Computer-Aided Design of Tooling for Casting Process

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Abstract

Tooling development is an important activity bridging product design and manufacturing activities, and is often a bottleneck in new product development. Ever-shrinking product life cycles have made it necessary to explore, adopt and adapt new technologies to produce quality tooling in a shorter time while remaining competitive. This is especially true of metal casting sector, where long lead times (weeks to months) for producing the first article of approval are no longer acceptable.

This paper shows how to compress the tooling development time for metal casting using an intelligent integrated approach. This is based on combining three ‘young’ but proven technologies: (1) solid modeling of part design, (2) knowledge-based tooling design and (3) rapid prototyping and tooling. With this approach, it has been possible to produce pattern and coreboxes (for small complex parts required in low quantity), within a working week, and costs slightly higher than high-speed NC milling. As the technologies become more mature and user-friendly, it is foreseen that well within a decade, they will become more economically viable and might largely replace the current approach to produce the tooling for casting. Tooling engineers need to be proactive and start exploring the new technologies: it is better to be prepared in advance!

Keywords: casting, tooling design, pattern, mold, die, rapid prototyping, CAD/CAM.

“You see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast.”
- From ‘Alice in Wonderland’ by Lewis Carroll.

1. Survival of the Fastest

In an age when innovation or change is the only constant, time has emerged as the single most important factor for competitive success. Rising customer demands and fierce global competition are forcing engineering and consumer product companies to continuously seek ways to compress the lead-time from concept to market – in the case of new products, this could mean the difference between assured growth and doubtful survival. The automobile sector – where the above scenario has unfolded in a global context – has witnessed slower players being replaced by those who have been proactive in exploring, adopting and adapting new technologies for slashing the development time. Indeed, the lead-time to introduce a new automobile (from concept to market), which was more than 60 months a decade back, has reduced to less than 18 months today.

However, product designers generally delay the freezing of the design to the extent possible to accommodate the feedback from all departments, who in turn have to take into account the latest technologies and trends. This includes industrial designers, who have to visualize which designs will become ‘fashionable’ a few months later and remain ‘acceptable’ for another few years. Since component designs can not be completely finalized until manufacturing and testing, this naturally puts the pressure on all downstream activities (after product design) to be compressed to the logical minimum. Thus tooling development, which is a prerequisite to manufacturing, becomes the most critical activity since it is not only consumes expensive resources, but also can become a bottleneck and potentially throw the entire project out of gear.

The above is especially true in the case of cast components, tooling for which takes weeks to months to develop. Indeed, in a recent benchmarking survey of American foundries, in which the first author was involved, it was found that the average lead time for the first article of approval is 10-14 weeks, of which tooling development accounted for nearly 70% of the total lead time [Creese,1996].

Over the last ten years, researchers have developed and improved several technologies which are gradually being accepted by the
industry, and are of direct interest to tooling engineers. This paper describes three of those technologies in the context of the metal casting sector: (1) solid modeling of cast components, (2) knowledge-based casting design and (3) rapid prototyping and tooling of patterns and dies.

2. Solid Modeling of Cast Components

The casting geometry conceived by the product designer is usually communicated to the tooling engineer through engineering drawings in terms of orthographic and sectional views. These drawings have to be interpreted for mental reconstruction of the three dimensional product before proceeding with the design of pattern and core boxes. It is a challenging task, particularly in case of intricate castings, and may take several hours for even experienced engineers. The tooling design is communicated to pattern makers and foundry engineers through another set of drawings. Trial runs are made to validate the design, and any changes are recorded. If the tool design is modified, (in some difficult-to-cast cases, even product design has to be modified), a fresh set of drawings are prepared. This is a time-consuming exercise and prone to errors. Replacing traditional drafting practice with computer-aided drafting has greatly reduced the time taken to produce drawings of modified designs. Advances such as automatic dimensioning, bill of material generation and customized title block generation have further increased the productivity of designers.

However, 3D CAD or solid modeling represents a giant leap forward. A solid model is not only useful for visualizing the part features, but also is the main input for an array of CAD/CAM/CAE packages available today. These programs help in automatic generation of orthographic and sectional views, stress analysis, weight calculation, design of pattern, mold, cores, feeding and gating, simulation of flow and solidification of molten metal in mold, NC cutter path generation for tool manufacture, materials planning, cost estimation and computer-controlled inspection.

A number of solid modeling programs are available today, including AutoCAD R14, CATIA, DUCT, Euklid, I-DEAS, Pro-Engineer, SolidWorks, Unigraphics, etc. In these systems, solid models are created using Boolean operations: union, intersection and difference on pairs of simpler models to create the desired shape. A library of solid primitives such as cube, cylinder, sphere, cone and torus are provided to initiate the modeling. The model created by combining primitive solids is then combined with other primitives or other solids to eventually obtain the designed shape. The initial model can also be created by sweeping a 2-dimensional section through a straight or curved path to produce solids of revolution and extruded shapes. Advanced sweep-based modelers handle contoured paths along B-spline curves and change in section shape along the path. Complex contoured shapes are defined using Coons, Bezier, B-spline or non-uniform rational B-spline (NURBS) surface patches.

The majority of castings, which are quite complex when compared to machined components, require a combination of all the above techniques. The designer requires training and experience in deciding the strategy for modeling, in particular, combinations of primitive solids, which will lead to the final shape with minimal number of steps. Sometimes it becomes necessary to retrace the steps during modeling and take a different approach to complete the shape.

In summary, the ease of visualization, time-saving in subsequent modifications and the benefits of using the model for other applications far outweigh the initial effort in creating the solid model. Thus, while the first model may take 10-100 hours to create (depending on complexity), any minor subsequent changes can be done in minutes. Automatic and accurate weight calculation takes just a few seconds!

The next section describes how the solid model of the part can be used for designing the casting and creating the pattern model.

3. Knowledge-Based Casting Design

In the context of this paper, we will refer to casting design as the activity (as well as the result) of converting the part model into the cavity shape which is filled by molten metal during the casting process. This includes the following decisions and design activities:

- selecting the best orientation of the part in the mold,
- determining the parting line,
- identifying features that have to be produced by cores,
- design of cores (including their supports or core-prints),
- design of core boxes to produce the cores,
- design of risers to provide feed metal (number, location, shape, dimensions),
- design of gating system to lead molten metal into the mold,
- layout of cavities in the mold,
- design of match-plate pattern or die (including applying allowances),
- other systems (mainly for die casting: guidance, cooling, ejection, etc.).

These decisions require an in-depth knowledge of the metal-specific casting process and considerable experience in casting design for a range of applications. During the last two decades, many researchers and some enthusiastic foundry engineers have attempted to capture the relevant knowledge in rules and empirical equations, which can be coded into a computer program. Typically, the user enters the type of cast metal, part weight, section modulus, average section thickness, type of risers and gating system, their location, etc., and the program calculates the dimensions of the riser and gating channels based on. These values are useful for creating a casting model (with risers and gating) in a solid modeling system.

A few advanced programs for simulating the casting process are also available today [AFS, 1997]. These programs help in predicting the location and intensity of major casting defects such as shrinkage cavities, porosity, air entrapment, erosion and cold shuts. Thus foundry engineers can check several different alternatives for feeding and gating design and finalize the optimal layout without pouring a single casting. However, the engineer still requires experience for taking the key decisions, setting up the simulation run, interpreting the results of simulation and finalizing the design. The programs for designing various elements of a casting as well as programs for modeling and simulation programs are all different (developed and offered by different companies). Thus the user has the additional burden of managing these programs and switching between them; also there is a high possibility of errors when transferring the data (manually or electronically) between the programs.

We propose an intelligent integrated approach to enable better and faster decision making during casting design. Intelligent CAD software is distinguished from conventional CAD by its capability to perform tasks which require domain knowledge and geometric reasoning. (Expert Systems, which also contain domain knowledge and an inference engine, can not handle geometry). Geometric reasoning is required for automatic recognition of casting features (such as cored holes from a solid model of the part). The domain knowledge is required for assessing the features recognized (for example, determining whether the feature has to be produced by a core, designing the core print and evaluating the entire core in terms of strength, venting, cooling and other criteria). Intelligent CAD software will thus act like a manufacturing expert, on call anytime, to assist product engineers in design for manufacture; tooling and casting engineers can verify their decisions and ensure that a feasible design alternative has not been overlooked. Such an intelligent assistant to casting designers – called AutoCAST – has been developed [Ravi, 1999]. It simulates the way expert engineers design various elements of a casting such as parting line, core, mold, feeders and gating (Fig. 1). All programs of this system are linked through an in-built casting project database management system.

Fig. 1 Casting design and analysis for an automobile part.
A geometric reasoning engine built into the program automatically computes average section thickness (useful for determining the ideal filling time) and section modulus (useful for designing the feeders). This not only saves valuable time of engineers, but also ensures accurate results the very first time. The reasoning engine also suggests a suitable position of the parting, feeder or ingate, and the designer can either accept the suggestion or override it and enter his own choice.

In addition, AutoCAST includes 20 "health-check" criteria to assess the castability of a given component. This includes minimum section thickness of the part, draw distance for a given parting and complexity of a core. All these affect the quality, lead time or cost of a casting. A weighted assessment of the entire casting design is also provided, so the design can verify the effect of any design modification on the overall castability of the component.

The knowledge-based approach to casting design dramatically reduces the total time for optimizing a casting. For example, 6-10 iterations may be required for optimizing the feeder design alone for a small-to-medium complex part, and the total time for feeder design-model-simulate using separate programs may take 10-15 days (1.5 to 2 days per iteration). For optimizing the entire casting design (including orientation, gating, etc.), more iterations, and hence more time will be needed. An intelligent program like AutoCAST not only reduces the iteration time, but also cuts down the number of iterations required (by giving good first solutions), with the result that a casting design can be optimized within a single day!

After the casting design is optimized, the pattern model can be generated using a solid modeling program. This involves splitting across the parting line, removing the holes, adding core prints, applying draft, fillets and various allowances. Some solid modeling programs have semi-automatic facilities to speed up the above steps. The pattern model is needed for the next step: actual fabrication of the tooling.

4. Rapid Prototyping and Tooling

Rapid prototyping (RP) techniques enable complex shaped parts to be produced directly from a computer model within a few hours: no part-specific tooling or machining is required. These models can be directly used as patterns for casting or can be used for producing the tooling through rapid tooling (RT) processes. While RP techniques were initially intended for creating prototypes of complex shaped products (to verify their form, fit and to some extent, their function), in recent years these techniques have been combined with RT techniques by several foundries, tool rooms and service bureaus. This has enabled significant reductions in the lead-time to manufacture cast products. The two technologies (RP and RT) are outlined below, and the next section will describe how these can be applied to the metal casting sector.

4.1 Rapid Prototyping Techniques

The Rapid Prototyping (RP) technology is based on the philosophy of fabricating the cross-sectional layers on top of each other to produce a part. The sections are generated from a solid model of the part created on a computer and then fabricated using one of the several RP techniques available. These include selective liquid solidification, liquid deposition, powder binding and sheet laminating [Xue,1996]. The main RP techniques currently available in the industry include stereolithography (SLA), solid ground curing (SGC), fused deposition modeling (FDM), laminated object manufacturing (LOM) and selective laser sintering (SLS). These are briefly described here (also see Fig.2).

Stereolithography uses an ultraviolet laser beam moving in a criss-cross fashion to cure photocurable polymer resin contained in a vat. The polymer layer is lowered by a platform attached to it to enable generating the next layer on top. Solid Ground Curing is similar to stereolithography; the difference is that the entire layer of polymer within the specified boundary is cured by a flood of ultraviolet light passing through a glass mask containing a negative image of the cross-section.

Fused Deposition Modeling technique relies on melting and depositing a thin filament of thermoplastic polymer to form each layer. A separate head deposits the support material in each layer, which can be broken off later.

Laminated Object Manufacturing involves laser beam cutting of cross-section contours out of sheets of heat sensitive or polymer coated paper; the adjacent layers are joined by heating and compression by a roller.

Selective Laser Sintering process uses a high power laser beam to melt thermoplastic powder spread on a layer. A roller spreads the next layer of powder on the previous layer. The unsintered powder serves the function of supports for undercuts. Table 1 provides a summary of the characteristics of the above RP techniques.
Fig. 2 Rapid Prototyping processes: top- FDM, middle- SLA, bottom- LOM.

Table 1: Comparison of Rapid Prototyping processes
[Kruth, 1991; Karunakaran 1998]

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>SLA</th>
<th>SGC</th>
<th>FDM</th>
<th>LOM</th>
<th>SLS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PHOTO-POLYMERS (UV): ACRYLATES</td>
<td>PHOTO-POLYMERS (UV): ACRYLATES</td>
<td>THERMOPLASTICS: INVESTMENT WAX, MACHINABLE WAX, NYLON LIKE MATERIAL, WAX FILLED PLASTIC ADHESIVE</td>
<td>PAPER, CELLULOSE PLASTICS, METALS, FABRICS SYNTHETIC MATERIAL ANY SHEET PRE-COATED WITH HEAT ACTIVE ADHESIVE</td>
<td>POWDERS: THERMOPLASTICS (ABS, NYLON, PVC, PC), WAX, METALS, POLYMER COATED CERAMICS</td>
</tr>
<tr>
<td>RAW FORM</td>
<td>LIQUID</td>
<td>LIQUID</td>
<td>1.25 mm WIRE</td>
<td>SHEET FOIL</td>
<td>POWDER</td>
</tr>
<tr>
<td>BUILD ENVELOP (mm)</td>
<td>SLA - 250: 250x250x250</td>
<td>SOLIDER - 4600: 350x350x350</td>
<td>FDM - 1650: 254x254x254</td>
<td>LOM - 1015: 380x250x350</td>
<td>SINTER STATION 300x300</td>
</tr>
<tr>
<td>BUILD RATE (mm³/Sec)</td>
<td>100</td>
<td>365</td>
<td>5</td>
<td>500</td>
<td>20</td>
</tr>
<tr>
<td>ACCURACY (mm)</td>
<td>XY - PLANE</td>
<td>Z – PLANE</td>
<td>0.1</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>LAYER THICKNESS (mm)</td>
<td>0.1 - 0.7</td>
<td>0.05 - 0.15</td>
<td>0.925 - 1.25</td>
<td>0.51 - 0.15</td>
<td>0.08 - 0.13</td>
</tr>
<tr>
<td>NEED FOR SUPPORT</td>
<td>YES</td>
<td>NO</td>
<td>SOMETIMES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>POST CURING</td>
<td>YES, OVEN CURING</td>
<td>YES, MELTING OF WAX</td>
<td>NO</td>
<td>NO</td>
<td>NO, EXCEPT COATED CERAMICS</td>
</tr>
<tr>
<td>INITIAL COSTS ($)</td>
<td>70,000 TO 490,000</td>
<td>295,000 TO 475,000</td>
<td>110,000 TO 120,000</td>
<td>140,000 TO 272,000</td>
<td>366,000 TO 450,000</td>
</tr>
<tr>
<td>FLOOR SPACE (meter)</td>
<td>0.7x1.2x1.6 - 1.8x1.2x2.0</td>
<td>1.8x2.4x2.9</td>
<td>0.6x0.8x0.93 - 0.9x0.92x1.07</td>
<td>1.2x0.99x1.27 - 2.0x1.47x1.4</td>
<td>3.02x1.53x1.93</td>
</tr>
<tr>
<td>COMPANY</td>
<td>3D SYSTEMS</td>
<td>CUBITAL</td>
<td>STRATASYS INC.</td>
<td>HELYSYS CORP.</td>
<td>DTM CORP.</td>
</tr>
</tbody>
</table>
4.2 Rapid Tooling Techniques

Rapid tooling can be considered as secondary operations, which produce a negative replica or mold from a master (the master can be produced by Rapid Prototyping processes). The mold can be used to obtain a replica of the original model. Different processes used in secondary operations can thus produce the desired tooling through several routes (Fig.3). Some of the routes are useful for creating one-off parts, others are useful for small, medium or large batch products. The most widely used materials for producing rapid tooling include thermosetting polymers: epoxy resins, polyurethanes (elastomers and foams) and silicones. Metals, especially those with low melting point are also used in some processes. Some of the important operations employed for rapid tooling are outlined here: epoxy resin casting, laminated shell molding, silicone rubber molding, polyurethane casting, metal arc spraying and investment casting [Reg,1999].

**Epoxy Resin Casting** process essentially involves mixing a suitable epoxy resin with a hardener and pouring it into a mold or onto the face of the model placed in a box. A parting agent applied to the face of the mold facilitates easy release of the fabricated model.

**Laminated Shell Molding** involves creating a laminated shell around a master model using alternate layers of gel, epoxy resin and glass cloth. While it is labor intensive and time consuming, it couples light weight with good strength, suitable for large flat parts.

**Silicone Rubber Molding** involves pouring RTV silicone rubber around a master model and cutting open the mold after curing. These molds have excellent chemical resistance, low shrinkage and high dimensional stability, suitable for producing parts in polyester, epoxy and polyurethane foam by injection molding.

**Polyurethane Casting** involves pouring the resin around a master placed in a box, similar to epoxy casting. The material is more expensive than epoxy, but sets faster and can produce better detail.

**Metal Arc Spraying** process uses a high velocity electric arc metal spray generating system to deposit finely atomized particles of molten metal (usually kirksite) onto a model surface to create a metal shell mold. The metal shell can be reinforced by epoxy.

**Investment Casting** requires an expendable pattern (usually of wax) which is coated with layers of silica slurry to obtain a shell, which is heated to remove the wax. Molten metal is poured in the shell and allowed to solidify to give a metal replica of the wax model.

Fig.3 Rapid Tooling processes: from top PU casting, silicone rubber mold, laminated shell, and SLA QuickCast.
5. Rapid Tooling for Casting

The range of RP and RT techniques available today provides several routes for producing the tooling for metal casting. Some of these are useful for creating one-off parts or master patterns, others are useful for creating patterns and coreboxes that can be used for short, medium or long runs. Indeed, RPT technologists are continuously opening up new materials and routes for producing the tooling (for various casting processes): polymer patterns, investment patterns, polyurethane foam patterns, metal patterns, pattern plates and coreboxes. Various rapid prototyping and tooling techniques suitable for fabricating different types of patterns are briefly described here [Karunakaran, 1998].

Patterns: Models fabricated by a few RP systems can be directly used as casting patterns for low to medium size batches. The LOM process has been the most widely used for this purpose, since it produces wood-like models. The low cost of the fabrication material and the fast build rate makes the LOM process economical for large size patterns, where dimensional accuracy is not very critical. These patterns are however, required to be initially and periodically coated with lacquer to maintain a smooth surface finish and have a longer life. The ABS models produced by the FDM process and some polymer models produced by SLA, SGC and BPM processes can also be used as casting patterns. These are more suited to small, intricate components requiring good dimensional accuracy and surface finish. All these patterns are lightweight, have adequate strength, produce good surface finish, are easy to clean after molding and are economical for small to medium runs. The plastic patterns can also be hand finished to obtain a smooth surface and can be coated with resins, both initially and periodically, to enhance their life. The SLS process can directly produce silica shell molds into which metal can be poured to produce metal patterns.

Investment Patterns: RP processes can directly produce models in wax or a polymer which can be used in the investment casting process. Most RP manufacturers have recognized the importance of addressing this requirement and offer special materials and build techniques to produce investment patterns. The FDM machine comes with a special head to produce wax models. The SLA equipment now supports a photocurable resin suitable for investment casting and uses a proprietary QuickCast build technique to produce patterns with hollow honeycomb-type walls ensuring better collapsibility during burnout. Even LOM models can be invested, though they leave a high ash residue. The SLS process can produce metal molds, which can be used for producing investment casting wax patterns. Wax and polyurethane foam patterns can also be produced by injecting wax/resin in a silicone rubber or polyurethane mold produced by the rapid tooling techniques.

Pattern Plates and Coreboxes: Pattern plates and coreboxes can be produced by making a negative replica of the corresponding master model using epoxy resin. For producing a pattern plate, a negative (mold) is first produced by pouring epoxy or polyurethane resin around a master model placed in a box. After curing both sides of the mold, the pattern is then cast by pouring the resin in the epoxy mold. The epoxy patterns can be reinforced with glass cloth during curing or enclosed in a metal frame. No reinforcement is required if the patterns are to be used on automatic high pressure molding equipment, since there is no jolting action as in conventional molding machines. For producing a corebox, a model of the core is required. This is can be easily fabricated by extracting the corresponding feature (hole) from the computer model of the component, reversing the feature to obtain the corresponding solid and fabricating the model on an RP machine. The corebox is then build around the core feature by either epoxy resin casting or laminated shell molding. While such pattern plates and coreboxes are suitable for small to medium runs, the ease of manufacture and repair makes them quite attractive, especially for complex shapes.

Given the number of RP and RT processes, there are a large number of routes to produce the tooling for casting processes. Each route has its own capabilities, strengths and limitations, in terms of materials, quality characteristics and costs. Choosing the correct route for a given set of requirements is therefore an important task. Once the route is chosen, fabricating the actual tooling involves creating the master pattern or master mold using RP, and then creating the master mold or regular pattern using RT. If the solid model of the pattern is ready, the first step (RP) may take 12-60 hours depending on size, and the second step (RT) may take 24-48 hours depending on the process. The patterns can thus be fabricated within a working week!

6. Conclusion

This paper described how three new technologies: solid modeling, knowledge-based casting design and rapid prototyping & tooling can help in compressing the total lead time for producing the patterns for metal casting. All three require substantial initial investment in terms of hardware, software and trained ‘humanware’. Equally important, they require a change of culture from the one relying on cost-cutting
measure to increase profitability, to the one which uses time (in terms of shorter time as well as assured delivery) to add value and gain competitive advantage. Already there are hundreds of new-age tool-rooms in USA and Europe, which use these technologies to deliver tooling to their customers in days instead of weeks. As the technologies mature, the costs are likely to reduce to an extent that these routes become economic enough to replace conventional pattern-making techniques. Pattern and tool-makers need to be aware of these new developments taking place, start building up their knowledge and experience in this area, and take the critical step of transition before it is too late.

7. References


