Use of Casting Simulation and Rapid Prototyping in an Undergraduate Course in Manufacturing Processes

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Abstract

Mechanical Engineering students at Milwaukee School of Engineering (MSOE) study manufacturing processes in the junior year. Part of their study in this course is a project to create an original casting. This project encompasses several steps. First is to design the part and the associated mold system (gates & risers) for sand-casting the part. Next, students analyze performance of their mold layout through the use of SolidCast casting simulation software and make improvements to the initial mold layout. A final version of the casting design is submitted to the MSOE rapid prototyping center for fabrication of the casting patterns. The last step is to make an aluminum sand-cast part, in a small-scale foundry in MSOE’s labs. The project emphasizes the basic premise of the course; a manufactured part must be designed within the limitations and capabilities of the manufacturing process.

Successful completion of the project covers several key course outcomes, including: 1) understand the steps involved in basic green-sand casting process along with its capabilities and limitations, 2) apply this knowledge to design a component and mold layout, 3) understand the characteristics of a good versus poor mold layout, 4) apply modern computing methods as a means to do design of an effective mold for sand casting.

With the successful implementation of SolidCast™ and rapid prototyping methods into this project, students learn course outcomes at a much higher level. In the past, the lab was an informative exercise where students made sand cast parts. Now it is a true engineering design experience for the students. They are able to approach mold design as a fluids problem, a heat transfer problem, and a manufacturing quality and cost problem.

Introduction

Mechanical Engineering students at Milwaukee School of Engineering (MSOE) study manufacturing processes in the junior year. This is an overview course where students learn about a wide range of manufacturing processes. The major course outcome is to develop an understanding of the capabilities and limitations of various manufacturing processes commonly used to make mechanical components. To design a specific component, students must take into account the service conditions and design requirements. These may include such characteristics as minimizing stress from applied loads, proper pathways for adequate heat transfer or the effect of part surfaces on fluid flow around the component. These are the design approaches students learn about in courses in Mechanics of Materials, Heat Transfer and Fluid Dynamics. For the Manufacturing course, the ideal is for students to understand how the selection of a manufacturing process will also influence the dimensions and characteristics of their part design. To facilitate this, students at MSOE complete a casting design project. The project spans 7 weeks, start to finish, within a 10-week course.
Students work with lab partners to design a part of their own choice, to be made by sand casting at the end of the quarter. Required elements of the project include design of the individual parts, designing a mold layout to make those parts, and analyzing mold performance through the use of SolidCast™ solidification modeling software. Each lab group will typically incorporate 2 to 4 parts to be made in one mold layout. The mold layout including the necessary gates and risers is modeled using SolidCast. This program simulates the heat transfer and solidification behavior of the mold system and helps to identify potential problem areas. Students are required to show at least 3 different iterations on the mold layout and provide evidence of improvement in either quality of the parts or efficiency of the mold system design. Students have the option to have part patterns made at MSOE’s Rapid Prototyping Center.

Learning outcomes accomplished through this assignment are as follows. Students will:

1) Understand the steps involved in basic green-sand casting process.

2) Know the basic elements of a mold system and the function of each element: part pattern, gating system, riser, vents and sprue.

3) Understand how sand molds are made.

4) Know the capabilities and limitations of sand casting and apply this knowledge to design a component that is compatible with sand casting. Specifically, parts should be designed for good fluid flow, should promote directional solidification, have adequate draft angles for pattern removal from the sand, and avoid thin walls and fine details in the part.

5) Understand the characteristics of a good versus poor mold layout when casting multiple parts in one mold. Directional solidification of the parts should be promoted such that solidification progresses back towards the riser and begins away from the riser. The riser must be adequately sized to prevent shrinkage defects in the parts.

6) Apply engineering simulation tools (casting simulation using SolidCast™ software) as a means to do design of an effective mold layout.

7) Learn about methods for Rapid Prototyping and how this can be used for making patterns for sand casting.

In a larger context the project helps students make the transition between engineering fundamentals and professional practice. The goal within MSOE mechanical engineering curriculum is to prepare students for professional practice by providing experiences which are based on complex design constraints including part function, manufacturability, safety and cost considerations. For the Manufacturing course, the ideal is for students to understand how the selection of a manufacturing process will influence the dimensions and characteristics of their part design.
Details of the Project

As part of the project, students must work on design of a cast part and the necessary mold system to make that part. The process specified is sand casting using standard green sand mold making techniques. This is not simply a design project. Students eventually make sand molds and cast their parts at the end of the term. A general project schedule is shown in Table 1.

<table>
<thead>
<tr>
<th>Project Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SolidCast Tutorial</strong></td>
</tr>
<tr>
<td><strong>Mold Practice</strong></td>
</tr>
<tr>
<td><strong>SolidCast Mold Design</strong></td>
</tr>
<tr>
<td><strong>Part Designs to RPC</strong></td>
</tr>
<tr>
<td><strong>RPC Patterns Completed</strong></td>
</tr>
<tr>
<td><strong>Casting</strong></td>
</tr>
</tbody>
</table>

Table 1; Casting project schedule, completed within the 10 week manufacturing course.

The overall project takes four 2-hour lab periods spread out over the term. One lab session (week 2 of the course) is used to work through a SolidCast™ tutorial example. SolidCast™ is a casting simulation program from Finite Solutions, Inc., which can be used to analyze the cooling, solidification and flow within a mold. The tutorial problem was developed at MSOE and is designed to show how to use the software and teach students the basic steps of running a simulation. The tutorial, developed at includes 4 simulation runs: single part alone with no riser, then three different layout options of 3 parts plus gates and a central riser. In a second lab session students simply practice the mold making process for green sand molding. A third lab session (week 4) is when students start to analyze their own parts. Many students design something specifically for this project and have the patterns made in MSOE’s rapid prototyping center. Others simply duplicate an existing part using that part as a pattern. Some students make their own patterns by other methods. In any case, the input to the simulation program requires a simple CAD model of the part. MSOE uses SolidWorks as the standard CAD software so
students use this to make the required model. Lab groups, typically 3 students, work together on the project. It is up to the group to decide to make 1, 2, or 3 parts in the mold. A few weeks are allowed for students to complete their analyses and write the design report. Finally, the fourth lab session is when students make the mold and cast their parts. The casting material used is aluminum alloy 355. It is melted in crucibles in small batches and poured by hand.

**Rapid Prototype Patterns**

Patterns of students’ final designs are often made via rapid prototyping. Designs are submitted to the MSOE’s rapid prototyping center for fabrication. One method that works best is selective laser sintering (SLS) of glass-filled nylon material on a 3D Systems Sinterstation 2500 Plus. In past years other methods have been tried. One method that is also good is 3D printing on a Z-Corp Spectrum Z510. These patterns work well but are somewhat more fragile and have a little more tendency to stick in the sand when removing the pattern, due to a slightly rougher surface. Another method tried, with less than optimal results, was Laminated Object Manufacturing on a Helisys LOM 2030E. Those patterns are very much like the consistency of wood, which is a traditional material for sand mold patterns. However, the LOM patterns had much more tendency to stick to the mold when removing the patterns. Draft angles with those patterns needed to be about 10 degrees as compared to 5 degrees for the SLS patterns.

**Design for Sand Casting**

To accommodate the sand casting process the student must change their thought process from “what must this component do?” to “how will this component be made?” They must consider each step of the process and how that step may change the way they design the part. For sand casting this includes several important considerations. First, the part must be designed for good fluid flow paths for the incoming liquid metal to enter the mold cavity. Second, the part must be designed with adequate heat transfer paths to allow for favorable cooling as the part solidifies. The specific pattern of solidification is important, not simply solidification time. For example, a part which solidifies starting from one side and progresses towards the opposite side will generally be an easier mold layout and will produce better quality parts. This is referred to as directional solidification. On the other hand, a part that solidifies starting at the outer edges then progressing toward the middle may be more difficult to work with. Third, green sand molding utilizes a pattern for producing the mold cavity in sand. Before the part is cast this pattern must be removed from the sand mold. This step seems obvious but removal of the pattern from the sand is a factor which must be considered in the part design. Because of this step, draft angles must be added on any surfaces that must slide over the sand mold. Also, fine details or relatively deep features cannot be designed into the component. Finally, there is the simple constraint of the size of the flask used in mold-making. The flasks used are 10” x 12” x 8” deep. The entire mold layout must be designed within this space. As an added challenge, if a lab group wants to make multiple parts they must figure out how to make those 2 or 3 or 4 parts in one mold layout, not multiple casting trials. For all of these considerations the designer must understand they are not just working with “the component” but are designing an entire mold system including the gates, runners, a riser and the pouring sprue. In this course, SolidCast™ simulation software is used only to look at cooling and solidification considerations. Finite Solutions Corp. also has a FlowCast™ module which will similarly analyze the flow patterns in the mold system. However,
that level of analysis is beyond what can be taught in the time available in the manufacturing course.

Using SolidCast™ to Design a Mold Layout

Assessment of students’ project reports is based on 2 key factors: 1) correctly using the SolidCast™ software to analyze a part and a mold layout and then 2) using that tool to show some improvement of the mold layout. Students are required to analyze 3 different possible mold layouts and make a technical justification for which of the 3 they think is best. Some groups choose to look at many more than three options. Demonstrated improvement could be better quality characteristics of the part or improvement could be better yield (efficiency) of the mold layout. For the first step in the analysis, students use SolidCast™ software to analyze the cooling and solidification tendencies of each individual part (without gates and riser). This preliminary analysis is a necessary first step. It shows the mold designer the natural tendencies of a part for directional solidification or not. Those natural tendencies could be forced to change when the part is incorporated into a mold layout. A mold layout may include 2 or 3 parts and a riser and gating system. It is helpful to see the natural tendencies of each part alone before considering the more complex problem of a mold system design. Once the initial simulation runs are completed, students must design a first pass at a mold layout. The mold layout would include the position of all parts to be cast, riser size and location, and all the related gating between riser and parts. A down sprue and pouring cup are required for the mold but are not a required part of their analysis. Figure 1 shows the basic elements of a mold layout on two finished castings.

Figure 1 Two examples of a complete mold layout. Casting on the left is shown in the orientation it was cast. Two parts in the foreground, cylindrical riser in the middle and the down sprue in the background. The thin protrusions up from the parts are vents, which filled with aluminum as the mold filled. Casting on the right is shown in an upside-down orientation from how it was cast. Four parts around a central riser and the down sprue and pouring cup on the right of the picture.
Figure 2 shows a simple part and then SolidCast™ simulation results for that individual part. This is a preliminary run, as it would be impossible to cast a part without at least a runner and gate added. The purpose is to show the natural tendencies of the part. This particular part is one that is used for a tutorial exercise which students do in the first SolidCast™ lab session.

Figure 2: Left: a simple part used for the SolidCast™ tutorial exercise. The part is 2” long and 1” deep. Right: SolidCast™ result for solidification of the part alone. This plot shows “critical fraction solid time”, which essentially indicates that the outer regions of the part has solidified and the round (darker) region has not at 0.25 minutes. As expected, the last material to solidify is in the thickest region of the casting.

Figure 3: one possible arrangement of 3 parts around a central riser.

The first common strategy is typically to follow the natural tendency of the part and try to position the gate as directly as possible into the regions that are the last to solidify. This method was used for the layout shown above.
In Figure 4, the plot on the left shows the simulation results for the mold arrangement shown in Figure 3. Poor results are indicated by the fact that large regions of each part remain liquid (dark) yet the runners (between riser and parts) are completely solidified (shown at time = 0.20 minutes). In this case, the riser would be ineffective at feeding additional molten metal to the parts. Even though the solidification time of the riser is longer than solidification time for the part the riser cannot effectively feed that material to the parts. This case would likely result in shrinkage voids in the parts. The plot on the right shows an improved arrangement of the same 3 parts and riser. Pathways through the gating area remain un-solidified further into the process (0.275 minutes) which will effectively allow metal to flow to the parts as they cool and solidify. Once an acceptable cooling pattern is established, the next step could be to try to minimize riser and gating to use less material while maintaining good flow and cooling patterns.

Another way to evaluate the effectiveness of a mold is by plotting “material density” results in SolidCast™. Ideally, a finished part will be 100% dense, meaning no voids or shrinkage. The material density plot is not a prefect predictor of shrinkage flaws but is does show the relative likelihood that those flaws would appear and where they would most likely occur. Figure 5 below shows material density plots for the two previous cases.
Figure 5  For the same to mold layouts shown in Figure 4 above. These are material density plots. Mold system on the right show very small regions of low porosity (threshold for the plot is 99%) and mold on the left show larger regions susceptible to porosity, even though plotted at a lower threshold 98% (lower % density = more porosity = worse part). The conclusion would be that the mold on the right will make better quality parts.

Student Examples

There are multiple strategies for designing a successful mold layout. One standard method is to design the parts for directional solidification and then arrange parts in the mold to follow the natural tendencies of each part.

Student Examples: Designing for Directional Solidification

Many students want to make a team logo or automobile medallion. A nice example of this is shown below. Figure 6 shows 3 versions of the same part: the SolidWorks CAD model, the rapid prototype pattern and the final sand cast part. The original student design for the part in Figure 6 was essentially flat and uniformly 0.5” thick. It had the overall shape of the part and 3 shallow lines across the “M” to make the desired appearance. It is common that students want to make a decorative part. They usually start out thinking in a 2-dimensional sense, trying to “draw” elements of their design on the surface of a flat part using shallow inscribed lines or slight raised ridges. The problem is that sand casting is not great for shallow inscribed lines or slight raised ridges. The version shown is more compatible with sand casting. By using multiple thickness in the part (from 0.25” to 0.625”), the student was able to get the desired image and also add a 3 dimensional effect. The shape itself is easier to make in sand. Additionally, this simple design change promotes directional solidification from left to right.
Another example of changing a part to promote directional solidification is shown below in Figure 7. Again, the original part was essentially flat uniform thickness with shallow lines added. In the version shown below the student re-designed to add thickness level changes to create the effect of the feathers and the hair. This creates a nice 3-D effect to the finished part and also promotes directional solidification from left to right, which makes the part easier to cast.
Student Examples: Arrangement of parts

A significant benefit of using the SolidCast™ analysis is that it allows students the opportunity to try out so many different possible options for making a mold layout. Even a simple mold with 2 or 3 parts has many possible solutions to the question, “how do I arrange the parts?” In the example below, two students made a business card holder and a C-clamp. In all, they tried out 6 different arrangements of those parts in a mold and looked at the effects of different layouts on the SolidCast™ analysis results. Figure 8 shows the first and last iterations.

The layout on the left is very typical of what students do to start, with everything laid out at 90 degrees or 180 degrees and gating into the middle of a part. The option shown on the right has the parts laid out in such a way as to promote solidification from one end to the other instead of back toward the middle of each part. Analysis results for these two options are shown below.
Both of these potential mold layouts have advantages and disadvantages. In this case it is not obvious that one option is better than the other. The real point of the exercise is that the students thought up and tried 6 different possibilities. They analyzed each and looked for characteristics like directional flow and potential for flaws (shrinkage voids) in the parts as it related to the mold layout.

Student Examples: Riser Sizing and Increased Yield

In evaluating a mold layout, one important characteristic for production molds would be the percentage yield. This is simply the fraction of metal in a finished cast part, versus the total metal required to make a mold (with riser, gates, etc.). This parameter is important since it contributes to the cost of manufacturing the part. A more efficient mold (higher yield %) means a lower cost part.

Some students show very good analysis results in their first run, primarily because they were very conservative in their riser sizing (very large riser). In this case they can re-work the mold layout or riser design in order to show improvement in yield percentage.
In the result shown in Figure 10, the initial result was good as far as solidification and would be fine for a one-of-a-kind part made in lab. SolidCast™ has an easy feature to determine amount of metal going to part and riser. In the initial layout design, the part alone weighs 0.041 lbs. while the total for part, gate and riser is 0.161 lbs., which is a yield of 25%. This is relatively poor mold efficiency. The version on the right has several changes: a) the riser has been changed from cylindrical to rectangular, b) the overall riser volume is decreased, c) the riser is set down slightly (in the vertical direction) relative to the part, d) the length of the gate is shortened and e) gating into the part is at the mid-plane rather than at the bottom surface of the part. All of these contributed to an increase from 25% to 44% yield for the mold.

Student Examples: Fine Details and Thin Walls

One of the main learning outcomes for this multi-week exercise is for students to learn how to design parts to be compatible with chosen manufacturing process. It is an “experiment” and as such some of the learning is learning through trial and failure. Often students are told in lecture or read about such guidelines as “needs draft angle” and “not too thin” or “no fine features.” However, when students design a part it is not clear how thin is “thin” and how fine is “fine.” Often students will quote some source where they read “a draft angle of 2° is adequate.” Well, sometimes it may be but sometimes it isn’t. Students are allowed to push these limits and see what happens. At the end of casting week, everyone sees and we review the results of everyone’s trials. This is really one of the best learning opportunities of the project. Experience is a good teacher, or at least, he makes for memorable lessons.
Figure 11  Design of a mantis (?). The rapid prototype process used had no problem with fine details in the wings and body of the mantis. The casting process was able to reproduce some of those details, but, there were also problems with inadequate draft on the inside border.

Figure 12  Replica of an oversized penny. Fine details in the surface of the part turned out surprisingly well.
Casting the Parts in MSOE’s Foundry

Figure 13  Casting the finished parts in MSOE’s foundry.

Conclusions

In past years MSOE students did sand molding in lab but did not use the SolidCast™ simulation. The approach used was very simple and based on an accepted “rule of thumb” that the solidification time for a riser should be at least 1.25 times the solidification time of the parts. Solidification time of each can be calculated based on Chvorinov’s rule.

\[
\text{Solidification time } t(s) = B \left( \frac{V}{A} \right)^2
\]

Where \( V \) = volume of the part or riser, \( A \) = surface area of the part or riser, \( B \) = an empirical mold constant. Then, according to general guidelines the riser should be designed such that \( t(s) \) for the riser > 1.25 \( t(s) \) for the parts. With the successful implementation of SolidCast™ students learn course outcomes at a much higher level. In the past the lab was an informative lab exercise where students could see the casting process. Now it is a true engineering design experience for the students. They are able to approach mold design as a fluids problem, a heat transfer problem, and a manufacturing quality and cost problem.
This project incorporates several aspects of manufacturing but emphasizes the basic premise of the course; a manufactured part must be designed with the limitations and capabilities of the manufacturing process in mind. In a larger context the project helps students make the transition between engineering fundamentals and professional practice. The goal within Milwaukee School of Engineering mechanical engineering curriculum is to prepare students for professional practice by providing experiences which are based on complex design constraints including part function, manufacturability, safety and cost considerations. Successful completion of the project requires the students understand the capabilities of the sand molding process as well and the rapid prototyping process used to make the part patterns. Concepts learned include: proper riser size, good and bad orientation of parts within the mold layout, shrinkage flaws and how to avoid them, required draft and other mold design details, and limits on ability to make fine details and thin sections. This project teaches key concepts of the Manufacturing course but also reinforces skills the students learned in introductory CAD, materials/metallurgy and heat transfer. It also provides the opportunity to incorporate a design experience into the curriculum.

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