

Worcester Polytechnic Institute

Optimized Design of Gating/Riser System in Casting Based on CAD and Simulation Technology



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Abstract

Casting as a manufacturing process to make complex shapes of metal materials in mass production may experience many different defects such as porosity and incomplete filling. How to improve the casting quality becomes important. Gating/riser system design is critical to improving casting quality. The objective of the research presented in this thesis is to optimize gating/riser systems based on CAD and simulation technology with the goal of improving casting quality such as reducing incomplete filling area, decreasing large porosity and increasing yield.

Therefore in the thesis, an optimization framework is presented based on CAD and simulation technology. Given a CAD model of part design and after converted to a casting model, it is the first step to evaluate castability of the casting design. Then the runner and risers are represented parametrically, and CAD models generated by varying parameters can be used in the simulation. After analyzing simulation results, the gating/riser system design is optimized to improve casting quality.

In the thesis, one engine block is used to verify the effectiveness of the optimization method. Compared with the initial design, it is found that the optimized casting design can decrease porosity around 18% while the yield increases 16%.

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Chapter 1 Introduction

Casting is a manufacturing process for making complex shapes of metal materials in mass production. There are two main consecutive stages, filling process and solidification process, in casting production. In filling process gating system composed of pouring cup, runner, sprue, sprue well and ingate, is designed to guide liquid metal filling. Riser system is used to compensate shrinkage caused by casting solidification. Casting process design is important for production quality and efficiency.

It is unavoidable that many different defects occur in casting process, such as porosity and incomplete filling. How to improve the casting quality becomes important. Casting quality is heavily dependent on the success of gating/riser system design, which currently is conducted mainly relied on technicians' experience. Therefore there is a need for the development of a computer-aided casting process design tool with CAD, simulation, and optimization functions to ensure the quality of casting.

The objective of the research presented in this thesis is to optimize gating/riser systems based on CAD and simulation technology with the goal of improving casting quality such as reducing incomplete filling area, decreasing large porosity and increasing yield.

Therefore in the thesis, a CAD and simulation technology based optimization framework is presented. Given a CAD model of part design and after its being converted to casting model, the first objective is to evaluate castability of the casting design. Then runner and risers are presented parametrically. By varying each parameter, all CAD

models will be obtained. After analyzing simulation results, the original gating/riser system design will be optimized to improve casting quality.

In this thesis, one engine block is used to verify the effectiveness of the optimization method. Compared with the initial design, the optimized casting assembly can decrease porosity around 18% while the yield increases 16%.

Chapter 2 Background

This chapter provides an introduction to sand casting process. First the steps of sand casting process are addressed. Then, considerations required for casting process design are stated. Next, casting quality and some common defects are discussed. After this, gating/riser system and castability analysis are explained in detail. Finally, the remained problems of casting process design and the objective of the thesis are given.

2.1 Sand Casting Processes

Sand casting consists of placing a pattern (having the shape of the desired casting) in sand to make an imprint, incorporating a gating system, filling the resulting cavity with molten metal, allowing the metal to cool until it solidifies ^[21]. Sand casting is still the most popular form of casting. The steps to make sand castings are illustrated in Fig 2.1 ^[3].

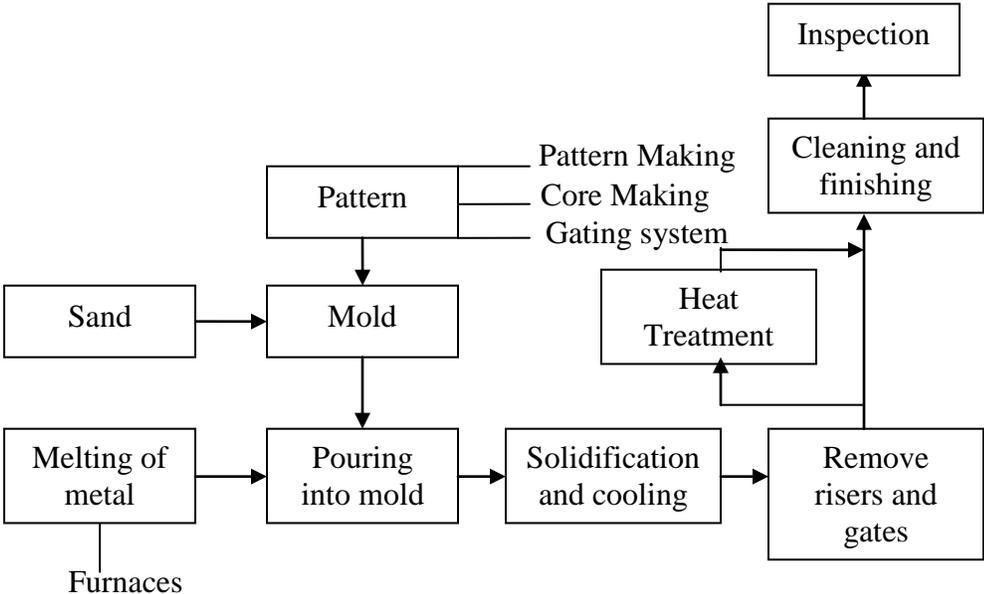


Figure 2.1 Production steps in a typical sand casting process

Basically sand casting process consists of:

- 1) Placing a pattern (having the shape of the desired casting) in sand to make an imprint;
- 2) Incorporating a gating system;
- 3) Removing the pattern and filling the mold cavity with the molten metal;
- 4) Allowing the metal to cool until it solidifies;
- 5) Breaking away the sand mold;
- 6) Removing the casting.

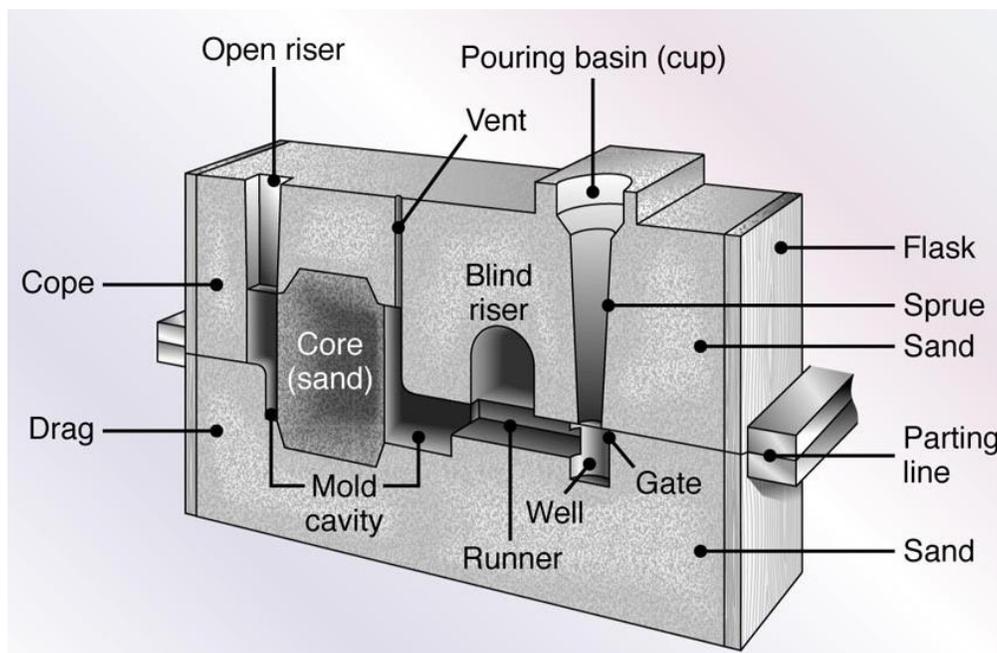


Figure 2.2 Schematic illustration of a sand mold

2.2 Sand Casting Process Design

The main objective of the sand casting process design is to produce the satisfied sand mold illustrated in the following figure.

The typical sand casting process design consists of the following steps.

- Sand Selection ^[3]

Several factors are important in the selection of sand for molds, and it involves certain tradeoffs with respect to properties. Although fine-grained sand enhances mold strength, the fine grains also lower mold permeability. Good permeability of molds and cores allows gases and steam evolved during the casting to escape easily. The mold should have good collapsibility to allow for the casting to shrink while cooling and, thus, to avoid defects in the casting, such as hot tearing and cracking.

- Parting line

Parting line ^[3] is the line or plane separating the upper and the lower halves of molds. In general, the parting line should be along a flat plane rather than be contoured. Whenever possible, the parting line should be at the corners or edges of castings rather than on flat surfaces in the middle of the casting. It should be placed as low as possible for less dense metals and located at around mid-height for denser metals.

- Pattern design

The pattern ^[1] is a replica of the object to be cast, used to prepare the cavity into which molten material will be poured during the casting process. Patterns used in sand casting may be made of wood, metal, plastic or other materials. Patterns are made to exacting standards of construction, so that they can last for a reasonable length of time.

The mold is made by packing some readily formed aggregate material, such as molding sand, around the pattern. When the pattern is withdrawn, its imprint provides the mold cavity, which is ultimately filled with metal to become the casting.

During the design process of pattern, some considerations should be taken. For example, the pattern needs to incorporate contraction allowances, which are suitable allowances for shrinkage. And also it needs to incorporate suitable allowances for draft. If the casting is to be hollow, as in the case of pipe fittings, additional patterns, referred to as cores, are used to form these cavities.

- Core design

Cores are forms, usually made of sand, which are placed into a mold cavity to form the interior surfaces of castings. Thus the void space between the core and mold-cavity surface is what eventually becomes the casting. The following picture shows the sand cores.

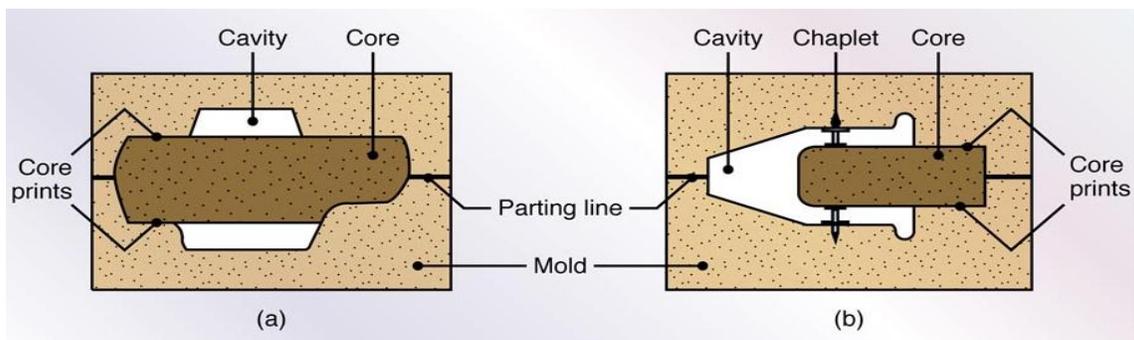


Figure 2.3 Examples of sand casting

- Gating/riser system design and optimization

The preparation of molten metal for casting is referred to simply as melting. Melting is usually done in a specifically designated area of the foundry, and the molten metal is transferred to the pouring area where the molds are filled.

After pouring metal, it will flow through the gating system until the cavity is fully filled. Then the metal begins to cool and solidify with the occurrence of shrinkage. Riser system is designed to compensate such shrinkage. Gating/riser system has great effects

on the final quality of casting. A foundry can produce the best quality molds, cores and molten aluminum and still end up with a poor quality casting by using poorly designed gating and riser systems. So how to design a satisfied gating/riser system is very important.

2.3 Quality Problems in Sand Casting Process

During the metal casting process, various defects can develop. They are illustrated in figure 2.2 [6]. It is important to improve the casting quality by eliminating or minimizing the effects caused by those defects.

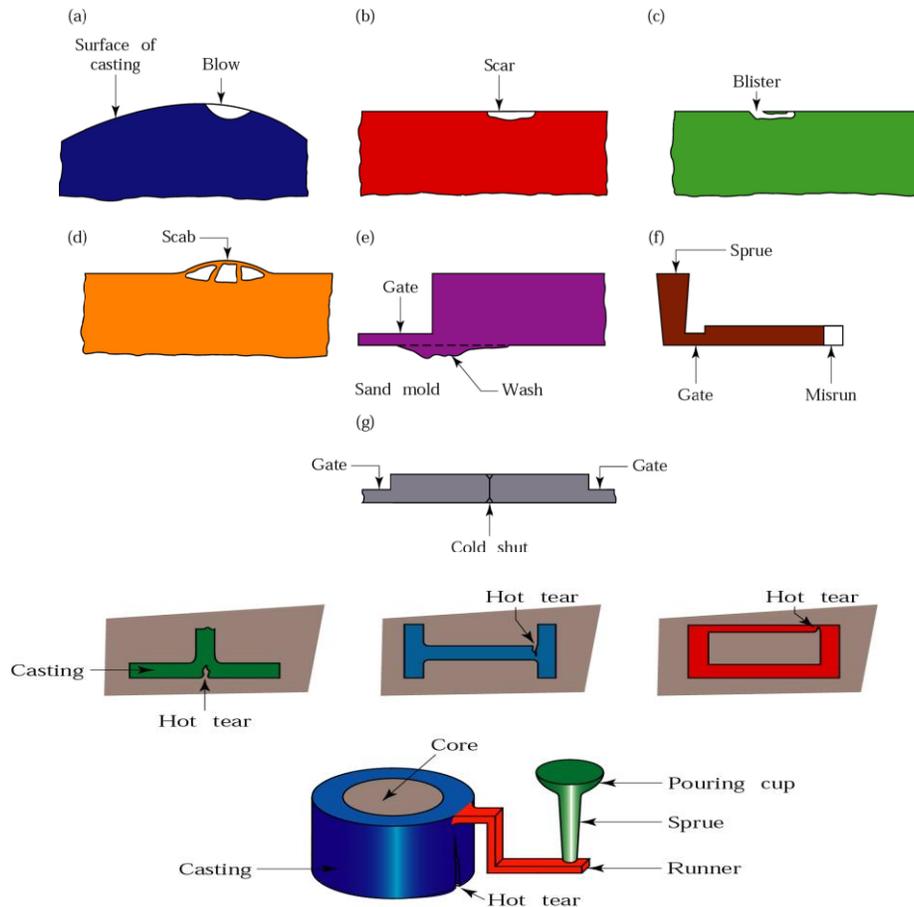


Figure 2.4 Some defects in sand casting

Two common defects in sand casting process are caused by porosity and incomplete filling.

Porosity may be the most persistent phenomena in casting, and it is hard to be eliminated completely. Porosity is harmful to the ductility of the casting and its surface finish. Porosity in castings is due to bubbles being trapped during solidification. It may be caused by shrinkage, or gases, or both. There are many factors contribute to the development of porosity such as the entrapped air during filling, blowholes from unvented cores, dissolved gases from melting, etc. Because liquid metals have much greater solubility for gases than do solid metals, when a metal begins to solidify, the dissolved gases are expelled from the solution. It will cause microporosity or accumulate in regions of existing porosity.

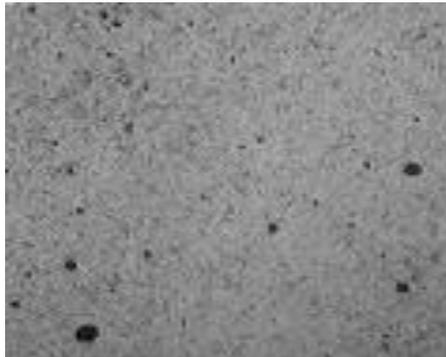


Figure 2.5 Example of porosity

Incomplete filling ^[2] is primarily caused by poor fluidity of molten metal, and manifests in the form of a cold shut or misrun. A cold shut occurs when two streams of molten metal coming from opposite directions meet, but don't fuse completely. A misrun occurs when the molten metal does not completely fill a section of the mould cavity. The presence of surface oxides and impurities on the advancing front of liquid metal aggravates such defects.

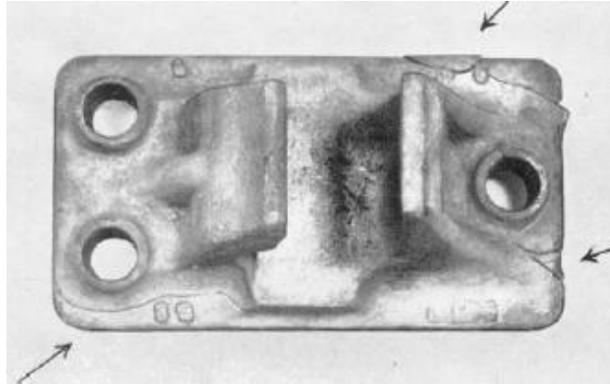


Figure 2.6 Cold-shut defect



Figure 2.7 Misrun defect

The casting quality is heavily dependent on the success of gating/riser system design. Next the gating/riser system will be introduced in detail.

2.4 Gating/Riser System

A key element in producing quality aluminum castings is the proper design and sizing of the gating and riser systems ^[10]. A foundry can produce the best quality molds, cores and molten aluminum and still end up with a poor quality casting by using poorly designed gating and riser systems. A typical gating/riser system is shown below.

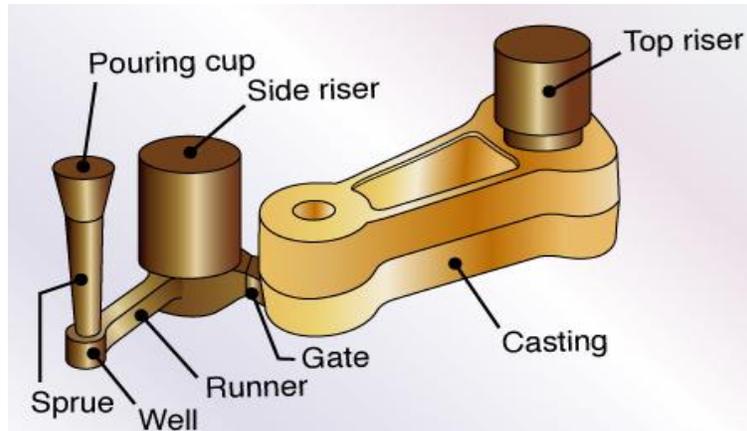


Figure 2.8 Typical gating/riser system

2.4.1 Gating System

The main objective ^[2] of a gating system is to lead clean molten metal poured from ladle to the casting cavity, ensuring smooth, uniform and complete filling. Clean metal implies preventing the entry of slag and inclusions into the mould cavity, and minimizing surface turbulence. Smooth filling implies minimizing bulk turbulence. Uniform filling implies that all portions of the casting fill in a controlled manner, usually at the same time. Complete filling implies leading molten metal to thin and end sections with minimum resistance.

2.4.1.1 Fluidity of Molten Aluminum

Fluidity is the reciprocal of viscosity which measures the resistance of a fluid being deformed by either shear stress or extensional stress. In general terms, fluidity represents the extent of the molten aluminum to completely flow and fill the mold cavity. The factors that have great influence on the fluidity include:

(1) Temperature: If the casting has thinner cross sections and if the pouring temperature is low, misruns can be easily developed. So casting temperatures should be just high enough to prevent flow misruns.

(2) Chemistry: Of the chemical elements added to aluminum alloys, silicon has the greatest affect on fluid life. The higher the silicon level, the greater the fluid life. While the chemistry of the alloy used also affects its solidification range. Pure metals, eutectic alloys and narrow freezing range alloys tend to exhibit the best fluid life.

(3) Entrained gas and inclusions: It is easy to understand that both entrained gas and inclusions tend to increase the viscosity of molten metal, so accordingly its fluidity will be decreased.

2.4.1.2 Requirements of Gating System

There are many factors affecting the design of an ideal gating system. For example, the gating system should be designed to allow the molten metal flow through with the least amount of turbulence. It is a better design of the gating system that it can be removed easily from the casting after filling. The gating system should be designed in such a way to promote the directional solidification. After meeting other requirements of gating system, it will also need lower yield.

2.4.1.3 Runner

Runner is typically located in the drag of the casting. Because molten aluminum often changes its direction during the flow process in the runner, turbulence often accumulates. For a good runner design, it must not promote turbulence. There are some

useful experience in real foundry such as always use radiused corners, never sharp corners, etc.

As described earlier, two primary requirements of a gating system are to prevent cold shuts and misruns during mold filling. To meet these requirements, all the gates must be feeding at the same time. This can be accomplished by stepping down the runner as each gate is passed. In real foundry environment, engineers prefer to taper the runner without stepping down to decrease the turbulence.

2.4.1.4 Gates

Gates are the inlets into the mold cavity. The gates can be no thicker than the casting section to which they are attached. Even more it usually is best to have the gates slightly thinner than the casting section. If the gating system is not completely filled during the entire pour, it will not function correctly, and defective castings can result.

2.4.2 Riser

A riser ^[1] or a feeder is a reservoir built into a metal casting mold to prevent cavities due to shrinkage. Because metals are less dense as liquids than as solids (with some exceptions), castings shrink as they cool. This can leave a void, generally at the last point to solidify. Risers prevent this by providing molten metal at the point of likely shrinkage, so that the cavity forms in the riser, not the casting.

2.4.2.1 Solidification

After molten metal is poured into a mold, solidification will take place. In the casting process, solidification plays a critical role because the speed at which

solidification occurs largely determines the mechanical properties of the casting. The faster the solidification rate, the finer the solidified structure and the higher the mechanical properties.

Solidification normally begins on the surface of the casting and moves inward toward the center of the casting or toward the source of feed metal. So solidification can take place in two directions in the casting. One is called progressive solidification occurring from the sidewalls of the casting toward the center. The other called directional solidification occurs toward the source of feed metal.

If progressive solidification moves faster than directional solidification, shrinkage voids will occur in the casting. Following figure illustrates this kind of shrinkage.

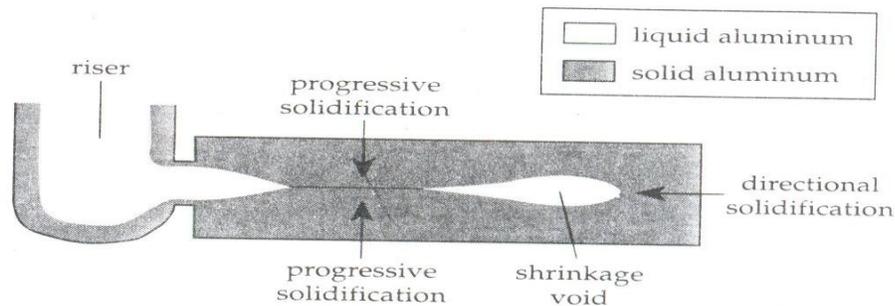


Figure 2.9 Progressive solidification can cause a shrinkage

2.4.2.2 Shrinkage

Like nearly all materials, metals are less dense as a liquid than a solid. So castings shrink will always occur when they cool. There can be three different kinds of shrinkage taking place in the casting: liquid shrinkage, solidification shrinkage and solid shrinkage.

Liquid shrinkage takes place when the molten metal cools. Solidification shrinkage occurs from the time the first solid metal appears until the casting is completely solid. Risers can be used to compensate these two types of shrinkage. Solid shrinkage is often called “patternmaker’s shrink” because a patternmaker can make a slightly larger pattern than the finished casting dimensions to compensate for the solid shrinkage. The casting cools to ambient temperature after it is completely solidified. During this time, solid shrinkage takes place.

2.4.2.3 *Riser Design*

Risers are used to compensate for liquid shrinkage and solidification shrinkage. But it only works if the riser cools after the rest of the casting. Chvorinov's rule states that the solidification time t of molten metal is related to the constant C (which depends on the thermal properties of the mold and the material) and the local volume (V) and surface area (A) of the material, according to the relationship

$$t = C \times \left(\frac{V}{A}\right)^2 .$$

Therefore, to ensure that the casting solidifies before the riser, the ratio of the volume to the surface area of the riser should be greater than that of the casting. The riser must satisfy two requirements: it must be large enough so that it solidifies after the casting (i.e. satisfies Chvorinov's rule) and it must contain a sufficient volume of metal to supply the shrinkage contraction which occurs on cooling from the casting temperature to the completion of solidification.

Hence the casting should be designed to produce directional solidification which sweeps from the extremities of the mold cavity toward the riser. In this way, the riser can

feed molten metal continuously and will compensate for the solidification shrinkage of the entire mold cavity. If this type of solidification is not possible, multiple risers may be necessary with various sections of the casting solidifying toward their respective risers.

(1) Riser shape

Because it is required that the ratio of the volume to the surface area of the riser should be greater than that of the casting, the riser's geometric shape should be adjusted to have a larger ratio. For a given volume of molten aluminum, the shape selected should have the least possible amount of surface area.

(2) Riser size

Currently riser size can be calculated with the aid of modulus. As described in chapter 3, modulus equals to the ratio between its volume and its surface area. The modulus method compares the modulus of the riser and that of the casting or section to be fed. Most literatures say the modulus of the riser should be 20% larger than that of section being fed. This method can also be used to determine the size of riser neck. It is commonly agreed that the modulus of the riser neck should be 10% larger than that of the section being fed.

(3) Feeding distance

The distance a riser can deliver feed metal into the casting section to which it is attached is called its feeding distance. If the feeding distance of one riser exceeds its limit, it will become ineffective and shrinkage may be produced.

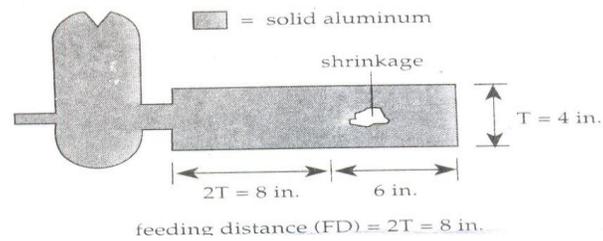


Figure 2.10 Too large feeding distance can cause shrinkage

Feeding distance of risers is determined by the alloy being poured and by the thickness of the section being fed. For aluminum castings, the following formula can be used to approximate the theoretical feeding distance of a hot riser:

$$FD = 2T$$

In the above equation, FD is the feeding distance and T is the thickness of the section being fed.

Because gating/riser system is important in guaranteeing the casting quality, there is a need to optimize the gating/riser system.

2.5 Current Gating/Riser Design and Optimization

Methods

Researchers and foundry engineers have taken many investigations on the correlation between gating/riser parameters with casting quality ^{[22] [23]}. Although there were some general guidelines for gating/riser system design, the variations in casting parameters chosen by different researchers have led to significant difference in empirical guidelines ^{[24] [25]}.

Traditionally gating/riser system design was performed by engineers' own experience. It is high cost to do trial and error practice to find the optimal gating/riser

system design. The first application of numerical optimization methodology to optimize a gating system was conducted ^[27]. Later the computer modeling enabled visualization of mold filling and casting solidification which made the gating/riser system design and optimization cost-effectively. Numerical simulators based on FDM and FEM methods provide powerful means of analyzing various phenomena occurring during the casting process ^[28].

In the casting process, there are lots of factors contribute to the final result of casting quality. It is unrealistic to find and use all factors, so most cases some factors may be selected to conduct investigation. The gating/riser system can be optimized by comparing the simulation results output from casting simulation software. In previous study the simulation technology was used to design and optimize gating system ^[30]. And Taguchi method with multiple performance characteristics was also used to optimize the gating system parameters ^[26]. In this research, the author selected four independent gating parameters of ingate height, ingate width, runner height and runner width. By analyzing the simulation results from MAGASOFT, the optimal gating system could be produced.

2.6 Castability Analysis

Castability analysis can help engineers evaluate if one part is suitable for casting. It will decrease cost if sound castability analysis can be done before real casting process.

2.6.1 Importance of Castability Analysis

Castability analysis is an important step in sand casting process. It may include two tasks. Given a cast part, the first task is to evaluate if the part can be produced with casting method. The second task focuses on analyzing the structural layout of the cast

part, such as the better position of the gating, the optimized number and position of risers, etc.

Only after castability analysis, it can be rightly determined if a part is suitable for casting. If not, some suggestions should be given to design engineers and it is helpful for them to make modifications. And the more important thing is it can help engineers get the right positions to integrate gating and risers, which has great effects on the final casting quality.

2.6.2 Current Castability Analysis Methods

Before castability analysis was totally based on technicians' experience. Now CAD and simulation technology become more mature, more efforts have been paid to computer aided castability analysis. Professor B. Ravi from Indian Institute of Technology has done a lot related work. According to his description, there are three major approaches for castability analysis: process simulation, parametric cost estimation and features-based castability checks.

Casting simulation relies on computer aided technologies to simulate all aspects of casting process such as mould filling, solidification, grain structures, etc. If solid models of product and material properties of part and mould can be given, theoretically it can simulate all phases of casting process. Based on the simulation result, it can predict casting defects such as shrinkage porosity, hard spots and cracks. But for this method, it has some drawbacks such as it requires considerable expertise which it may not be easily available to product designers.

If the casting cost exceeds the limit of financial plan, the casting process can't meet the requirement either. So casting cost estimation is also important. Different kinds

of parameters relate to the casting cost such as material property, the complexity of the part, quality specifications, type of parting lines, the number and the shape of risers, etc. The coefficients must be continuously updated to adjust for the current rates of material, labour and energy.

Castability guidelines are very useful for design engineers to finish initial design. These guidelines can be found in technical literature and also in companies' technical documents. There are some examples^[2] illustrated in the following figure.

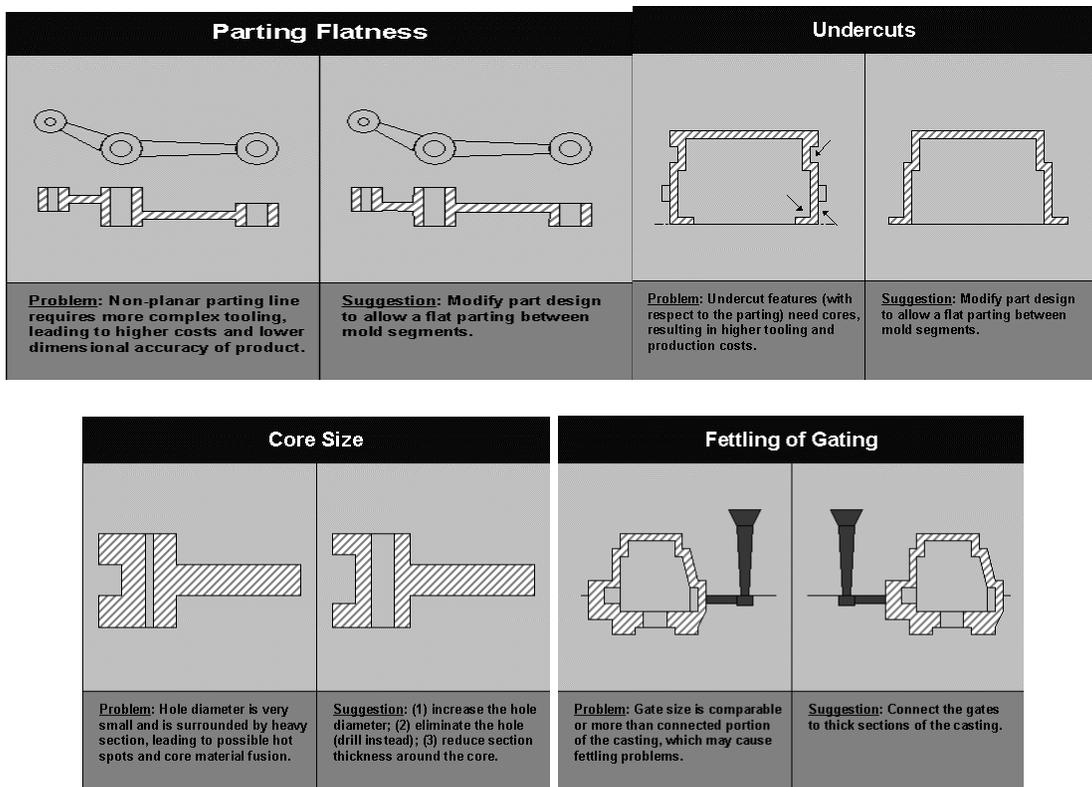


Figure 2.11 Several castability guidelines examples

2.7 Problems Remained In Castability Analysis And Gating/Riser Design And Optimization

Although CAD and simulation technology makes sand casting process design more efficient, there are some remained problems needs more consideration.

Currently castability analysis is mostly based on the experts' experiences. But it is difficult to convert these experiences into computer readable knowledge rule. How to find quantity methods to do castability analysis is important.

As just mentioned, the success of gating/riser system design has great effects on the final quality of casting. How to optimize gating/riser system is important. Currently the gating/riser system design and optimization can be implemented by running simulation software and analyzing simulation results. But given a CAD model and possible parameters to change in the experiment, it is also important to know how to semi-automatically or even automatically get all possible CAD models. Unfortunately this kind of research wasn't found in previous work.

2.8 Thesis Objectives

The objectives of this thesis are:

- 1) To provide the system framework for the computer-aided casting process design tool
- 2) To propose a method for castability analysis. With the aim of locating the possible hot spots, this method calculates and compares modulus of inputted CAD model

3) To change parameters of runner and risers or build templates of gating/riser system. This will provide a semi-automatically way to build all CAD models of runners and risers, which are the input of simulation software.

4) To design a method to optimize gating/riser system based on CAD and simulation technology in order to reduce large porosity, decrease incomplete filling area, and increase yield

Chapter 3 System Framework

This chapter presents the computer aided casting process design framework based on CAD and simulation technology. First the workflow of the framework is addressed. Then some steps in the workflow are explained in detail.

3.1 Workflow of the System Framework

The workflow of the framework is illustrated in Fig 3.1.

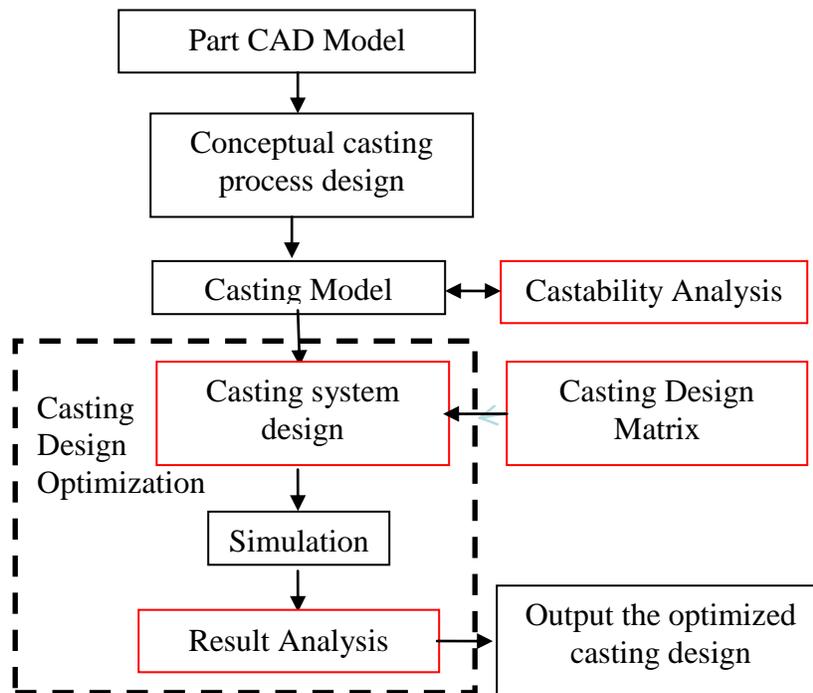


Figure 3.1 Computer aided system workflow

For a given CAD model, the first step of the process will include a complete conceptual casting process design such as locating the parting line, initial design of gating/riser system, casting parameters definition, possible casting defects prediction, etc. In the next step, the part CAD model will be converted to casting model, which is heavily dependent on the result of castability analysis. After completing casting model

parametrically, the casting design matrix can be generated with some selected parameters. Consequentially all casting design models based on the matrix can be generated as input to the simulation software. After analyzing simulation results, it will output the optimized casting system design.

In this chapter, the steps of castability analysis and gating/riser system optimization will be further explained.

3.2 Castability Analysis

It is important to verify the suitability of the given casting CAD model. When it is not suitable, engineers may have interests in getting help from the output suggestions to know the possible reasons.

Castability implies ease of producing a casting, minimizing cost, defects and lead-time. This is facilitated by high compatibility between product requirements and process capabilities ^[2]. There are many factors may affect the castability of one casting product. In the view of product design, three aspects will influence its castability such as material selection, part geometry and quality specifications ^[2].

Part material is usually selected to satisfy the functional requirements of the product, based on mechanical, physical and chemical properties such as tensile strength, melting point and corrosion resistance. Cast metals are characterized by their casting properties such as pouring temperature, fluidity, volumetric shrinkage during solidification and slag/dross formation tendency. These influence the casting quality in terms of dimensional stability and internal integrity.

Part geometry directly affects the complexity and number of tooling elements (pattern and cores) and therefore their cost. The location of the parting line depends on

the extent of undercuts, which in turn depends on internal features in the part. Part geometry also influences progressive directional solidification which governs internal integrity. Long thin sections are difficult to fill. Critical surfaces can be planned in drag section of the mould to ensure a dense and smooth casting sub-surface free from any inclusions. For heavy parts, lifting arrangements can be provided to facilitate handling during machining, assembly and shipping.

Quality specifications include defect-free surfaces, internal soundness (often pressure tightness), dimensional accuracy and the desired surface roughness. Some of the major defects that lead to rejection include macro shrinkage, cracks, blowholes, gas porosity, sand/slag inclusions and cold shuts. Other defects, such as micro-porosity (in non-critical sections), dimensional inaccuracy and rough surface will lead to rejection only if quality specifications are stringent. Problem features such as excess rib thickness, inadequate fillet radius, narrow holes and tight tolerances are quite common in cast components, which result in high percentage of defects and avoidable labor costs for repair work. Specifying a particular quality testing method (such as radiography and pressure testing) should be justified for the desired quality level, which will otherwise increase the manufacturing cost.

3.3 Casting Design Matrix

Most CAD software has embedded functions to support modeling parametrically. For example, the runner with the circle cross section can be modeled with the parameters of the radius of the circle and the length of the runner. And if each parameter takes two possible values, it can produce the 2×2 design matrix. In the thesis, the similar method will be used to get the design matrix of runner and risers.

3.4 Casting System Design

Based on the casting design matrix, all possible casting models as an input to simulation software can be generated with CAD technology. In the thesis, two methods are applied to produce the CAD models semi-automatically. One method is totally dependent on the internal parametrical function provided by UG. If the runner or riser is modeled parametrically, each parameter is expressed as a string name. The CAD models will be changed and updated accordingly with the variation of expression values. The implementation of the other method relies on the knowledge fusion module embedded in UG. It has several advantages over the first method such as help users build more comprehensive rules, let users develop their own user interface, and facilitate users connecting with outer data sources.

3.5 Simulation Results Analysis and Gating/Riser

Optimization

It should be firstly to process simulation results such as extracting useful information, formulating problem definitions, etc.

Gating/riser design can be optimized with the simulation results analysis. In the first step, the optimization objectives should be defined well. Then range analysis method is used to analyze the results and get the optimized gating/riser system.

In this chapter, the system framework is addressed and some of work that will be studied in this thesis is briefly introduced. In the next chapter, the castability analysis will be explained in detail.

Chapter 4 Castability Analysis

This chapter presents a modulus based castability analysis method. First, the castability analysis workflow in this thesis is illustrated. Then, the modulus based castability analysis method is explained in detail.

4.1 Castability Analysis Workflow

In the casting design process, at least two aspects, material selection and part geometry, influence the part castability. Mechanical, physical and chemical properties such as tensile strength, melting point and corrosion resistance, etc. will affect the part's castability. If the part has higher complicated shape and structure, it will make flowing process more difficult and thus have lower casting quality. In this paper, shape complexity will be only discussed, and the flowchart is illustrated in Fig 4.1.

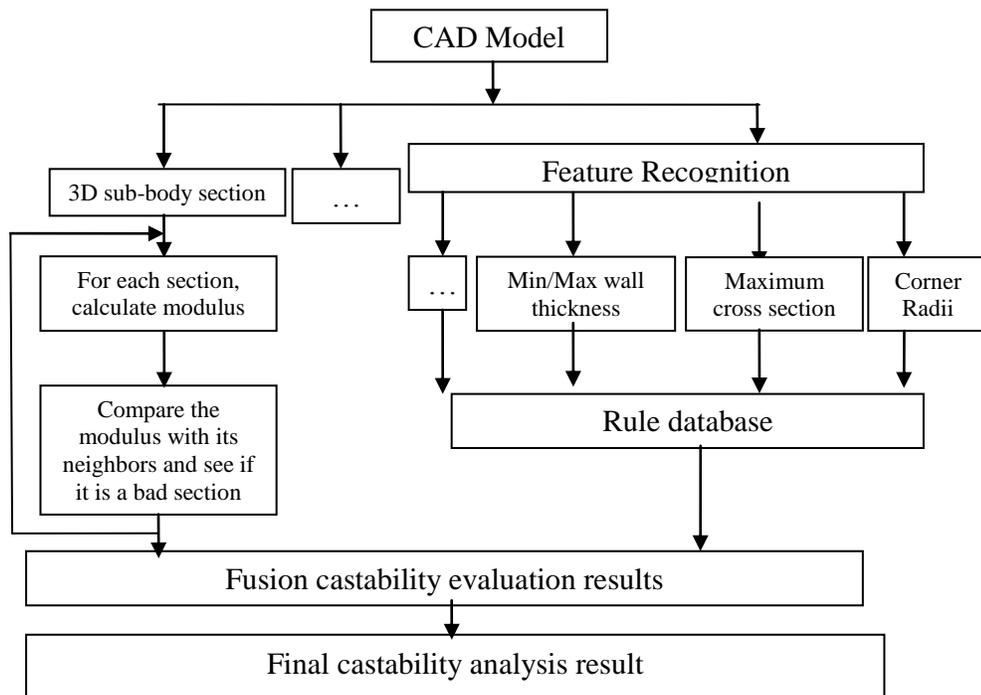


Figure 4.1 Castability analysis flowchart

4.2 Modulus Based Castability Analysis Method

Casting modulus M is defined as the ratio between the casting volume V and the cooling surface area A , that is $M = V/A$. With modulus calculation it becomes possible to predict hot spot occurrence because of the fact that the isolated hot spot is located in regions of high modulus surrounded by regions of lower modulus.

For example, considering a cylinder, its modulus is $M=r*h/2*(r+h)$ if all its surfaces have cooling effects, in which r represents the radius and h represents the height. For simple geometry shape, it is easy to calculate its modulus. But in most cases, due to the casting model's complexity, it is hard to get the exact modulus values. There are some research works focusing on how to calculate modulus in different situations.

In this thesis, relying on the volume calculation function provided by the UG, the modulus is calculated based on its definition. If the given CAD model is like the one in Fig 4.2, the steps to calculate the modulus are listed below:

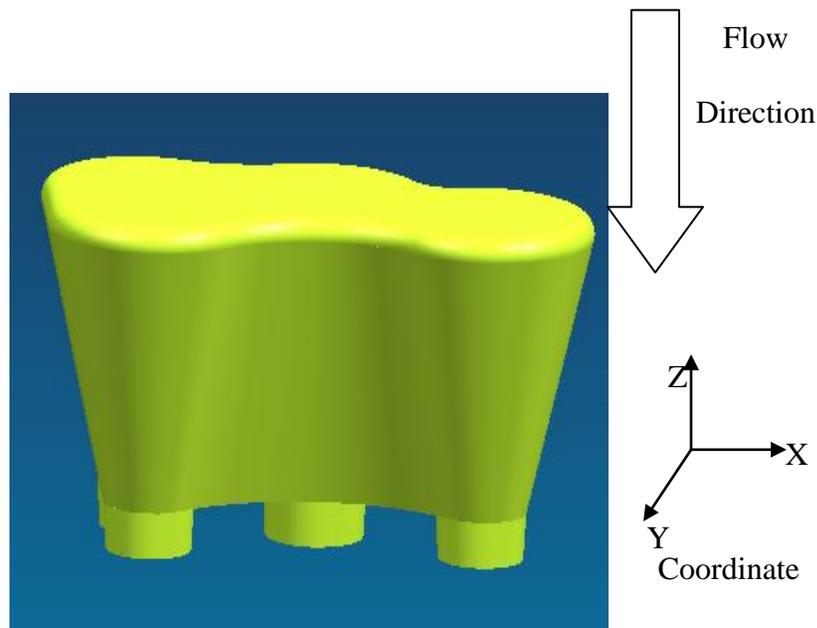


Figure 4.2 CAD model used to illustrate the calculation of modulus

(1) split the body

Given an input CAD model, its bounding box can be obtained, X_{\max} , Y_{\max} and Z_{\max} , and we can split it into S_n sub-bodies, each of them can be represented as M_{si} .

(2) Calculate modulus

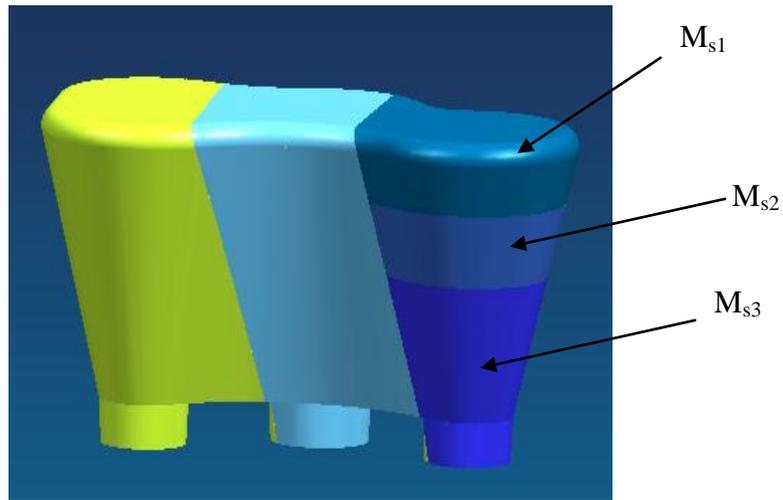


Figure 4.3 Split body

Suppose we only split the body along X and Z direction, the resulted split bodies are shown in Fig 4.3. For each sub-body, according to the definition of modulus, it can be calculated. Take M_{s2} as an example (Fig 4.4):

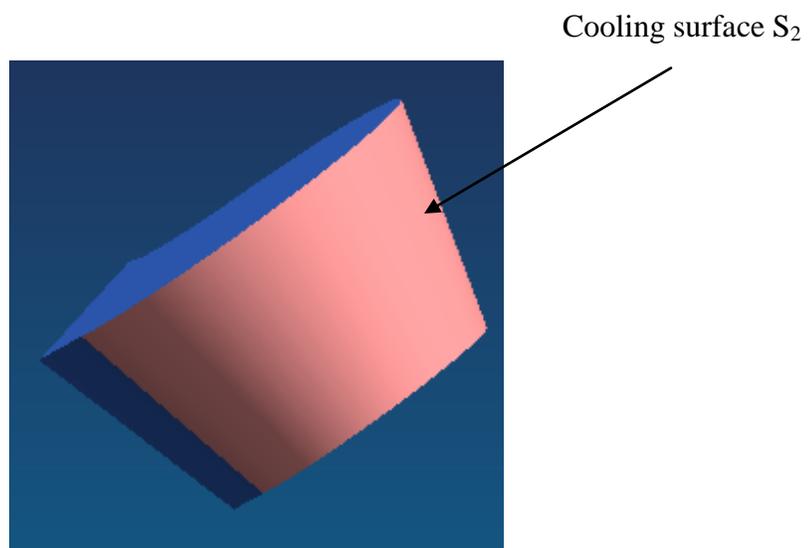


Figure 4.4 Example of calculating modulus

The modulus can be calculated as the ratio between the volume and the cooling surface area. Its Volume, V , can be easily obtained by using the internal function provided by UG. The exterior surface in this example can be treated as cooling surface. So the modulus is:

$$M_2 = V/\text{Area of } S_2$$

(3) Evaluate the castability by using modulus

In the similar way, all sub-bodies' modulus can be obtained with the representation of a map like: $M(i,j,k)$. i is X index, j is Y index and k is Z index. Then compare the current modulus with all its neighbor spots. Its algorithm can be illustrated as below:

```

For (i =0; i<Nmaxx; i++)
{
    For(j =0; j< Nmaxy; j++)
    {
        For( k=0; k<Nmaxz; k++)
        {
            If(M(i,j,k) > M(i,j,k-1))
                Return "it is a bad spot"
        }
    }
}

```

In the end, get the number of bad spots, and calculate the ratio between this number and the total number of sub-bodies. If the ratio exceeds the predefined value, this part can be thought as not suitable for casting.

4.3 Part Feature Recognition

Part geometry influences progressive directional solidification (from thin to thicker to thickest regions). Some special features recognition can help engineers evaluate the part's castability analysis.

(1) Sudden variations in section thickness

Sudden variations in section thickness can cause turbulence during filling process. So it is good to avoid sudden variations. Take the model in Fig 3.3 as an example, along the flow direction, and use m reference planes to create m section planes. Then for each section plane, get its width and compare the width with its previous section plane. If the number of section planes having sudden variations exceeds the predefined value, the part can be evaluated as not suitable for casting.

(2) Sharp corner

Sharp corner has the nearly same problems as sudden variations. For each corner in a given CAD model, it is easy to get its radii from the function in Unigraphics. If the value is smaller than the predefined value, it can be deemed as a sharp corner. And if the total number of sharp corners exceeds the predefined value value, the part can be thought of not good for casting.

(3) Long thin section

If one part has long thin section, it is difficult to fill completely. For a given section plane, calculate the ratio between its length and width. If the ratio is bigger, that section is thought as long thin section. In the end, if the total number of long thin sections exceeds predefined values, the part might be not good for casting.

In this chapter, the castability analysis workflow is introduced, and the modulus based castability analysis method is detailed explained. In the next chapter, the gating/riser system optimization method will be addressed.

Chapter 5 Gating/riser Optimization

This chapter presents gating/riser system optimization process. One engine block is used to illustrate this process. First, the current gating/riser system of the engine block is presented. Then, runner and riser optimization process is explained. Finally, the simulation results are analyzed and that the optimized casting system assembly is determined.

One engine block is used to illustrate the optimization process. Its current gating/riser system is shown in the following figure.

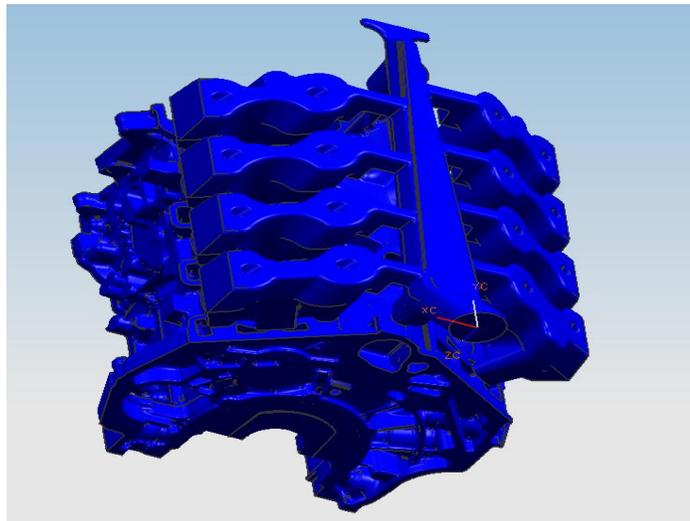


Figure 5.1 Current gating/riser system design

Liquid metal pours by using low pressure pump and passes through runner. Because the velocity at the entry of the runner is very high, the end area of the runner has been increased to reduce the velocity. Filling is not uniform because the gates that connect the risers and runner are straight. There are 10 risers on the each side and they interconnected with each other. All risers are feeding the thick sections of casting under gravity.

Conventional gravity pouring of aluminum alloys results in turbulent flow and the formation of oxides in the casting is predominant. To overcome this problem, counter gravity filling of the liquid aluminum from the bottom of the mould has become the preferred method of casting. But this method has one major disadvantage of slow production rates. So currently the method was used of disconnecting the mould from the filling system and rotating the mould while the casting was still liquid. Once the mould and casting are rotated through 180° the risers which supply liquid metal during the solidification phase of the cast process are on top of the casting and gravity feed the required liquid metal into the contracting casting.

There are three major problems in the current casting system.

- (1) Filling incompletely of runner;
- (2) Riser can't feed effectively with the result of some large porosity;
- (3) Lower yield. Yield equals to the ratio between the weight of casting and sum of casting weight and the gating/riser weight.

So there exists the need to optimize the current gating/riser system to solve the above problems.

5.1 Optimization Objectives and Initial Conditions

Based on the problems of the current gating/riser system, the main optimization objectives include:

- (1) To fill completely in the runner;
- (2) To produce less porosity;
- (3) To have high yield.

In the optimization process, the gating/riser system layout will be similar as the current one. But their geometric shape and size will be optimized and changed. Other initial conditions will be the same as those currently used, which include:

- (1) pump: the cross section shape of the pump is circle and its area at the beginning is 1963mm^2 ;
- (2) flow rate: $920\text{cm}^3/\text{sec}$;
- (3) Material: aluminum alloy
- (4) Melting temperature: 720°C
- (5) Liner material: cast iron
- (6) Chill material: steel

5.2 Flow Chart of Optimization Process

For this specific engine block, its gating system only includes runner. So the optimization process consists of two major tasks. One is the optimization of the runner, and the other one is the optimization of riser. Both optimizations have similar steps. In the first step, the cross section shape is defined. Then the parameters representing runner or riser are listed and used for building design matrix. By varying each parameter, all CAD models are produced semi-automatically. After getting simulation results, the optimized gating/riser system and the whole casting system assembly are output.

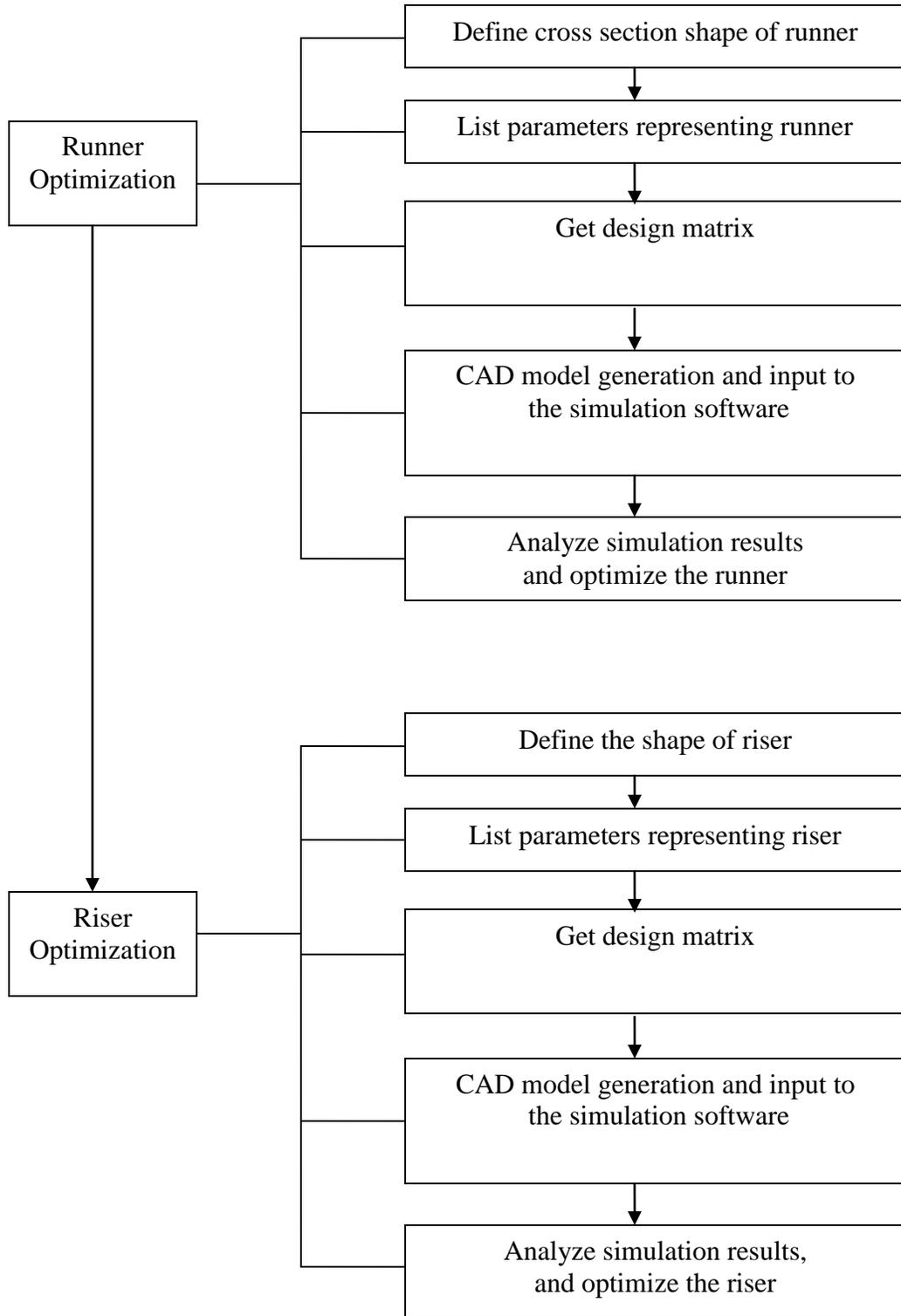


Figure 5.2 Flow chart of optimization process

5.2.1 Runner Optimization

As a key element in the gating system, the objectives of runner optimization should include many goals. In this thesis, only filling surface area and maximum filling velocity will be considered.

5.2.1.1 Parameters Representing Runner

Currently the runner used has a rectangle cross section shape. In this thesis this kind of cross section is used. The length of runner is fixed as equal to the length of the casting model. It is around 400mm. The CAD model of the runner is shown in the following figure.

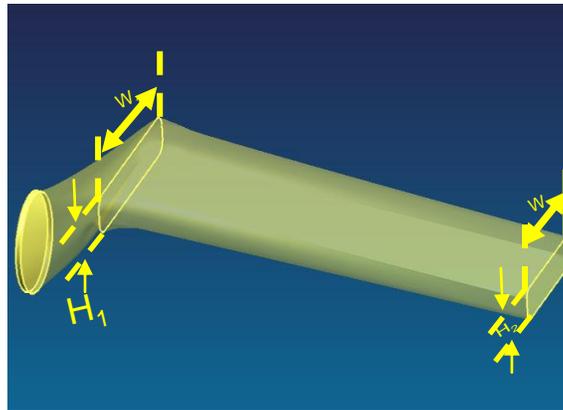


Figure 5.3 Runner and its parameters

Four parameters are used to represent the runner. W_1 is the width of the runner front, H_1 is the height of runner front, W_2 is the width of runner end, and H_2 is the height of runner end.

5.2.1.2 CAD Model Generation

In this thesis, two ways are introduced to build CAD models. For the first method, UG provides a way to vary the value of each parameter.

1. Method 1: change parameter value directly

For example, the runner can be presented with 14 parameters illustrated in the following figure, and each parameter's value can be varied.

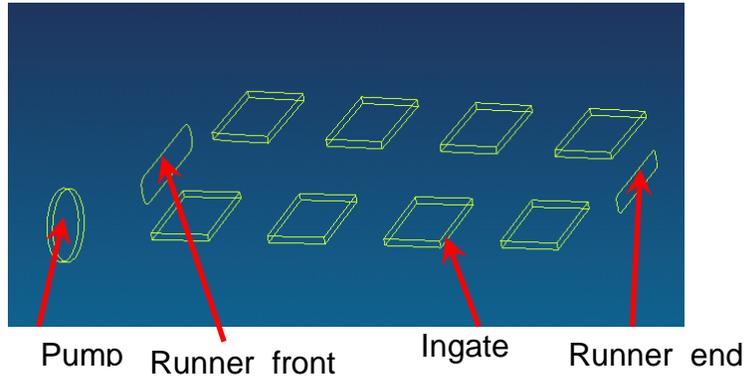


Figure 5.4 Runner presented parametrically

For the pump, its diameter can be changed. And for the runner front, there are five dimensions can be changed, which includes the width, height, fillet radius, horizontal distance between pump and runner, vertical distance between pump and runner front. For the runner end, four parameters can be changed such as the width, height, fillet radius, and horizontal distance between the front runner and the end runner. For the ingate, four parameters can be changed, for example the width, height, location and angle between the ingate and the side face of runner. The following figure shows the size of runner front height changes from 16mm to 20mm.

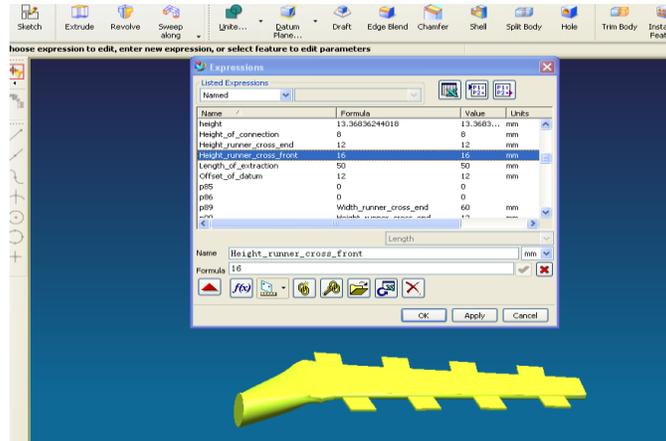


Figure 5.5 Runner parameterized presentation

Another method of CAD template can be used to build CAD models.

2. Method 2: knowledge fusion based CAD model generation

Knowledge-based engineering (KBE) ^[1] is a discipline with roots in CAD and knowledge-based system. Success of early KBE prototypes led to KBE being considered as the basis for generative design with many expectations for hands-off performance where there would be limited human involvement in the design process.

KBE ^[11] allows capturing and structuring of a design and its design process. KBE allows the designer to automate the routine work, which gives the designer more time for creative work. A typical KBE system is illustrated in the following figure.

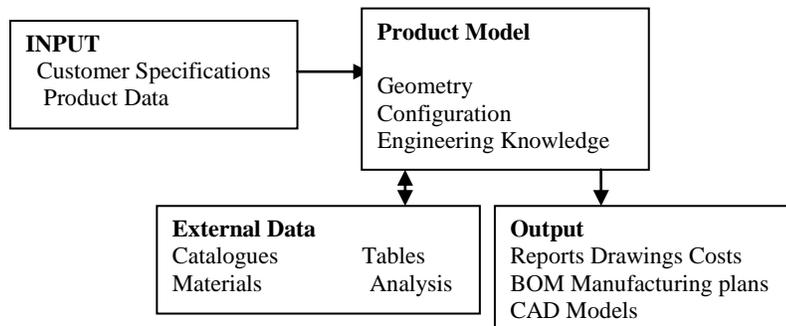


Figure 5.6 The KBE system

Input includes any kinds of product data or customer specification. Based on the input, product model can be developed where the knowledge from the process and the product is stored. Product model can update itself with interaction with external data. Output can vary from drawing, costs and/or reports.

- Introduction of Knowledge Fusion ^[11]

The rule engine in KBE is called Knowledge Fusion (KF) and the underlying technology for a whole set of so-called “process wizards”. By activating these, the built-in knowledge gets available; it can be own specified processes or processes that are based on methods from experienced users. The template guides the user through the process and links complex operations into automatic sequences. The idea is that you don’t have to be an expert to be able to use the program.

In addition to the language itself, Knowledge Fusion provides an easy-to-use visual interface for capturing and handling engineering knowledge. Benefits include greatly reduced design cycle time, easy-to-understand models, and analysis standardization. Knowledge Fusion makes multidisciplinary optimization and probabilistic evaluations feasible which results in much more innovative and advanced designs. Capabilities such as these can have a profound impact on the competitive nature of a business. With reduced design time, you get automatically a financial benefit.

For example, there is a part illustrated in the following figure.

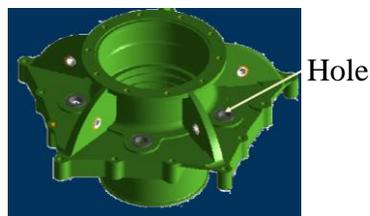


Figure 5.7 Part used for knowledge fusion

If expressions of hole are presented without KF but with driven parameters, it may look like below:

Diameter of hole = thickness of plate * 0.5;

Diameter of hole = if thickness of plate > 0.5

5, else 8

....

For this method, it can only be used in simple conditionals.

If presentation of hole is supported with KF, its supporting engine rules may like below:

Diameter of hole = ODBC Query (Access Database);

Diameter of hole = if material = steel,

5, else 10

Diameter of hole = if thickness of plate > 5

circle, else square

This method is driven topologically not parametrically. So it is easier to change material, access to database, changed round hole to square, etc.

- Implementation of gating/riser templates using KF

In casting assembly, if gating/riser can be represented as templates, it will become easier for user to vary parameters and get different CAD models. In this paper, KF technology will be used to build gating/riser templates. The process of building runner template is illustrated below.

- (1) Use UI-styler in UG to create the toolbar of main menu

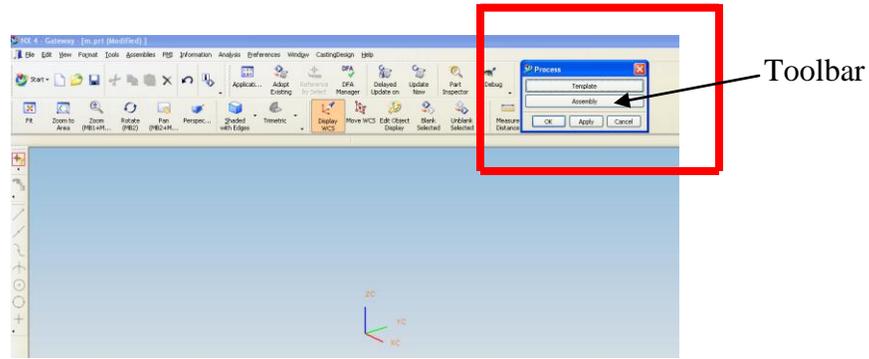


Figure 5.8 Toolbar

There are two buttons in this toolbar, one is template to create templates of gating/riser system, and the other is assembly to assemble gating/riser system with casting model. In this paper, template is only be considered.

(2) Press button of “Template”

If the button of “Template” is pressed, the following steps are illustrated in the following figure.

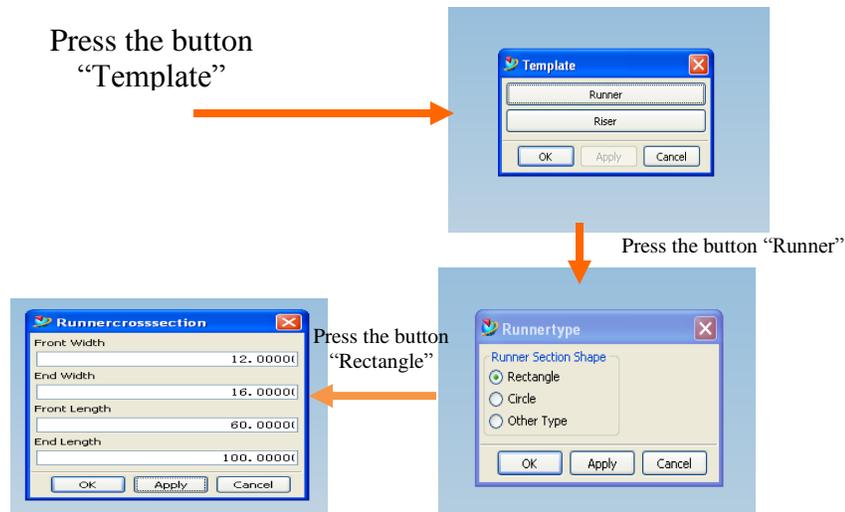


Figure 5.9 The steps to produce templates

If the “OK” button is pressed, the KF functions will be called and the corresponding runner will be created. The CAD model is shown in Fig 5.10.

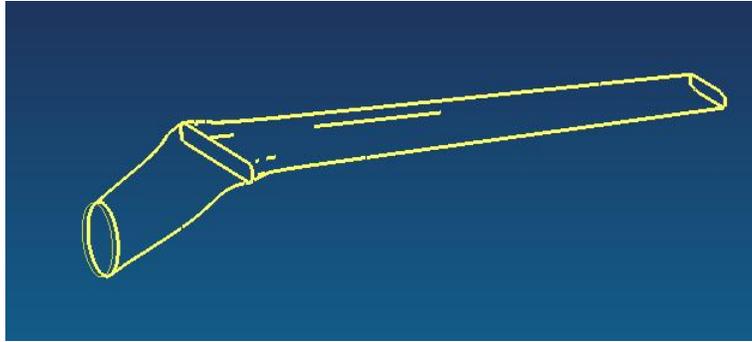


Figure 5.10 Runner created by using KF

The KF file to create this runner is enclosed in appendix.

5.2.1.3 Optimization Procedure

In this thesis, the orthogonal array testing strategy, one of Taguchi methods, is used as the main method to get the optimized parameter combinations representing runner and riser.

Orthogonal arrays, also often referred to Taguchi methods, have been a mainstay in experimental design in manufacturing fields for decades. Orthogonal arrays are two dimensional arrays of numbers which possess the interesting quality that by choosing any two columns in the array you receive an even distribution of all the pair-wise combinations of value in the array.

Orthogonal array ^[1] testing is a systematic, statistical way of testing. All orthogonal vectors exhibit orthogonality. Orthogonal vectors exhibit the following properties:

- (1) Each of the vectors conveys information different from any other vector in the sequence, i.e., each vector conveys unique information therefore avoiding redundancy.
- (2) On a linear addition, the signals may be separated easily.
- (3) Each of the vectors is statistically independent from each other.

(4) When linearly added, the resultant is the arithmetic sum of the individual components.

Benefits include:

- (1) Provides uniformly distributed coverage of the test domain.
- (2) Concise test set with fewer test cases is created.
- (3) All pair-wise combinations of test set created.
- (4) Arrives at complex combinations of all the variables.
- (5) Simpler to generate and less error prone than test sets created manually.
- (6) Reduces testing cycle time.
- (7) It does not guarantee the extensive coverage of test domain

The steps to use this technique are listed below ^[12]:

- (1) Decide how many independent variables will be tested for interaction.

This is also called factors of the array.

(2) Find the maximum number of values that each independent variable will take on. This is also called the levels of the array.

- (3) Get a suitable orthogonal array with smallest number of runs.
- (4) Map the factors and values onto the array
- (5) Choose values for any levels;

1. Use orthogonal array testing for the runner optimization

Four parameters are used to represent the runner. For each parameter, three different levels will be selected.

Table 5-1 Factors and levels used in runner optimization

Level Factor	Level1	Level2	Level3
H ₁	16	20	24
H ₂	12	14	16
W ₁	100	120	140
W ₂	60	80	100

So in this paper, the L₉ (3⁴) orthogonal matrix table will be used. It is illustrated in table 5-2.

Table 5-2 Orthogonal matrix of runner

Factors Experiments	Runner Factors			
	H ₂ (mm)	H ₁ (mm)	W ₂ (mm)	W ₁ (mm)
Run1	12	16	60	100
Run2	12	20	80	120
Run3	12	24	100	140
Run4	14	16	80	140
Run5	14	20	100	100
Run6	16	16	100	120
Run7	16	20	60	140
Run8	16	16	100	120
Run9	16	24	80	100

For each run, create the CAD model with the aid of Unigraphics' parameterized method or by template. For instance the following two figs show the two runs of run1

with $H1 = 20\text{mm}$, $H2 = 12\text{mm}$, $W1 = 120\text{mm}$ and $W2 = 80\text{mm}$, and run3 with $H1 = 24\text{mm}$, $H2 = 12\text{mm}$, $W1 = 140\text{mm}$ and $W2 = 100\text{mm}$

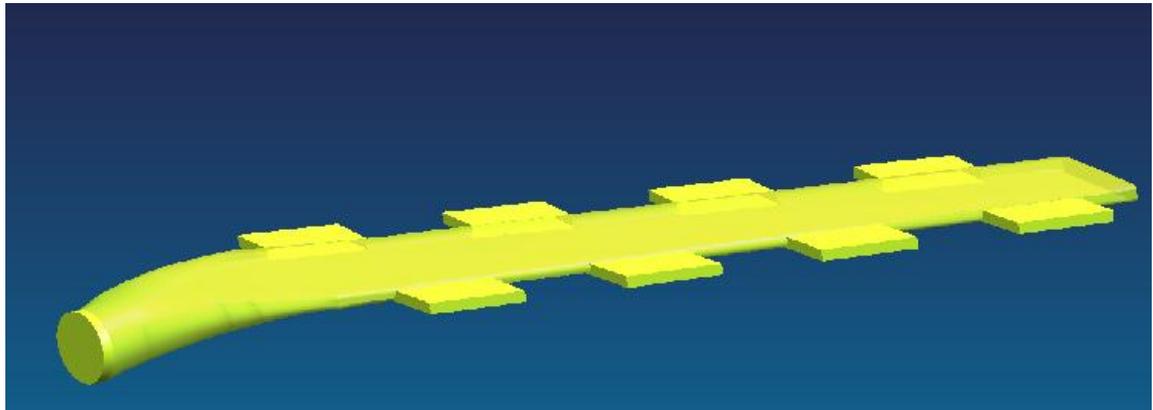


Figure 5.11 Runner1 with parameters - 1

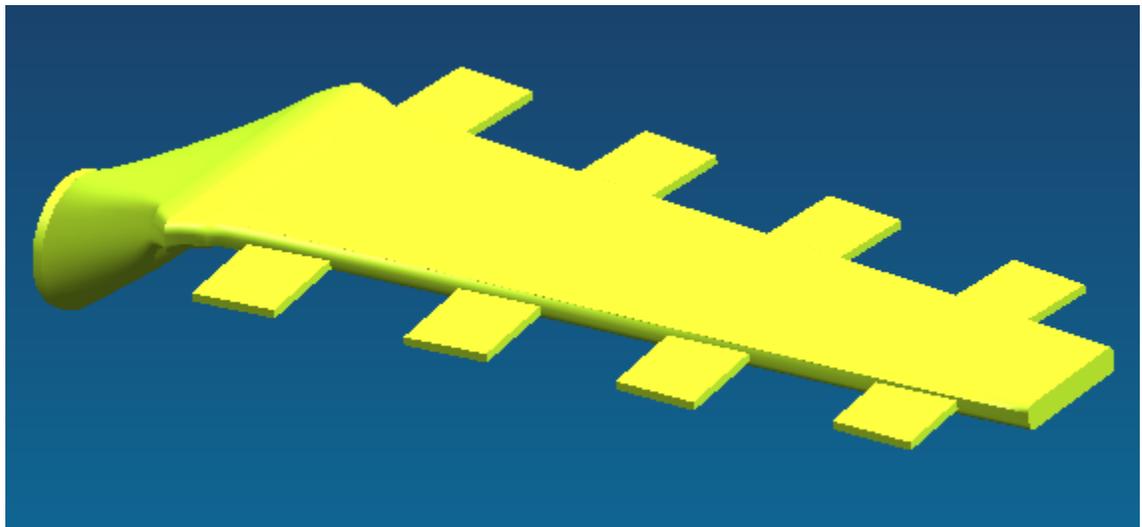


Figure 5.12 Runner3 with parameters - 2

After getting all these CAD models, input these models to the simulation software.

2. Introduction to the simulation software-WRAFTS ^[13]

WRAFTS (Weighted Residual Analysis of Flow Transients) is a computer simulation program which models transient fluid flow. The finite element method is used for compatibility with structural design analysis. WRAFTS has a good reputation for accurate and efficient simulations of mold filling transients. Using WRAFTS, foundry

process engineers can evaluate a wide variety of process parameters, ranging from gating design to inlet flow rates, sand permeability and vent locations. These can be varied to optimize productivity, improve product quality and reduce scrap.

Currently this software was used to simulate the casting process, so in this thesis, this software will be also used for the simulation.

3. Simulation results

For the runner optimization, how it can be filled completely is the first priority. At the same time, filling speed is another element should be considered. For each kind of metal, there exists critical velocity, for example the critical velocity for aluminum is 0.5m/s. It is the maximum velocity the metal liquid fills without creating defects. If the liquid exceeds the critical velocity there is a danger that the surface of the liquid metal may be folded over by surface turbulence. So there is the danger of surface entrainment leading to the defect creation when the filling velocity is above the critical velocity.

In this thesis, two simulation results, filling velocity and free filling surface area, for the runner optimization will be used. The filling velocity simulation result is illustrated in figure 5.13, and the free surface area simulation results are shown in figure5.14.

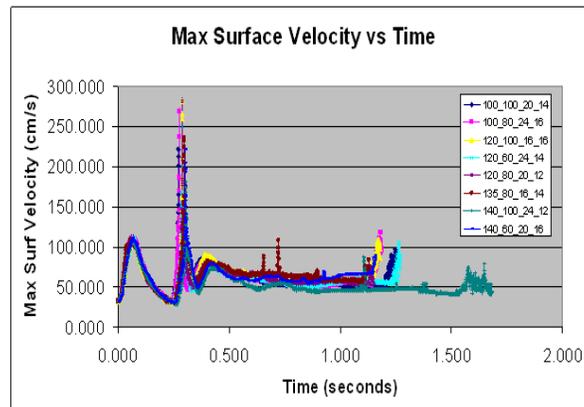


Figure 5.13 Runner filling velocity simulation result

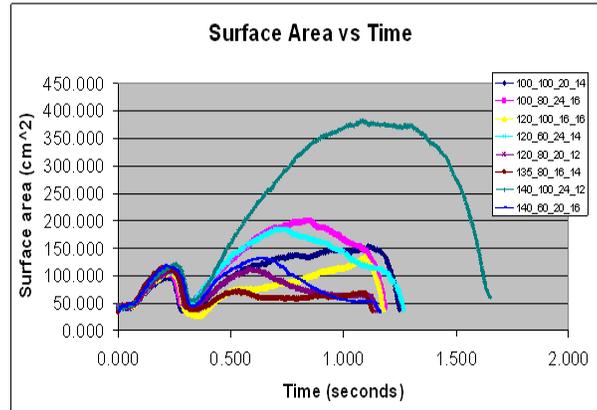


Figure 5.14 Runner free surface simulation result

4. Analyze simulation results

In this thesis, range analysis method will be used to analyze simulation results and optimize runner.

Optimization objects should be firstly defined. For runner optimization, free surface area and maximum velocity are two primary optimization goals. Accordingly its optimization goal function can be defined as follows:

$$Y_i = a_{i1}(w_{i1}) * y_{i1} + a_{i2}(w_{i2}) * y_{i2}$$

In which: i - the index of experiments;

y_{i1} - free surface area of runner while filling;

y_{i2} - maximum velocity of runner while filling;

w_{i1} - weight of free surface area;

w_{i2} - weight of maximum velocity.

Because minimizing free surface area is more important than controlling the maximum velocity for runner optimization, here w_{i1} will be set to 60 while w_{i2} is 40.

During the simulation process, WRAFTS can output time serial data of representing the change of free surface area and maximum velocity. For example table 5-3 illustrates one portion of the time serial data obtained from WRAFTS.

Table 5-3 Example of time serial data obtained from simulation

	time	surface area (cm ²)	Surface velocity (cm/s)
1	0.000	37.760	32.564
2	0.001	37.760	32.564
3	0.001	38.290	32.637
4	0.002	44.120	32.840
5	0.002	46.300	33.123
6	0.003	42.640	33.344
7	0.004	40.200	33.411
8	0.005	39.440	33.413
9	0.006	39.470	33.398
...
n			

Based on the above table, for the i^{th} experiment, y_{i1} equals to the average of free surface area. That means:

$$y_{i1} = \sum_{j=1}^n \text{surfacearea}_{ij} / n$$

For the i^{th} experiment, y_{i2} equals to the ratio between the numbers of elements in table 5-4 whose velocity are greater than a threshold value and the numbers of total elements.

Table 5-4 Simulation results analysis

	W_1	W_2	H_1	H_2	y_{i1}	y_{i2}	y_i
1	100	100	20	14	112	0.94	103
2	100	80	24	16	121	0.89	102
3	120	100	16	16	86	0.92	93
4	120	60	24	14	119	0.91	103
5	120	80	20	12	73	0.92	90
6	135	80	16	14	63	0.92	86
7	140	100	24	12	234	0.4	100
8	100	60	16	12	36	0.91	78
9	140	60	20	16	81	0.89	90
Sum1	285	272	259	268	Optimized combination: $W_1 = 140$ $W_2 = 60$ $H_1 = 16$ $H_2 = 12$ And H_1 has the most effects while W_1 has the least effects		
Sum2	287	279	283	293			
Sum3	277	297	306	287			
Aver1	95	90.7	86.3	89.3			
Aver2	95.7	93	94.3	97.7			
Aver3	92.3	99	102	95.7			
R	3.4	8.3	15.7	8.4			

In the above table:

$$y_i = y_{i1} * 60 / (y_{i1}(\max) - y_{i1}(\min)) + y_{i2} * 40 / (y_{i2}(\max) - y_{i2}(\min));$$

Sum_j equals the sum of y_i when all factors take the jth level;

Aver_j equals the ratio between Sum_j and total number of level;

R equals Aver_j(max) – Aver_j(min).

Because the optimization object of runner is to minimize free surface area and control surface speed, the optimized parameters combination is when W₁ take the third level, W₂, H₁ and H₂ take the first level. From R value, it also can be concluded that H₁ has the most effects on the final result because of its highest R value, while W₁ has the least effect.

5.2.2 Riser Optimization

The just optimized runner will be used for riser optimization. There are two major goals for riser optimization, low porosity and high yield.

The riser shape looks like the following figure.

Suppose angle *A* is set to a const value 3°. And due to the mate constraints between riser and the casting, its bottom circle radius is fixed. So there are four factors, H₁, H₂, H₃ and angle *B*, can be varied and each factor has three different levels.

The modulus of the riser should be more than that of casting sections the riser will feed. Based on this, the initial values of each factor can be obtained. The maximum modulus of the casting model M_c is around 4.0mm, and if the modulus of riser M_r = 1.5*M_c, so M_r = 6mm. Given M_r, the initial values of H₁, H₂, H₃ and *B* can be calculated as 28mm, 22mm, 6mm and 12°. So the orthogonal matrix of riser is shown in table 5-5.

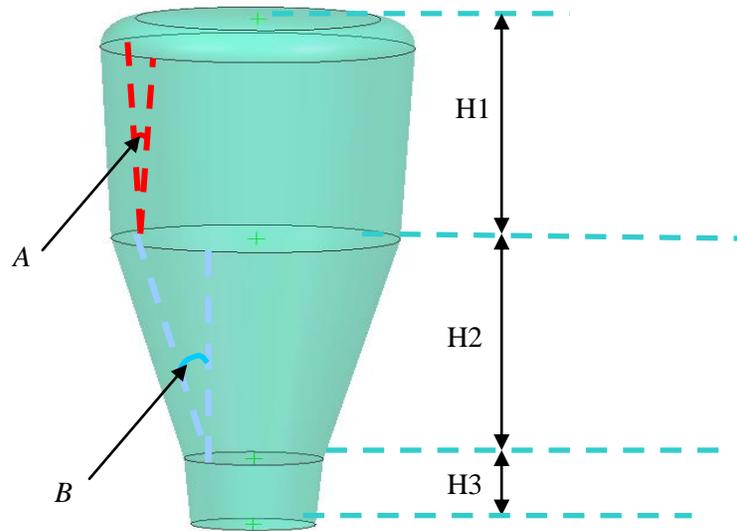


Figure 5.15 Riser shape

Table 5-5 Orthogonal matrix of riser

Factors experiments	Riser Factors			
	H ₁ (mm)	H ₂ (mm)	H ₃ (mm)	B(°)
Run1	30	25	5	15
Run2	35	30	8	15
Run3	40	35	11	15
Run4	30	30	11	20
Run5	35	35	5	20
Run6	40	25	8	20
Run7	30	35	8	25
Run8	35	25	11	25
Run9	40	30	5	25

Input these nine cases to WRAFTS, the simulation results are illustrated in table 5-

6.

Table 5-6 Simulation results of riser

Run #	Porosity volume (cm ^{^3})	Casting Yield (%)
Run1	22.01	0.777
Run2	19.31	0.742
Run3	17.52	0.710
Run4	19.3	0.738
Run5	16.88	0.706
Run6	17.46	0.713
Run7	17.21	0.707
Run8	17.68	0.712
Run9	15.21	0.673
Original	18.52	0.583

Also range analysis method will be used to get the optimized parameters combination of riser. For the riser optimization, it has the same importance between getting the lower porosity volume and improving yield. So the weights of porosity volume and yield are set to 50. The result analysis is shown in table 5-7.

Table 5-7 Simulation result analysis of riser

	H ₁ (mm)	H ₂ (mm)	H ₃ (mm)	B(°)	y _{i1}	y _{i2}	y _i
1	30	25	5	15	22.01	0.777	357.179
2	35	30	8	15	19.31	0.742	328.527
3	40	35	11	15	17.52	0.71	307.320
4	30	30	11	20	19.3	0.738	327.448
5	35	35	5	20	16.88	0.706	301.608
6	40	25	8	20	17.46	0.713	307.633
7	30	35	8	25	17.21	0.707	304.286
8	35	25	11	25	17.68	0.712	308.999
9	40	30	5	25	14.4	0.673	281.033
Sum1	988.914	973.812	939.821	993.026	Optimized combination: H ₁ = 40 H ₂ = 30 H ₃ = 5 B = 25° And B has the most effects while H ₃ has the least effects		
Sum2	939.135	937.008	940.447	936.690			
Sum3	895.987	913.216	943.768	894.319			
Aver1	329.638	324.604	313.273	331.008			
Aver2	313.045	312.336	313.482	312.230			
Aver3	298.662	304.405	314.589	298.106			
R	30.97	20.19	1.31	32.9			

So the optimized parameters combination is 40, 30, 5, 20°, and the porosity volume decreases around 18% while the yield increases around 16%.

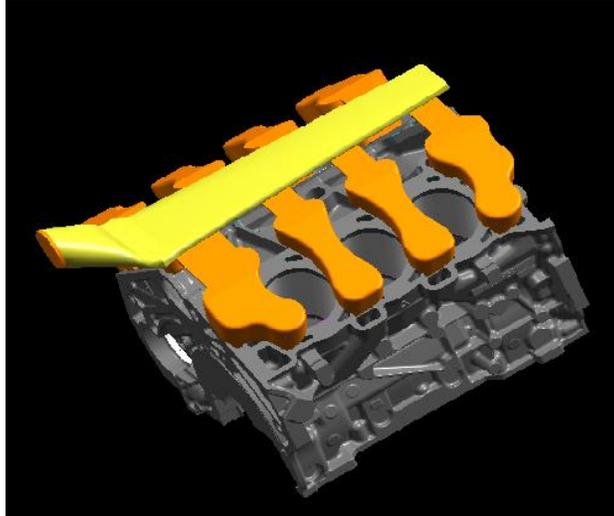


Figure 5.16 Final casting assembly

In this chapter, the optimization flowchart is illustrated. Two ways to produce CAD models semi-automatically are introduced. After analyzing simulation results, the optimized gating/riser system and the whole casting system assembly is produced.

Chapter 6 Summary and Conclusion

First, this chapter will present the summary and conclusion of the thesis. Then the future work of the thesis is discussed.

6.1 Summary

This paper introduces a CAD and simulation technology method to solve some common casting problems such as large porosity, and incomplete filling. It is important to verify the suitability of the given part CAD model to the casting process. In this paper, castability analysis is firstly presented. Then, modulus calculation, one of the most effective ways to evaluate casting cooling rate, is used in castability analysis. Quality must be the first consideration used in determining whether or not the CAD model is suitable for casting. A key element in producing quality aluminum castings is the proper design and sizing of the gating and riser systems. A foundry can produce the best quality molds, cores and molten aluminum and still end up with a poor quality casting by using poorly designed gating and riser systems. In this paper, with the aid of parametric modeling technology in UG, runner and riser are modeled parametrically. By varying each parameter, it is easy to get different casting CAD models. These models output data populate the orthogonal matrix, which is used in the orthogonal array testing strategy to define the most suitable combinations of runners and risers parameters. After inputting the completed orthogonal matrix data and all CAD models into the simulation software, WRAFTS, the simulation result can be obtained. Based on the predefined optimization objectives of runner and riser, the range analysis method is also used to analyze the simulation result and obtain the optimized runner and risers' parameters.

6.2 Conclusion

- To overcome the problems of current gating/riser system, a method based on CAD and simulation technology is implemented.
- Modulus based castability analysis is implemented to locate the possible hot spots.
- Runner and riser models are established parametrically.
- By analyzing simulation results, the optimized gating/riser system is determined.
- By comparing the simulation result of optimized casting model with that of the original model, it can be concluded that the porosity volume decreased by roughly 18% and the yield increased by about 16%.

6.3 Future Work

In this paper, only the system framework is proposed and the optimization method is initially explored. Future work may include.

(1) Castability Analysis

- In this paper, modulus calculation relies on the UG functions. Built-in functions may be explored along with alternative methods to calculate modulus;
- Castability analysis, as it stands now is a comprehensive task that requires extensive casting process experience. Detailed and systematic analysis of the decision making process used in castability analysis may yield a well defined, consistent-rules database that may be incorporated into the software to automate the evaluation of a part CAD model suitability for casting process.

(2) Gating/riser Optimization

- This study used orthogonal matrix and range to optimize the gating and riser design. Other optimization methods may be explored;

- One runner and riser shape currently used was analyzed. Other shapes should be explored..

(3) Gating/riser Templates

- Designing and integrating a gating/riser template database into the software will speed up the analysis and optimization process.

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