacture a casting pattern set and fabricate prototype castings was deemed expensive (over $4000.00); hence, the initial prototype was built using the FDM process. As rigidity and surface finish are key performance characteristics, a solid fill is utilized with a 0.18 mm slice thickness. The total process planning time was 55 min. to determine the optimal build strategies for the components. The build time was 72.25 hours using the Fortus 400 MC. Individual component post processing occurred in parallel with the fabrication process.

5.4. Smart phone charging station

A smart phone charging station was designed to showcase the FDM process on the Fortus 400 MC machine to economically fabricate a low volume part that cannot be fabricated using any other single manufacturing method. Clay modeling or sculpturing by hand could be used to produce this part; however, issues with dimensional accuracy, consistency between parts and cost to produce a part would arise due to the highly skilled manual nature of these processes. The design incorporates several Canadian Olympic hockey elements to form a functional charging station for two smart phones. The 'crossed hockey stick' symbol, Hockey Canada ™ logo and Olympic rings are utilized in the structure. An analysis of the design features with respect to traditional manufacturing processes from the base of the structure follows:

- The hockey player cut into the base contains internal sharp corners, requiring wire EDM (metal) or water jet (plastic) to produce.
- The Olympic rings attached to the base interlock like the links of an actual chain and would have to manufactured in a separate process then fastened to the base using a joining process such as welding or brazing (metal) or adhesive (plastic) The rings themselves would be difficult to produce using any automated manufacturing process due to their delicacy.
- As with the base, the hockey player cut into the 'crossed hockey stick' section contains internal sharp corners, requiring wire EDM (metal) or water jet (plastic) to produce.

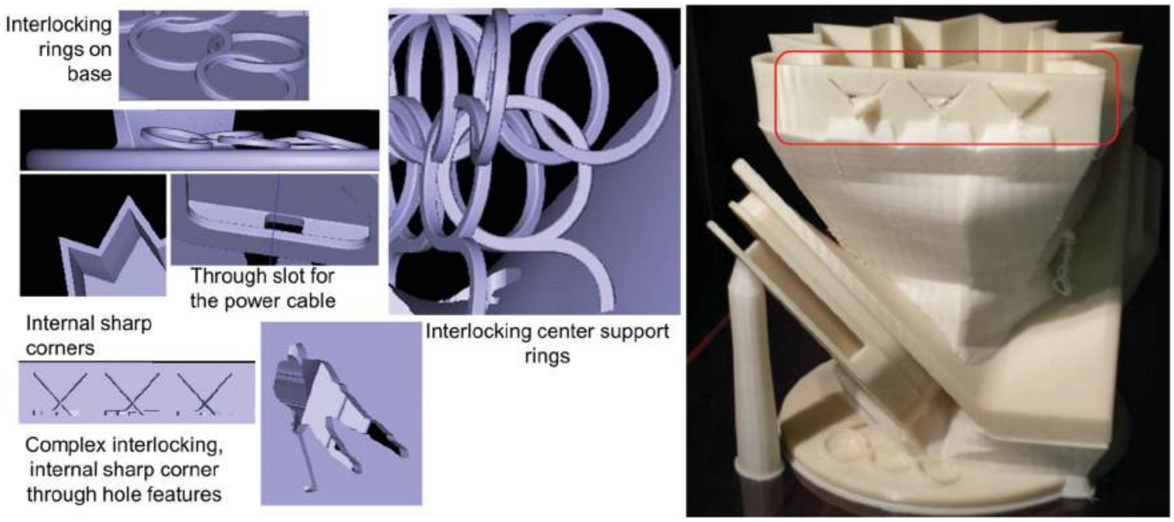


Figure 20. Specialty design characteristics for the smart phone holder, and the built model showing the support material, along with problematic build results.

- The interlocking Olympic rings supporting the maple leaf and Hockey Canada ™ logo would require an extremely complex core package to injection mold (plastic), or would have to be fabricated by an artisan by hand using welding, brazing and bending techniques.
- The maple leaf and Hockey Canada ™ logo on the top of the structure could be manufactured by machining, however sink EDM operations would have to be integrated into the process to produce the many internal sharp and small radius corners in the final part.

Fabricating this part also illustrates an issue when building thin-walled parts using the FDM process. As can be seen in Fig. 20, the material around the cut out crossed hockey sticks in the side of the maple leaf was not properly supported during fabrication, resulting in part of the wall breaking off. This was due to the build software not automatically adding support material inside the cut outs because the angle of the hockey stick shafts was greater than 45°. This issue could have been prevented by using the Insight ® software to manually add build material in this region.

6. Discussion

These components are complex, and are designed to be optimized for their applications, not for 'design for machining' considerations. Utilizing an AM approach reduces the process planning to a set of simple parameters. However, the overall build time for these components is long, varying between 29–162 hours. The FDM parts were very durable in the sand molding process. They were cleaned with an air hose to remove sand and they were easily cleaned back to their original condition. No long term testing was done to determine the effective piece count for a mold.

Addressing the surface finish was the biggest challenge for most of these projects. The layering and elliptical beads are especially problematic for small angles or 'shallow curvature' surface geometry, as there is a significant gap between layers. It would be helpful to be able to create a better surface finish on an FDM part by having finishing layers. A potential process improvement is to use one layer thickness to build the interior of the part and have several "finishing contours" of thinner thickness to have a better surface finish. Currently, OEM FDM process planning software cannot accommodate this change. This concept is analogous to adaptive slicing, which could also be incorporated [26], [30]. Another method that can be executed with the present state of the art is to create a 'cap piece', i.e., segment the part into an inner and outer piece, and assemble the outer piece over the inner piece. The outer component could be built using

Figure 21. FDM part distortion (Cope Module B) [35].

a finer slice thickness. However, this may significantly increase the amount support material being required (depending on the shape, such as the gear box examples), and increase the amount of post processing related to the support material removal. This solution may be problematic due to observed accuracy issues. The accuracy of the machine is not equivalent to the component build accuracy. Corner curling is observed (Fig. 21) and although all parts for the V6 engine section case study were manufactured from nominal dimensions, there was more sanding required than filling in, indicating variable shrinkage factors for the FDM process exist, and are not well understood.

7. Summary and 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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