

RP Process Selection for Rapid Tooling in Sand Casting

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ABSTRACT

The significant cycle-time improvements and geometrical capabilities of solid freeform fabrication systems have led to applications in sand casting industry for design verification and tooling. The time and cost effective deployment of rapid tooling processes using rapid prototyping technology has thus becoming an emerging area to be studied. To make full use of the advantages of rapid prototyping processes, the factors influencing the tooling approach must be identified and understood. This understanding is then used to develop a decision-making structure for RP process selection for rapid tooling in sand casting. In this manuscript we review our work in evaluating and building a framework for tooling process selection for sand casting.

Key words: rapid tooling, process selection, tool path selection, sand casting, rapid prototyping

1.0 Introduction

A sand casting is produced by pouring molten metal into a mold cavity. The mold cavity is created by packing sand around a pattern and then withdrawing the pattern. Since the pattern imprint forms the cavity, the pattern creates the external shape of the cast part. If the part has features or regions that are undercut relative to the parting line, these are formed by cores that are placed in the mold cavity. The cores are supported by core prints and chaplets in some cases that allow the molten metal to flow between the core and the mold wall. In addition, cores may be necessary to produce a desired "zero" draft external surface depending on the parting line selected. Figure 1 illustrates the tooling process for sand casting. Generally speaking, sand casting is a low cost approach to creating low volumes of parts with few restrictions on geometric complexity.

Rapid tooling (RT) has evolved from rapid prototyping technology and its applications. It uses the rapid prototyping model as a tooling master to create the patterns and cores through direct or intermediate tooling processes. Rapid prototyping and tooling have found wide spread application in sand casting design verification and tool making in recent years.

In practice, there are three kinds of tooling processes used: traditional manual pattern making, computer numerical control machining, and rapid prototyping. The method selected for making the pattern and cores, which we call "tool path selection", is determined by a series of decisions regarding the fabrication method, material, and tooling approach to be used. There are a number of publications that address a particular rapid tooling process in sand casting [1~5]. To our knowledge, however, studies on tool path selection for sand casting are very few. Related works

include Mensing and Gibson's [6] build time comparison study of large parts using SLA, Sanders, Stratasys, SLS, LOM and milling processes, and Paxton's [7] benchmarking study on rapid tooling processes. These investigations mainly focus on the time or cost comparison of the different processes, but do not address a methodology for decision-making. Stoll, et al [8] have done initial research in this area. Their work discusses decision variables, decision factors, decision structures and a decision process. A complete and integrated method to investigate the tooling path selection is presented. But article focuses on tool path selection at the macro-level, and does not present much detail on the selection of a particular rapid prototyping process.

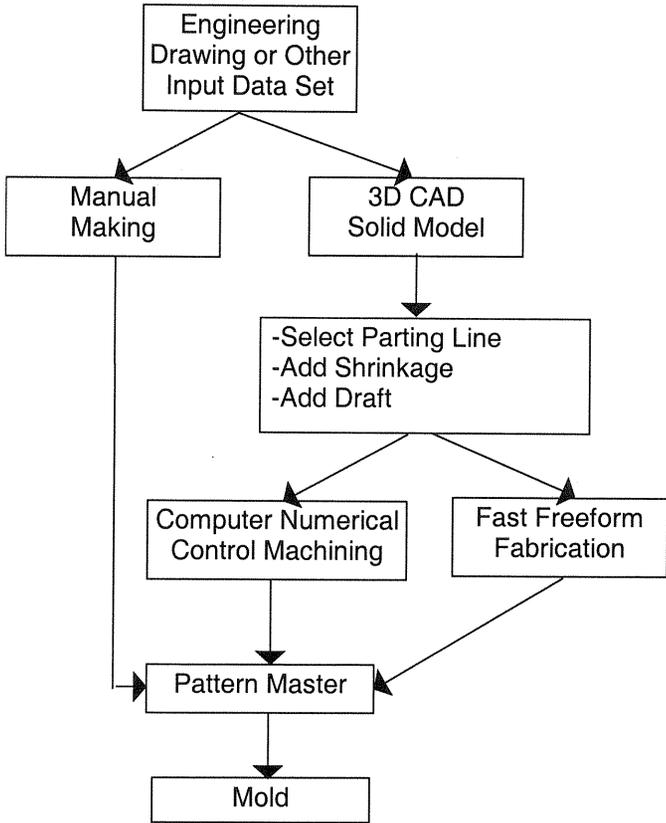


Figure 1. Tooling process for sand casting

In this paper, we first review the process characteristics of RP processes and then discuss the basic principles of tool path selection for sand casting. We then investigate criteria to select a RP process, determine the decision factors, organize the decision structure and develop integrated decision process. The present investigation is limited to tooling master fabrication. As such, we do not address direct tooling processes.

2.0 Review of Rapid Prototyping Processes

There are a number of rapid prototyping processes that find wide spread application in industry. Each process has its own characteristics, advantages and disadvantages. To make a "best" decision of RP process selection, one must have a clear understanding of those processes and their respective advantages and disadvantages.

Stereolithography Apparatus (SLA) involves selective curing of a photo-curable polymer using a laser beam directed by the computer in accordance with the tessellated version (.STL) of the CAD model. This process is generally highly accurate and can provide parts and/or pattern elements with good surface finish. The mechanical properties of the photo-cured polymer do not match most production engineering materials and shrinkage and warpage may occur in the post-processing process. Additionally, pre-building of a support base is needed [9]. This process is especially suitable for complex parts with thin-walls or lug features, small size or high precision requirements.

Laminated Object Manufacturing (LOM) stacks layers of thin sheets of paper to make the prototype. Each layer is cut to match a cross-section of the model. The finished model has the surface finish and consistency of wood. It is especially suitable for complex, large or bulky parts. The strength of the LOM model is above average. This process does not need support generation. Since post-processing is done manually, waste material removal is time consuming. Another disadvantage of this process is that the waste material can not be reused [10].

Fused Deposition Modeling (FDM) uses a spool of filament that feeds into the unit's heated extruding head like wire feeds into an automatic welder. The product has good dimensional accuracy and surface finish, and fast building speed. The material strength is low. Supports are needed in this process. [11]

Selective Laser Sintering (SLS) deposits and sinters a layer of heat-fusible powder to form the cross-section area of a model. An initial cross-section of the object under fabrication is selectively 'drawn' on the layer of powder by a heat generating CO₂ laser. This process achieves average accuracy and has multiple material choices. It can fabricate very strong metal composite inserts or molds used for injection molding. In sand casting, it can directly produce the sand mold using SandForm Zr II (zircon) or Si (silica) sand casting materials. This process does not need support generation thus is easy for post-processing. [12,13]

Solid Ground Curing (SGC) uses a glass photo-mask and an ultra-violet floodlight to build a model slice on a solid environment. This eliminates curling, warping, support structure, and any need for final curing. It is a high precision process. But the building time and cost is above average for the current RP market. [14]

Three Dimensional Printing (3DP) uses a technology similar to the ink-jet printing to spray a binder materials on a thin distribution of powder spread over the surface of a powder bed. The binder material joins particles where the object is to be formed. The accuracy is average, as is the strength. No support generation is needed. [15]

Sanders Prototype (SP) involves a liquid to solid inkjet plotter with a separate z-axis input. The dual inkjet subsystem rides on a precision x/y carriage and deposits both thermoplastic and wax materials on the build substrate under program control, according to the path generated by STL model. These droplets may be placed at any desired location upon the build substrate within 0.00025 inches (0.007 mm) in the x and y directions. The droplets adhere to each other during the liquid-to-solid phase transition to form a uniform mass. The drying process is fast enough to allow milling of the layers immediately following the deposition cycle. This process is claimed

as the most accurate amongst the RP processes. Support materials are required to support overhangs and cavities in the model during the model build sequence. [16]

3.0 Tool Path Selection for Sand Casting

In considering the tool path that selected for a particular sand casting, one must consider the *dimensions of decision space*: fabrication method, tool materials and tooling approach. There are three kinds of fabrication methods: manual, computer numeric control (CNC) machining and rapid prototyping (RP). Regarding the tool materials, there is a variety of materials that can be used, such as mahogany, pine, urethane plastic, synthetic materials, metals, and FFFF materials (e.g. polymers, papers, ABS plastics, and metal powders). For the tooling approach, loose pattern, gated pattern, match-plate pattern and cope & drag tooling are the mainstream methods of the foundry tooling industry.

The second consideration of tool path selection are the decision *factors* and *constraints*. It is a complex mental excise to comprehensively consider each aspect of the tooling process from the engineering drawing to the final foundry production. In this process, a tool engineer or decision maker must consider data status, production volume, state of development, the direct user of the tooling, part geometry, critical features, pattern shop capability, tool cost, lead-time, casting tolerance and accuracy, and tool durability. He must understand what are independent and dependent factors and the relationship or tradeoff among these factors.

For example, the decision-maker must know that each of the tool path selection factors imposes constraints on the selection process by eliminating certain decision variable combination from further consideration. Independent decision factors (e.g. production volume, geometric complexity, no draft allowed) typically impose rigid constraints that must be satisfied. A production quantity of 30 units is a rigid constraint, the tool must be capable of producing 30 acceptable castings. While the dependent factors (e. g. cost, time, accuracy, and durability) are negotiable because of the complex couplings and tradeoffs that exist between these factors. For example, there are many tool path alternatives that are capable of producing 30 castings. The tool path that is eventually selected will typically result in the most desirable tradeoff between cost, time, and quality. This, in turn, is likely to depend on the relative importance of the dependent decision factors.

The third consideration of tool path selection is the *decision structure* and *process*. The decision structure involves how to organize the decision space and factors, how to determine the possible decision options for tool path, and how to evaluate the criteria for optimal decision making. Once sufficient information is available, a rational decision process is necessary to make the final decision for tool path selection. Based on the industry practice, an integrated decision-making process is proposed by Stoll, *et al* [8]. The reader is referred to this paper for a more in-depth discussion on this topic. Figure 2 shows an example flow chart of the decision-making process for tool path selection for sand casting.

4.0 RP Process Selection for Tool Making

Selecting the best RP process for a given application involves a similar decision process. *RP process selection* is defined as the selection of an appropriate commercially available RP process by careful evaluation of the decision factors and customer's requirements.

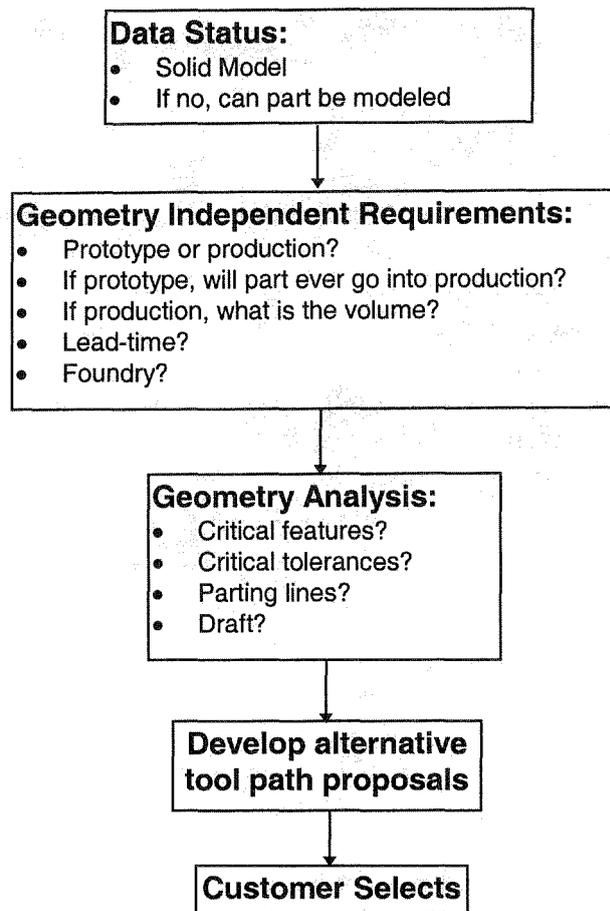


Figure 2. The tool path selection process.

4.1 Decision Factors

The decision factors associated with RP processes include part geometry and critical features, post-processing, building materials (strength and durability), production volume, time, cost and accuracy. There are also some factors that are common to all RP processes such as the data status (generally a 3D CAD model required), building orientation selection, slicing strategy (constant or variable thickness), and so forth.

4.1.1 Part Geometry and Critical Features

Part geometry constrains and underlies the selection of the best RP process. It constrains because only those processes that are capable of generating the desired geometry can be considered. It underlies the decision because each tool path that is favorable for producing the desired geometry will also be more or less suited for producing particular features or aspects of the geometry. Deciding on the right RP process for a given part geometry is therefore very dependent on the decision-maker's experience and judgment. For example, most experienced tool builders can look at a part and immediately determine that SLA is the best fabrication method or that LOM would not work well. The tool builder does this by noting specific features of the part geometry and then mentally filtering the possibilities based on learned experience. This mental evaluation is the "essence" of the tool path selection process.

In making the evaluation, the decision-maker generally considers several aspects of the part geometry. These include:

- Wall thickness
- Aspect ratio
- Special features such as fillets, lugs, small holes, and undercuts
- Surface complexity

Thin walls and severe aspect ratios can be a problem for some RP processes such as LOM. Conversely, a bulky part may be very suitable for the LOM process. Cross-section geometry such as fillets, rounds and transitions between features may be difficult for all RP processes if the angles between the Z-axis direction (layering direction) and the surface normal are bigger than 45°. Small lugs or holes may be suitable for the Sander technique. The tool-maker must understand the critical features of the parts so that an optimal process is chosen based on the part geometry and its application.

4.1.2 Post-processing

Post-processing is necessary for most RP processes. It generally includes two aspects: removing the support structure and finishing the surface. The amount of post-processing work required to achieve a level of surface finish differs widely amongst the processes. For example, it may be very difficult to remove the support materials from an internal cavity of a LOM model, while the same task may be relatively easy for the SLS or 3DP methods.

4.1.3 Building Materials (Strength and Durability)

There are a variety of building materials used in different RP processes such as paper, polymer, ABS plastic, wax, metal or ceramic powders, etc. Since different materials demonstrate different mechanical strength and durability, the building material will eventually affect the tool life and accuracy. To select the appropriate process, the tool-maker needs to know the production volume and how sand ramming of the pattern will influence tool life and tool wear.

4.1.4 Production Volume

The tooling material selected and the tooling approach used depends to a large extent on the *production volume*, which is the number of castings to be produced over the lifetime of the tool. If a large number of castings are to be produced, then the tooling material and approach is likely to differ from that used for a short production run. For example, if only a few castings are to be poured (<10), then many RP processes may be acceptable. If moderate production volumes (10 to 300) are anticipated, then some RP processes cannot be used only because of material strength and durability limitation. For large production volumes (>300), few tool "paths" can be used. For example, the RapidSteel process of SLS can produce highly durable metal molds.

4.1.5 Time, Cost and Accuracy Trade-Off

Time, cost and accuracy are dependent factors that affect the decision-making process. This is particularly true for RP processes because of the nature of layered manufacturing. The decision-maker needs to evaluate the trade-offs between these factors to find the best or most acceptable combination.

4.2 Decision Structure

The decision space must be investigated in making a RP process selection for tool making. More specifically, a tool engineer or decision-maker must understand what set of possible decision combinations are possible and what constitutes a “best” RP process selection.

4.2.1 Decision Space for RP Process Selection

Choosing RP process involves two independent decision variables: RP process and material. Product requirements (time, cost and accuracy) generally determine which combination of RP process and material is best. If we view each of these decision variables as a dimension of the RP process selection process, we can envision a decision table as shown in Table 1.

Table 1 Decision table for RP process selection

	SLA	LOM	SLS	FDM	SGC	3DP	SP
Polymer	X				X		
Paper		X					
Wax			X	X			X
ABS Plastics			X	X		X	
Metal Powder			X			X	
Ceramics		X	X			X	
Sand			X				
Composite		X					

In this table, there are 16 combinations of process and materials. For each material class, there are several options to be considered.

4.2.2 Decision Constraints

Each of the factors discussed in Section 4.1 imposes constraints on the RP process selection by eliminating certain decision variable combinations from further consideration. Independent decision factors typically impose rigid constraints that must be satisfied. These constraints include geometry, production volume, material strength, etc. A large size part with thin walls and many lugs as critical features may not be a good candidate for the LOM process. A very large volume production (>1000) may need RapidSteel to produce the master. For small or medium production volumes, a number of the RP processes can be used to create the elements of the tool.

4.3 Integrated Decision Process

RP process selection is a comprehensive mental exercise that is generally undertaken by an experienced tool builder. In general, the procedure followed by each tool-maker will depend upon both the decision-makers’ knowledge and experience and upon the pattern shop facilities available. The general flow of the RP process selection is shown in Fig. 3. It is important to note that, although the process appears to be linear, in reality, it is highly iterative and non-linear and may involve many conversations with the customer. Typically, the final decision emerges as the customer and the tool-maker work together to evolve an acceptable approach.

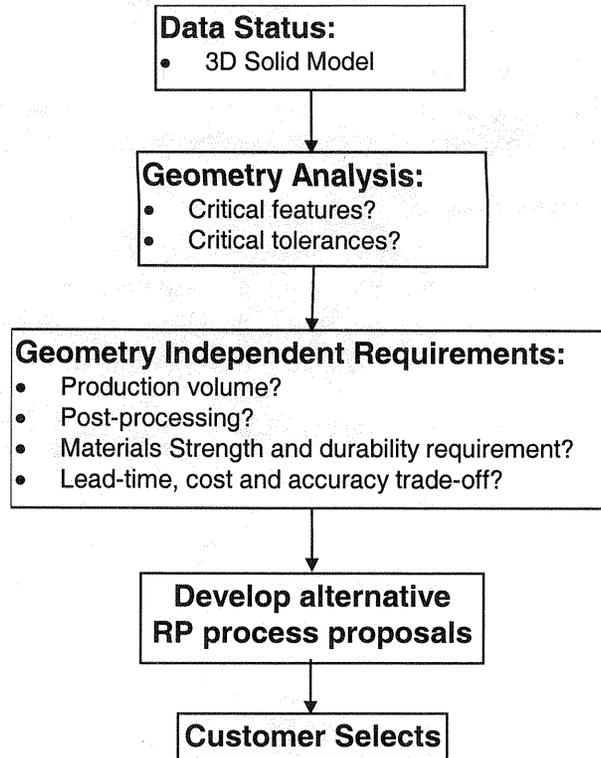


Figure 3 Integrated decision process for RP process selection

5.0 Conclusion

RP process selection for tool making, which involves the selection of a particular RP process and material, is a sub-decision that must be made as part of the tool path selection process. This paper reviews the general RP processes, discussed the tool path selection for sand casting, and investigates the decision factors and decision-making process for RP process selection. This investigation attempts to clarify the factors and their influences on the decision process so that a further optimal decision support system may be developed based upon this understanding.

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