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Numerical optimization of gating systems for light metals sand castings

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Numerical Optimization of Gating Systems For Light Metals Sand Castings

By

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ABSTRACT

This thesis proposed an optimization technique for design of gating system parameters of a light metal casting based on the Taguchi method with multiple performance characteristics. Firstly, the casting model with a gating system was designed and exported as International Graphics Exchange Standard (IGES) models by Unigraphic NX4.0®. Based on the IGES models of the casting, Finite Element(FE) Models were generated using Hypermesh® software. Then, mold filling and solidification processes of the castings were simulated with the MAGMASOFT®. Finally, the simulation result can be converted to numerical data according to the 3D coordinates of the FE model by MAGMALink module of MAGMASOFT®. The various designs of gating systems for the casting model were generated and the simulated results indicated that gating system parameters significantly affect the quality of the castings. To obtain the optimal process parameters of the gating system, the Taguchi method including the orthogonal array, the signal to noise(S/N) ratio, and the analysis of variance (ANOVA) were used to analyze the effect of various gating designs on cavity filling and casting quality using a weighting method. The gating system parameters were optimized with evaluating criteria including filling velocity, shrinkage porosity and product yield.

DEDICATION

To my parents, my wife, and my daughter. Their love and support enable me to go through the difficult time and finally complete this thesis.

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LIST OF ABBREVIATIONS

Ag	Cross Sectional Area of Ingate
As	Cross Sectional Area of Sprue
Ar	Cross Sectional Area of Runner
ANOVA	Analysis of Variance
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CFD	Computational Fluid Dynamics
DOE	Design of Experiments
FD	Finite Difference
FE	Finite Element
FEM	Finite Element Meshed
GA	Genetic Algorithm
HTC	Heat Transfer Coefficient
IGES	International Graphics Exchange Standard
MSD	Mean Square Deviation
NC	Numerical Control
S/N	Signal to Noise
SS	Sum of Squares
STL	Stereolithography

CHAPTER I
INTRODUCTION

1.1 Background

Casting design, in particular the gating system design, has a direct influence on the quality of cast components [1-3]. The gating system is used to introduce liquid metal into the mould cavity. The design of gating system is largely based on past experience and empirical rules and like most engineering design problems. Presently, casting design is primarily done on a trial and error basis as shown in Figure 1.1. With this approach, finding an acceptable gating system design proves to be an expensive and arduous process.

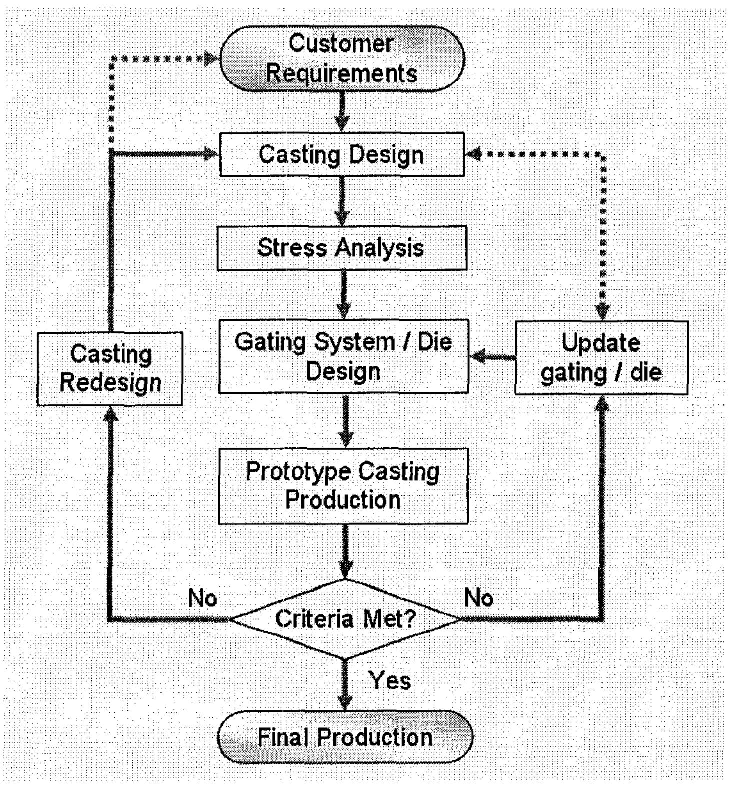


Figure 1.1 Traditional casting design on a trial and error basis

With the availability of modern numerical software, simulation has become an important tool for the design, analysis and optimization of casting processes. Numerical simulation of the casting process provides a powerful means of analyzing various phenomena occurring during casting processes. It can give the designer an insight into the details of fluid flow, heat transfer and solidification as well as prediction of porosity, inclusions, hot tears, and other casting defects. This enables designers to flexibly explore different options and avoid costly prototype trials[4-7]. The benefits of computer simulation have been demonstrated not only in the gating model design but also in process selection and shape design.

The process optimization requires intensive human interaction and numerous trial and error iterations. Even with the assistance of simulation tools, determining the optimal shapes, sizes and locations of the casting components while simultaneously trying to adhere to conflicting quality and cost constraints is difficult. Therefore, it requires not only extended time but also large resource to find an optimal gating system design.

1.2 Motivation

Casting problems often consist of multiple conflicting objectives that have to be taken into consideration, and the designer is faced with the problem of finding a compromise solution between them. Even with the assistance of simulation tools, it is difficult to determine the optimal gating shapes, sizes and locations of the casting components while simultaneously trying to adhere to conflicting quality and cost constraints. Numerous efforts have been made to improve the quality of castings and reduce cost and lead time using simulation tools. Since there is no methodical way of doing it, this process of finding an optimum design proves to be a challenging task.

Coupling numerical simulation with formal optimization methods is one way of employing a systematic approach towards casting design. Ultimately, the overall design process can be made considerably efficient, and repetitious tasks can be handled methodically. As a result, not only the design cycle time is considerably cut down but also the delivery of optimal products is accelerated.

The casting design practice is particularly impervious to changes due to its history of tradition. It has long been practiced on the basis of experimental trial and error due to the lack of fixed theoretical procedures to follow. Also, the casting design optimization problem is characterized by multiple control points and multiple conflicting objectives that involve many parameters. In addition, the casting design evaluation is a computationally intensive, costly, and time consuming process as it involves complex computational fluid dynamics (CFD) and heat transfer calculations.

The optimization process design is undoubtedly an attractive vision. Despite of their wide use in various engineering designs[8-10], the application of optimization methods for casting gating design is still little. This trend can be largely attributed to the experience-based casting design, which slows attempts in formal optimization processes.

1.3 Objectives

The fundamental goal of this thesis is to improve the efficiency of the gating system design by employing simulation and optimization techniques to (1) reduce the design circle and (2) improve the design quality at the same time. Therefore the first aim of this thesis is to formalize the casting design process and present a framework suitable for the gating system design optimization. The optimization framework should be generalized so that the optimal process parameter can be achieved for individual casting problem. The focus is primarily on the gating system where numerical simulation is employed to predict the performance of different designs.

Based on the above consideration, the objective of this project was to explore the optimization methodology for light metal castings design process with the numerical simulation tools. The gating system was taken to be demonstrated as one of the casting design process parameters during the optimization process. In order to achieve the proposed objectives, this project was divided into two stages. The first stage involved mould filling and solidification simulation by software including applying the casting rules to generate full casting models with gating system. In the second stage, the Taguchi method was employed to design the experiments, analyze the simulated results in an effort of obtaining the optimal parameters.

1.4 Organization of the thesis

The thesis is divided into seven chapters. A background of the casting design problem has been introduced in Chapter I. Chapter II is the literature review that introduces the casting design rules, gating system design, simulation software and optimization methodology. In Chapter III, a framework of casting optimization design is proposed along with the Taguchi method. Preliminary theories about the signal to noise(S/N) ratio with multiple performance characteristics and the analysis of variance(ANOVA) are presented. Evaluating criteria and objective function for casting production are further summarized in accordance with the actual casting production requirement. The numerical experimental procedures is described in Chapter IV, in which the application of the Taguchi method to optimize gating system parameters is demonstrated with numerical simulation tool. Chapter V reports detailed simulation results and discussion with respect to the optimal level of gating system parameters. The conclusions of the present study are summarized in Chapter VI. Finally, chapter VII gives the possible directions for future work.

Chapter II
LITERATURE REVIEW

2.1 Casting Design

2.1.1 Light metal casting

The light metal usually includes aluminum, and magnesium which are lighter than iron and steel. Aluminum alloy and Magnesium castings are widely used because of their light weight, high specific strength and superior performance.

2.1.1.1 Aluminum alloys

Aluminum casting alloys need to contain sufficient amounts of eutectic-forming elements so that molten metal have adequate fluidity to feed the shrinkage that occurs in the castings solidification. Required amounts of eutectic formers are different with casting processes. Sand casting is usually lower than those for casting in metal molds. A large number of aluminum alloys has been developed for casting, but generally including six basic types: aluminum-copper, aluminum-copper-silicon, aluminum-silicon, aluminum-magnesium, aluminum-zinc-magnesium and aluminum-tin alloys[11].

It is well known that liquid aluminum has a high susceptibility to the formation of oxides. Thus, solid oxide films form within milliseconds after exposition to air. However, since liquid aluminum is highly susceptible to oxidation and hydrogen absorption, aluminum alloy castings are vulnerable to certain defects such as porosity and oxide inclusions if the casting process is not appropriately selected. The alumina or the spinel films acts as a protective layer against continuous oxidation, preventing a catastrophic oxidation of the bulk melt [12-13]. However, the oxide film is weak and some stirring of the melt always occurs, leading to frequent disruptions of the film. As a result, there is a very strong tendency to incorporate oxide films to the bulk melt, followed by the formation of new oxide films on the melt surface.

These defects have significant influence on the mechanical properties of castings. It has been long recognized that casting design, in particular the design of gating and riser systems, has a major impact on the quality of castings. All liquid melt required to fill up the casting cavity needs to be introduced through the gating system. Thus, any damage of the liquid metal during mold filling would leave its signature in the final casting. Therefore, the gating system should be designed to allow a smooth flow of liquid metal into the mould cavity, minimizing the creation of turbulence to avoid gas entrapment and the formation of oxide inclusions.

2.1.1.2 Magnesium alloy

Low density (1800 kg/m^3 in alloy form), coupled with favorable casting properties, makes magnesium the material of choice for lightweight components. Magnesium-based alloy castings products have rapidly grown their applications in the automotive industry since the early 1990s. Magnesium also has the highest strength-to-weight ratio of any of commonly used metals. Moreover, many other advantages of magnesium (e.g. good cast ability, high die casting rates, electromagnetic interference shielding properties, parts consolidation, dimensional accuracy, and excellent machinability) promote the utilization of this interesting lightweight metal in the automotive industry[14]. Approximately 80% of this market is expected to go towards die casting automotive parts. Based on their chemical composition, the typical Magnesium Alloys for industry are listed as the following Table 2-1[15]. Based on the process method, the typical industrial applications of some Magnesium Alloys are listed as the Table 2-2[15].

Table 2-1 Typical composition of casting magnesium alloys[15]

Typical composition (wt%) of some cast and wrought magnesium alloys

Alloy	Form*	Al	Zn	Mn	Si	RE	Zr	Th
AM60A	CD	6		>0.13				
AM60B**	CD	6		>0.25				
AS41A	CD	4		0.3	1			
AZ31B	WB+ WS	3	1	0.3				
AZ61A	WF	6	1	0.2				
AZ80A	WB	8	0.5	0.2				
AZ81A	CS	7.5	0.7	0.2				
AZ91B	CD	9	0.7	>0.13				
AZ91D**	CD	9	0.7	>0.15				
AZ91E**	CS	9	0.7	0.2				
EZ33A	CS		3			3	0.8	
HK31A	WS						0.7	3
ZE41A	CS		4			1	0.7	
ZK60A	WB		6				>0.45	

* CS - sand casting; CP - permanent mold casting; CD - die casting; WS - sheet or plate; WF - forging; WB - bar, rod, shape, tube, or wire.
** High-purity alloys.

Table 2-2 Typical applications of magnesium alloys[15]

Characteristics and typical uses of some magnesium alloys

Alloy	Characteristics and typical uses
Cast Alloys	
AM60A/B	*high-pressure die-casting alloy with outstanding ductility in the -F condition; used for fans and automobile wheels*
AS41A	*die-casting alloy with good creep properties up to 150°C: used for automobile parts*
AZ81A AZ91C/E ZE41A	*general-purpose sand and permanent mold-casting alloy used for aircraft parts, machinery components, gearboxes*
AZ91B/D	*general-purpose die-casting alloy for automobile and computer parts, chain saws, sporting goods, cameras, projectors, and household equipment and appliances*
EZ33A	*high-temperature alloy for sand and permanent mold casting; excellent castability; creep resistant up to 250'C and pressure-tight; used in aerospace and military applications*
Wrought Alloys	
AZ31B/C	*moderate strength general-purpose alloy used for luggage, ladders, hand trucks, bakery racks, and concrete tools*
AZ61A AZ80A ZK60A	*higher strength alloys used in batteries, military components, shelters, tent poles, and tennis racquets*
HK31A	*elevated-temperature alloy used in aerospace and military applications*

2.1.2 Casting Design Rules

The gravity casting process normally involves high flow velocities, which tend to cause turbulence and air aspiration. Turbulence and air aspiration cooperate to form and entrain oxides, air bubbles and oxide films formed during casting an light metal part. The role of a properly designed gating system and casting process can prevent turbulence and air aspiration during mold filling. Alternative foundry processes have been developed, in which the filling flow velocity is better controlled than in simple gravity pouring, thus making the production of reliable parts easier [16]. Examples are tilt pouring, counter-gravity processes and squeeze casting. Alternatively, in vacuum assisted process, as in vacuum-high pressure die casting, the turbulence is allowed, since there is no air in the gating system and in the mold cavity to promote bubbles and oxide formation.

The basic purpose of the casting process design is to allow the filling of the mold cavity with clean and uncontaminated metal, assuring that the resulting casting has no defects caused by the metal flow [13,17]. To achieve the desired casting quality, numerous efforts and recommendations have been made in the literature [12,18]. The general guidelines for the conventional casting process of light metal alloys in gravity casting can be summarized as follows [12,19].

It has been demonstrated that both pouring method and the design of mold filling system are crucial to the attainment of reliable mechanical properties of the castings. The ten rules give some new concepts about gating and riser design methods such as avoiding the use of a sprue base and designing runners with low heights to guarantee 'one-pass' filling. According to Campbell[19], the sprue base well can produce an abrupt change of flow direction in its cross section and thus generates turbulence. Similarly, back filling can occur in thick runners when metal is introduced into the gating system and then promotes turbulence.

Based on foundry man's working, Campbell's ten rules[12,19], north American and the Chinese casting experience[20], the following design rules can be summarized for the gating and riser system of light metal castings. To clarify the presentations of the design rules, Figure 2.1 show a cylindrical casting with most components of gating system.

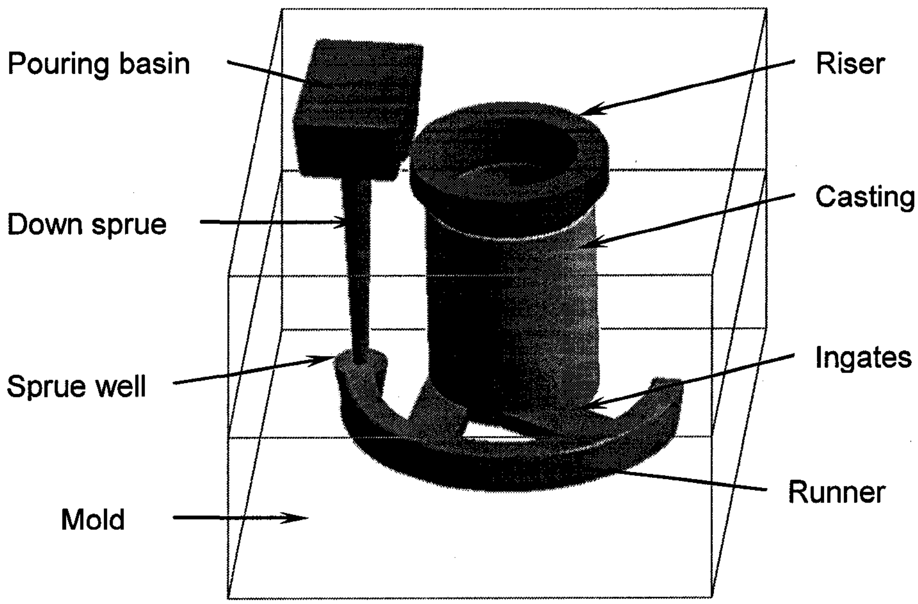


Figure 2.1 Major elements of a gating system

2.1.2.1 Pouring & Parting Line Position

1. The largest machining plane and main working plane should put in bottom or side;
2. Place the parting plane at the cross section of the largest area of the casting;
3. Place the parting plane as low as possible relative to the casting;

4. Place the casting such that top risers can be placed on high points on the casting for the heavy sections;
5. Minimize the height of the casting;
6. Place open spaces down;
7. For large shrinkage casting alloy, it should follow the order of solidification, that is the thick-part of casting shall be put on the top so that it is convenient for riser compensation;
8. Position the core for convenient placement and easy air venting;
9. For large plane casting, the main plane shall be put in bottom, or be placed vertically by revolving the mould to accommodate vertical pouring of metal;
10. The thinnest wall-thickness shall be put in casting bottom or side;
11. For mass production, the casting burring and joint flash shall be reduced, and also casting should be put in a position which is easy to clear;
12. Put Risers on the machining plane so that can reduce the clearing work;
13. To be easy to draft, parting line shall be put in the largest section of the casting, while mould heights of cope and drag are balanced;
14. For a simple shape, all casting or the main part of casting shall be put in one mould, so that mold and core shift can be reduced;
15. Reduce the quantity of parting line;
16. For high machining production, cores should be used instead of loose pieces (inserts);
17. Reduce the quantity of the cores; and
18. Make parting line on a plane if possible.

Part orientation and parting line are usually the first few decisions that need to be made in the design of a gating system. When filling the mould, the melt front should not come to a stop. If this happens, the stationary front becomes covered with a thick oxide film and it might not be possible to restart its advance again. The melt might break through and roll over the oxide layer, trapping it in the casting as an 'oxide lap'. If the arrest of the melt front is prolonged, the front may freeze again, creating a 'cold lap'.

Laps of either sort can act as cracks. Thus horizontal surfaces of castings should be avoided in design whenever possible. They can be avoided by tilting the mould or simply by filling these regions at a speed sufficient to reduce the problem to an acceptable level.

2.1.2.2 Pouring Basin

1. minimizes the possibility of air and oxide entrance into the mould cavity; and
2. In this study, an offset weir basin was used.

2.1.2.3 Riser Design

1. Locate near thick section of the casting, especially on the HUBS;
2. The cross section of riser shall be slightly larger than the section it feed;
3. For thin wall casting, side risers should be located on top of gates to eliminate shrinkage defects and maximize casting yield;
4. Top risers should be located on bosses, away from the gate;
5. For bottom-gated casting, fast filling of the mold with gates, use of insulated or exothermic risers, and chilling the gate area are safe to cure unfavorable temperature gradients;

6. Size of risers should be calculated based on the Modulus/ Volume of that part, *(that means risers should be greater volume to area ratios than the part itself.)* and be large enough to feed shrinkage(4-6%) volume of the section which they feed; and
7. The maximum feeding distance should also be considered, especially for multiple risers.

Adequate risers are required to avoid solidification related defects such as shrinkage, micro-porosities, hot tears and so on. The design of a riser should take into account its two objectives: eliminate shrinkage defects and maximize casting yield. The rules has been summarized in above. The roles of risers in metal castings have been long recognized in the literature [12, 21-23].

According to the above casting design rules, the casting should have directional solidification with a temperature gradient rising towards the riser.

2.1.2.4 Sprue & Well

1. The sprue should be sized to limit the flow rate of molten metal. If the sprue large, high metal flow rates cause dross problem;
2. The sprue should feed into a standard-sized well to reduce the kinetic energy of the molten metal;
3. Sprue should be designed as standard sizes and shapes;
4. If the metal flow rate is known, then the sprue exit area can be calculated by:

$$A = \frac{Q}{W\sqrt{2gh}}$$

Q: rate of flow

W: specific weight of metal (2700 kg/m^3 for Al)

A: cross-section area

g: gravitational acceleration

h: vertical height of metal in sprue;

5. Sprues should be tapered by more than 5% to avoid aspiration of the air and free fall;
6. The sprue should be located centrally on the runner, with an equal number of gates on each side;
7. The sprue should be located as far from the gates as possible;
8. The round –shaped sprues are more economical for small castings, and can not cause vortex problems;
9. Well area should be two or three times the area of the sprue exit;
10. Well needs to be 1.2-2 cm deeper than the runners; and
11. Rapid mold filling (but the velocity <= 0.5 m/s). Liquid aluminum alloy flow should not exceed a velocity of 0.5 m/s to maintain the stability of its meniscus front even in the down sprue.

2.1.2.5 Runner

1. Rectangular cross section and standard size are prefered in sand casting;
2. non-pressurized gating systems are used to minimize the velocity of ingate for light metal castings (Ratio = 1: 2 : 2 / 1 : 2 : 4) ;
3. Abrupt changes in the direction of the runners should be avoided;
4. Runners should run along the part for long parts, and for round parts, usually two runners running around the periphery of the part are recommended;

5. Runner blind ends are used to trap dross, which usually more than 2.5 cm in length;
6. The runners should maintain a minimum distance from the part; and
7. For light metal castings, usually use bottom filling of the mold cavity.

2.1.2.6 Ingate

1. Put ingate at thick regions;
2. Rectangular cross section and standard size are preferred;
3. Orienting the gates in the direction of the natural flow paths, which reduces agitation and avoids erosion of the sand mold by metal stream;
4. Fillets between gates and casting: a slight flare of the gates towards the casting is desirable;
5. Mutiple gating is desirable, which lower the puring temperature, reduce the temperature gradients in casting;
6. Maximum gate thickness should be 6-10 mm;
7. For easy cleaning casting, the first gate in a large casting should be located at a minimum 30-38 cm away from the sprue, and this distance shall be at least 4 cm for a small casting;
8. A minimum gate length of 2 cm is enough for small bench mold and 10cm for larger molds; and
9. Drag runners and cope ingates should be combined.

According to the above guidelines and rules for gating system design, non-pressurized systems should be applied to alloys that are highly sensitive to oxidation, like aluminum and magnesium alloys. In non-pressurized systems the flow-controlling constriction ("choke") occurs at the sprue, with cross sectional areas widening in the order: SPRUE:RUNNERS:INGATES. Normally the ratios between the cross sectional areas of the sprue: runners: ingates are 1:2:2, 1:2:4 or 1:4:4.

This type of gating systems has the advantage of reducing metal velocities in the gating systems as it approaches and enters the cavity of the castings, contributing to obtain a non turbulent filling of the casting cavity.

Thus, the non-pressurized gating systems guarantee non-turbulent filling of the casting cavity, but may produce air bubbles and oxide inclusions entrapment in the sprue base well, runners and ingates, impairing the quality of the castings.

2.1.3 Gating System Design

It has been long recognized that gating system design plays an important role in casting quality[19]. This is because all liquid melt required filling up the casting cavity needs to be introduced through the gating system. Any damage of the liquid metal during mold filling could leave its signature in the final casting [12, 24-25]. A number of casting defects such as porosity, burning-on, cold shut, misrun, inclusions, rough surface, and etc., are known to be attributed to the faulty design of gating system with incorrect mold filling process[45, 46]. These defects significantly influence the mechanical properties of castings. Therefore, the ideal gating system should be designed to allow a smooth flow of liquid metal into the mould cavity, minimizing the creation of turbulence to avoid gas entrapment and the formation of oxide inclusions.

The design of gating and riser systems has a major impact on the quality of the castings. Light metals such as aluminum castings are especially vulnerable to certain defects such as porosity and oxide inclusions if the casting process is not appropriately selected [12, 25]. These defects have significant influence on the mechanical properties of the castings. Campbell[13, 19] developed ten rules for the design and assurance of high quality castings. Among them are four rules that can be directly linked to the design of the gating and riser system by mathematical modeling and computer simulation:

- Prevent liquid front damage: Maximum meniscus velocity <0.5 m/sec. No top gating.
- Avoid liquid front arrests: Liquid should not stop at any point along the front, progressing only uphill in a continuous, uninterrupted advance.
- No bubble damage: Bubbles of air entrained by the filling system should not pass through the liquid metal into the mold cavity. Design the sprue and runner to fill in one pass. Avoid the use of wells.
- Eliminate shrinkage damage: No feeding uphill. Follow the feeding rules and run an appropriate solidification model.

2.1.3.1 Components and Types of Gating System

A mould cavity must be filled with clean metal in a controlled manner to ensure smooth, uniform and complete filling. This can be achieved by a well-designed gating system. The first step involves selecting the type of gating system and the layout of gating system: the orientation and position of sprue, runner and ingate(s). The most critical design decision is the ideal filling time, based on which the gating system are designed.

The main objective 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.

As shown in Figure 2.1, the major elements of a gating system include pouring basin, sprue, well, runner and ingate, in the sequence of flow of molten metal from the ladle to the mould cavity. The pouring basin that accepts the molten metal from the ladle. The sprue or downsprue, usually circular in cross-section, leads molten metal from the pouring basin to the sprue well. The sprue well or base changes the direction of molten metal by right-angle and sends it to the runner. The runner takes the metal from the sprue to close to the casting. Finally, the ingate leads the metal to the mould cavity.

Depending on the orientation of the parting plane, the gating systems can be classified as horizontal and vertical gating systems as shown in Figure 2.2[26]. Horizontal gating systems are those in which parting plane is horizontal and contains the runners and ingates. The sprue is vertical, perpendicular to the parting plane. These are suitable for flat castings filled under gravity, such as in green sand casting and gravity die casting. Vertical gating systems are those in which the parting plane is vertical and contains the runners and ingates. For gravity filling processes (high pressure sand moulding, shell moulding and gravity die casting) the sprue is vertical which is along the parting plane. The vertical gating system is suitable for tall castings.

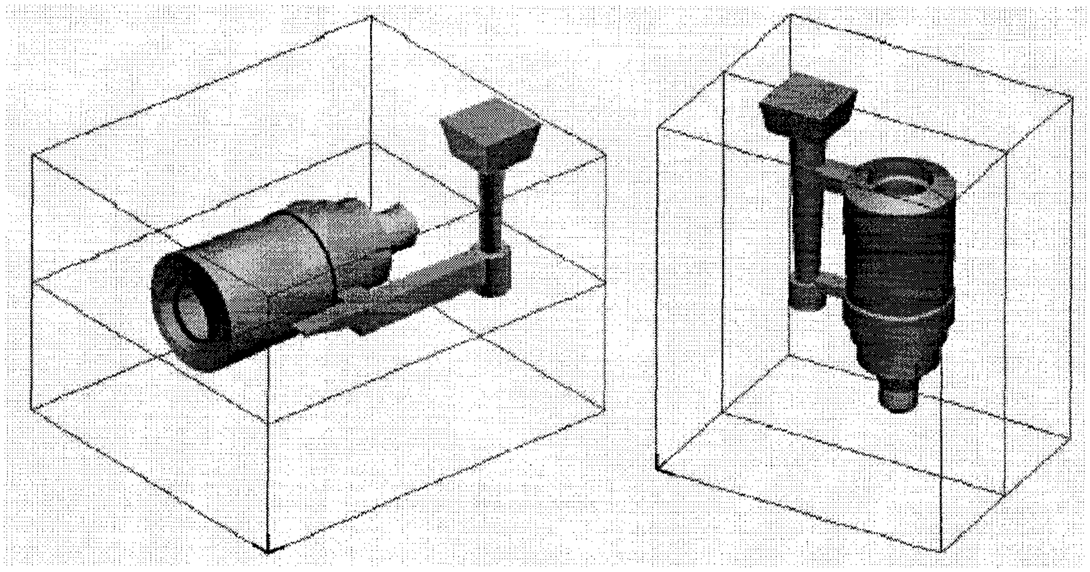


Figure 2.2 The horizontal and vertical gating systems[26]

Depending on the position of the ingate(s), gating systems can be classified as top, parting and bottom. Top gating systems, in which hot molten metal enters at the top of the casting, promote directional solidification from bottom to top of the casting. These are however, suitable only for flat castings to limit the damage to metal as well as the mould by free fall of the molten metal during initial filling. Bottom gating systems have the opposite characteristics: the metal enters at the bottom of the casting and gradually fills up the mould with minimal disturbances. It is recommended for tall castings, where free fall of molten metal (from top or parting gates) has to be avoided. Middle or side or parting gating systems combine the characteristics of top and bottom gating systems. The ingates and runner are usually at the parting plane, they are also easier to produce and modify during trial runs. The most widely used system is the horizontal gating with ingates at the parting plane. In vertical gating systems, ingates may be positioned at top, bottom and side.

The design of a gating system starts with the determination of the part orientation and parting plane. Identification of the gate location for uniform feeding is the next step. Having decided where the gates are located, an appropriate runner geometry is selected; The sprue location is determined so that it is as far from the nearest gate as possible. Sizing of the elements of the gating system is done using the geometry of the part and the above mentioned rules. Traditionally, these activities have been performed by process engineers based on their training and experience. The successful gating systems are usually trialed for many times in the production.

The gating system is also designed to promote sequential solidification of the casting. It has been pointed out[13, 19] that the filling of the mold is also important in preventing the entrapment of oxides and air in a casting. Since oxide formation is instantaneous in molten aluminum, the gating system should be designed to minimize the entrance of oxides on the surface of the molten metal into the casting and also to prevent turbulence in the metal stream, as this would entrap the surface oxides in the stream and lead to further oxidation on the surface when fresh metal is exposed to the atmosphere. Turbulence in the metal flow may be caused by excessive velocity of the molten metal, free-falling of the stream while passing from one level to another, vortices formed, or abrupt changes in the flow direction. Sharp changes in the flow direction promote eddies at corners, which cause aspiration of air and mold gases into the molten metal[19].

2.1.3.2 Critical Points of Gating System Design

The gating system determines how the liquid metal is delivered into the mould cavity. A well-designed pouring basin can ease the filling of the mould and also minimizes the possibility of air and oxide entrance into the mould cavity. If the pouring basin is off-set from the sprue (in contrast to a conical basin which is set in-line with the sprue) and has a small vertical step (the weir), excellent introductory flow of liquid metal into the filling system can be achieved. In this study, an offset weir basin was used.

During mold pouring following critical points shall be considered:

(i) Melt pouring exposes large areas of liquid metal surface to oxidation, promoting the generation of an oxide tube around the metal stream;

(ii) During pouring, as potential energy is transformed into kinetic energy, the metal velocity increases, reaching its maximum, normally between 200 and 300 cm/s, at the sprue base; and

(iii) The high metal velocity must be reduced in runners and ingates, in order to fill the cavity without turbulence.

The sprue is a vertical channel from the filling basin that conveys the metal to the lowest point of the filling system. Inside the sprue, the free fall of the melt accelerates the stream velocity, reducing its transversal area proportionally (Law of Continuity). Consequently the sprue must be tapered, narrowing towards the base to achieve the reduction of the metal stream area [27]. Therefore, the liquid metal would be unable to jump or splash and any entrainment of its own surface would be largely avoided, thus avoiding the folding-in of oxide cracks in the liquid.

Runyoro[28] has also pointed out that the liquid aluminum alloy flow should not exceed a velocity of 50 cm/s to maintain the stability of its meniscus front even in the down sprue. Otherwise the surface oxide film may get folded into the bulk of the liquid and constitute initiation sites for gas evolution, shrinkage cavities and hot tears, decreasing leak tightness, corrosion resistance and the strength of the casting.

According to Bernoulli's equation, after falling only 1.25 cm in height under gravity, liquid aluminum reaches a critical velocity of 50 cm/s. Therefore, runners and ingates placed after the sprue have the crucial task of decreasing the flow velocity of liquid metal. Typically, non-pressurized gating systems are used to minimize the velocity of liquid metal as it passes through the ingate and enters the mould cavity. Usually the downsprue and runner junction is a place where liquid metal has to change direction rapidly through a 90° angle. This usually results in a lot of splashing which creates trap defects. Traditional gating designs impose the use of enlarged runner and ingate sections for a non-pressurized system that may promote turbulence and back filling especially when the gating system is incompletely filled at the beginning of pouring [17].

If the height of the runner is too high, liquid metal can flow back to fill the cavity between the joint part of the sprue and runner, resulting in gas inclusion too. Campbell[19] emphasized that one-pass filling pattern is desired. Rezvani et al[21] proposed the application of a thin filling system in order to guarantee the enlargement of the runner cross section area without the risk of rolling back-waves. A slim runner with a height of only 7 mm was used to minimize the back filling problem and to allow the enlargement of the cross section area of the runner in relation to the sprue cross section area.

These narrow filling designs have been called 'one-pass' filling methods because no rolling back-waves and thus no backward flow causing a turbulent and protracted priming phase can occur. The development of 'slim' runners allows the use of non-pressurized gating systems without the risk of turbulence or air aspiration inside the gates.

Therefore, surface turbulence and bubble generation are significantly limited. The avoidance of bubble generation has also recently been found to be of major significance to the integrity of castings. The bubble trail is itself a serious defect and can lead to the initiation of further defects such as shrinkage porosity and hot tears [19].

Recently, it has been shown [13] that during mold filling, the stability of the meniscus front must be maintained to avoid entrained oxides due to surface turbulence. In order to achieve this stability, it is necessary to control the liquid velocity under approximately 50cm/s. As above discussion, in most gravity castings it would be "impossible" to produce aluminum castings without oxide films entrapment [20]. Actually, a flow velocity higher than that critical velocity may be acceptable, since the metal flow is constrained so that the metal does not detach from the mold wall. This is obtained by means of the proper design of the runners and of the junction between sprue and runners.

Since there is no mold wall to constrain the metal flow as it enters the casting cavity, the metal flow velocity must be reduced to below the critical velocity (50 cm/s) before arriving at this point. So, Both of the following conditions should be satisfied for a gating system which guarantee the production of sound castings by gravity pouring[20, 22]. The condition (1) usually is used in sprue and runner design, and the condition (2) shall be considered for designing the ingate.

(i) Condition 1 - The metal stream must be constrained by the gating system walls without detachment of its surface, whenever the metal flow velocity is high (over 50cm/s);

(ii) Condition 2 - The metal flow velocity must be reduced to under 50cm/s before reaching the casting cavity, to prevent turbulence and air aspiration during the cavity filling.

2.1.4 Design Procedures of A Gating System

In light metal casting practice, the design of a gating system includes determination of the following aspects:

1. pouring method (horizontal or vertical; from top of the casting, parting line or bottom of the casting);
2. gating system ratio (pressurized or unpressurized);
3. pouring time (the rate of mould filling);
4. ingate and runner's geometry shape, dimension, number and location;
5. sprue geometry shape, dimension, location; and
6. pouring basin, sprue well, runner extensions, etc.

Traditionally, these activities are performed by casting process engineers based on their individual knowledge and experience. In many cases, the gating system design is not optimal and often based on trial and error practice.

As light metal has high susceptibility to oxidation and hydrogen absorption, light metal castings are vulnerable to certain defects such as porosity and oxide inclusions if the gating system is not appropriately designed. It has been indicated[19] that the filling of a mod is also important in preventing the entrapment of oxides and air in the casting. Due to rapidness of oxide formation in aluminum and magnesium, their gating systems need to be designed to minimize the introduction of oxide on the surface of molten metal entering the casting, and also to prevent turbulent flow in molten metal. This is because the turbulent flow would entrap surface oxides in the metal stream and result in further oxidation on the surface as fresh molten metal is exposed to the atmosphere. Furthermore, the presence of oxides as films or discrete folded particles reduces the fluidity of molten metal, which leads to poor cavity filling of castings. To reduce turbulent flow in the metal, high velocities of molten metal should be reduced, free falling of the metal stream be controlled, and abrupt changes in flow directions be avoided. Nevertheless, those detrimental oxides and gases affect the resultant casting's mechanical properties, such as fatigue properties.

The use of a good gating system is even more important if a casting is produced by a gravity process[29]. Compared with cast iron, light metal alloys are sensitive for receiving damage during the filling and have high susceptibility to oxidation and hydrogen absorption. Because oxide formation is instantaneous in magnesium, the design of gating system plays more important role on minimizing the entrance of oxides on the surface of the molten metal into the casting and also to prevent turbulence in the metal stream resulting from excessive velocities of the molten metal, free-falling of the stream while passing from one level to another, vortices formed, or abrupt changes in the flow direction[30]. Therefore, light metal castings are vulnerable to certain defects such as porosity, oxide inclusions, which are known to be attributed to the faulty design of gating systems with incorrect mold filling.

In an effort to obtaining an adequate gating system, it is essential to start from fundamental hydraulic principles. In the past decades, equations based on empirical relationships have been derived and used to design a gating system[31]. After applying these relationships, a gating system of questionable quality is obtained. A lot of effort has been made to understand the influence of gating system design on mold filling using various techniques. A given design of gating system is usually validated by pouring and sectioning the test casting, or by observing the flow of molten metal in a sand mould using radiography, real time X-ray and video camera[29], or the flow of water in a transparent mould, or using contact wire sensing using computerized data acquisition[32]. Typically, modifying gating geometry by applying this trial-and-error approach, an enhanced gating system can be achieved. However, this trial-and-error approach is time-consuming and expensive.

In applying above mentioned principles to design of a specific gating system, several design decisions must be made before the actual sizes of the various components can be calculated:

- Cope runners and drag ingates;
- Stepped or slopped runners;
- Off-set pouring basin & tapered sprue;
- Pressurized or Unpressurized gating ratio based on the metal which are sensitive to oxide and dross formation;
- Vertical or horizontal gating arrangement based on the orientation of the mold parting line; and
- The rectangular geometric shape of runners and ingates.

2.2 Simulation

2.2.1 Casting Process Simulation

Casting process simulation has become an industry standard. Almost 90% of the foundry industry that produces high quality castings uses the simulation as a necessary tool. Simulation can prove to be a decisive factor in getting the high quality low cost castings. It can help in calculating the real costs of the job, and it can be used as a tool in the negotiations in getting the quality right.

With the evolution of three 3D Computer Aided Design (CAD) programs, the modeling has been made easy for designers. The foundry engineer can generate full casting model with gating system based on the CAD product model. Simulation is just next application of 3D full casting modeling.

It has been estimated that about 90% of the defects in components are due to mistakes in design and only 10% are due to manufacturing problems[33]. It has been calculated that the costs to change the design increase so much. Therefore application of casting process simulation and analysis software can significantly reduce the casting cost. It is more and more important for foundry man to realize that they have to work together with product designer in optimizing the component weight using simulation as a tool. In those cases, either the foundry or the design engineer has made the simulations with the help of software during early stages of the product design. Because casting simulation has helped foundries to point out the factors that have a significant effect on the price of the casting.

It is quite common that the foundry contacts the customer only after the first unsuccessful test castings, and proposes changes to the design, to be able to produce defect-free castings profitably. Quite often it is a question of minor changes e.g. in machining allowances, which can be resolved easily. However, as a result of the unsuccessful test castings, high cost of producing castings and shortened lead time complicate design revision.

2.2.2 Simulation software

The software applied in the current foundry industry can be summarized to two types: (1) Computer Aided Engineering (CAE) software for Casting Process Design; (2)

Casting simulation including filling, solidification and stress analysis. The Table 2-3 listed the current commercial software for casting software. Now, many software developers try to integrate two types software together in the same package.

The goal of current simulation software is naturally improvement in quality and reduced costs and lead time. The simulation software involves the following phases:

- initial product design of the component;
- assessment of the feasibility of casting for the component;
- the quality requirements (stress); and
- inspection by the customer.

The solidification simulation with casting CAE module, except the above phases, is also applied in the following phases:

- designing of the gating and riser system;
- modification of the casting design; and
- optimization on casting process parameters.

Therefore, the casting process simulation software with CAE module is proposed as the direction of casting design. Now, more and more developers added CAE function into their software package.

Table 2-3. Commercial software for casting simulation.

Software	Developer	Website
ABAQUS	ABAQUS Inc.,USA	www.abaqus.com
ANSYS	Ansys Inc.,USA	www.ansys.com
CAPCAST,WRAFTS,KENT	EKK,Inc.,USA	www.ekkinc.com
CastCAE,CastCHECK	CT-Castech Inc. Oy, Finland	www.castech.fi
CASTEM	Kobe Steel Ltd.,Japan	www.castem.co.jp
CastTherm,CastFlow	CASTEC(Australia) Pty Ltd., Austrilia	www.diecasting.asn.au
FLOW-3D	Flow Science,USA	www.flow3d.com
MAGMASOFT	Magmasoft Inc.,Germerny	www.magmasoft.com
Nova Flow & Solid	Novacast AB., Sweden	www.novacast.se
PASSAGE®/PowerCAST	Technalysis, Inc.,USA	www.technalysis.us
ProCAST	ESI Group, France	www.esi-group.com
SIMTEC	Simtec,Inc.,USA	www.simtec-inc.com
SOLDIA	KOMATSU,Japan	www.komatsu.com
SOLSTAR	Feseco Inc.,UK	www.komatsu.com
SUTCAST	SPG Media Limited,UK	www.aerospace-technology.com

2.2.3 Challenges of casting simulation

2.2.3.1 3D CAD Model

Figure 2.3 shows a flowchart of the most typical casting production situation today, in which 3D CAD and simulation tool are used by foundry engineers and product engineers. The design of experiments is conducted by the researchers during the initial casting design period.

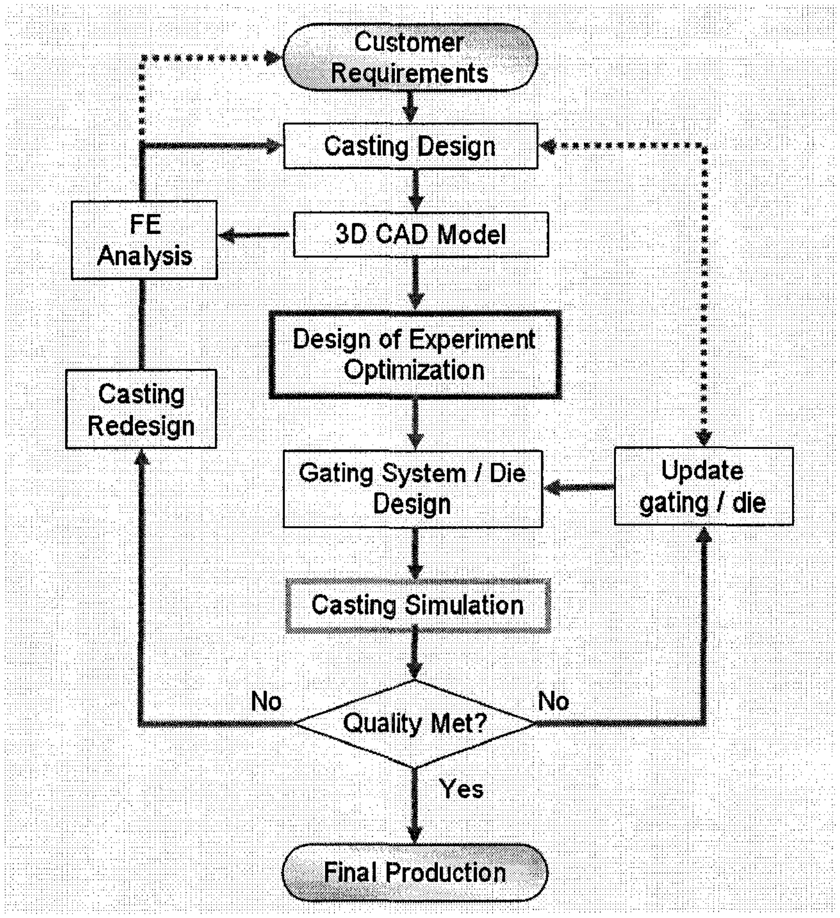


Figure 2.3 Flowchart of the typical casting production design today

The obstacle to castings and product engineers is the lack of the same 3D CAD systems or their incompatibility. 2D CAD systems are quite common in most machine shops during product process, but quite few of them utilize 3D design. Recently, the application of 3D CAD model has gained popularity, because of the introduction of simulation on top of Numerical Control (NC) machining of patterns.

The another problem is the data transferring between 3D CAD design software and the casting simulation software. The implementation of the standard data transfer formats (e.g. IGES) are not consistent between different CAD systems. This means that the data transfer quite often fails. Perhaps the most consistent way to transfer data today is the simple Stereolithography (STL) format, which can be used not only for rapid prototyping but for both simulation and patternmaking. However, the present 3D CAD system is not quite effective when creating casting feature models with assemblies. If the casting machining allowance, draft angle, gating riser system and cast components generation, can be included in the current 3D CAD software, during casting simulation, the same 3D casting model would be used as the machining process. As a result of this procedure, the design mistakes and imperfections can be avoided and the turn-around time could decrease.

2.2.3.2 Integration with optimization analysis tool

With the availability of numerical software, simulation of the casting process becomes an important tool and provides powerful means of analyzing various phenomena occurring in the metal casting industry. It can predict and visualize heat transfer, fluid flow and solidification events that are integral to the casting process[33]. However, despite the existence of such software, the interpretation of computed results still relies heavily on the expertise of casting specialists. Even with the colorful visualization of the predicted results of heat transfer and fluid flow events occurring during casting, it is still difficult to systematically optimize the design of castings without the help of human interaction and numerous manual trial-and-error iterations[35, 36].

The process simulation tools are not fully utilized in the initial product design process, but instead are most commonly used for troubleshooting in the prototype and foundry trial phases of the casting development after the product, casting and gating system have been designed and the alloy and casting process have been selected. Moreover, there is no optimization technique involved in conventional casting design processes. This results in long casting development cycles and low reliability of the casting design process, due to the variation of individual knowledge and experience.

Even with the assistance of simulation tools, determining the optimal shapes, sizes and locations of the casting components while simultaneously trying to adhere to conflicting quality and cost constraints is difficult. In order to overcome the above problems, coupling casting design with optimization tool is needed for process engineers to optimize the design of casting geometries and gating/riser systems, as well as casting process procedures, to ensure high quality castings with minimum lead time and cost. As a result, significant energy and cost savings can be realized by reducing scrap and increasing yield, and by improving the mechanical properties and durability of cast components.

Usually, the gating and riser system need to be modified frequently during actual foundry production. It is a generally accepted fact that the later the changes are made in the design and production process, the more expensive they are. But the problem is that the product designers have not known enough about casting requirements. They are used to designing components and adding machining allowance, drafts, etc., but the casting process parameter (gating riser system, parting line, puring method, etc.) optimization has still remain unsolved.

Some of the casting simulation developers integrated these optimization analysis tools to the package, such as MAGMAfrontier, and CastCHECK, etc. With these packages, the designer needs to obtain the Stereolithography file (STL) from any 3D CAD solid modeling program. Also, if the casting method and the material are given, the prototype of design can be proposed by the program. The minimum wall thickness of the component needs to be given to the program, to define how many calculation elements are needed in the analysis. All information the program needs is given in one dialog. Finally, the analysis results are shown as 3D pictures which describe the potential defect areas in the component. After the optimal casting design obtained, the final simulation should be conducted effectively based on the optimized design.

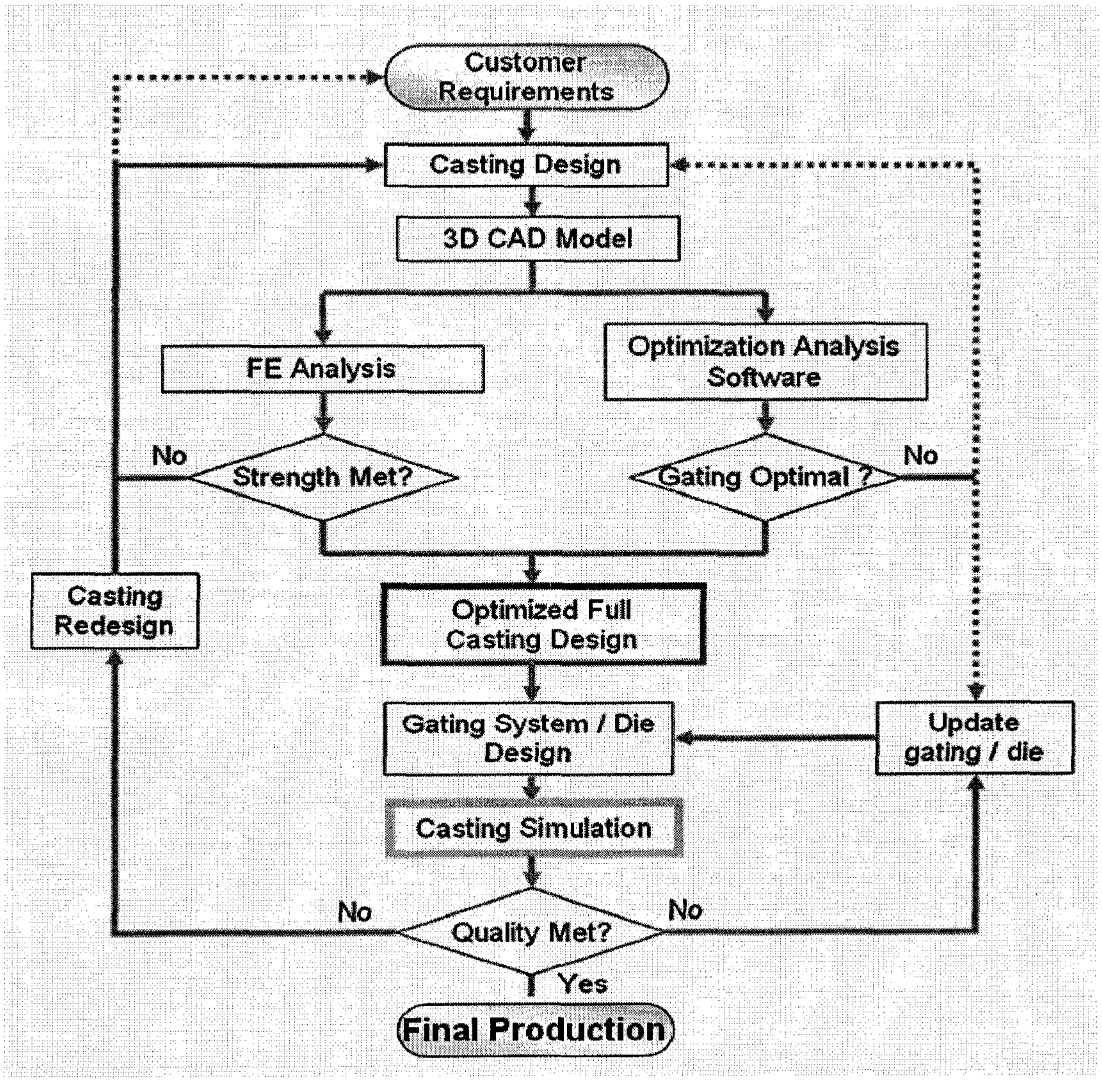


Figure 2.4 Flowchart of casting design with optimization analysis tool

Figure 2.4 shows a flowchart, in which 3D CAD, optimization analysis and simulation tools are applied both by the product engineer and the foundry engineer. This procedure is expected to be reality in most cases of designing new castings in near future.

2.3 Optimization Methodology

To achieve an optimum gating system design with minimum lead time and maximum yield and casting quality, it is necessary to incorporate casting design rules with computational tools. However, without a formal optimization strategy, the process of finding an optimum design proves to be a challenging task.

The first research showing an effect to apply a numerical optimization methodology to optimize a gating system is due to Bradley and Heinemann in 1993[37]. They used simple hydraulic models to simulate the optimization of gating during filling of molds. In 1997, McDavid and Dantzig[41] used a mathematical fluid flow modeling and numerical analysis. They presented their work using design sensitivity analysis coupled together with finite element analysis for a runner system design optimization.

Other related work that employed the design sensitivity analysis approach includes the casting riser optimization carried out by Dantzig et al[38] and Ebrahimi et al [39], in which direct differentiation methods were used to calculate the sensitivities. Their approach was demonstrated on investment castings. Analysis of the design was based on 2-dimensional calculations, and it was apparent that the sensitivity results were greatly affected by the time step size during the solidification process.

Esparza [4] presented a numerical optimization technique based on a gradient-search method for the gating system design of aluminum castings. In his approach, sequential quadratic programming was used, taking into account the mathematical structure of the problem. This approach required preliminary experiments and the performance was affected by the choice of the starting solution and the step size used.

Instead of coupling with numerical simulation, a geometric approach for optimizing riser designs was proposed by Das et al [9]. He pointed out that using a finite element or finite difference based numerical simulation becomes impractical when time is critical. He proposed an optimization scheme based on the riser modulus calculations for providing a quick estimate of the solidification process. In other related work, Guleyupoglu et al [8]and Jacob et al [40] used genetic algorithms with the modulus criterion to optimize metal yield in riser design.

By the end of the 90s, the computer modeling enables visualization of mold filling to be carried out cost-effectively in casting design and optimization of gating system. Numerical simulators based on Finite Difference (FD) and Finite Element (FE) methods provide powerful means of analyzing various phenomena occurring during the casting process[5,41]. The trial-and-error approach practices moved away from the real model to the virtual one. Numerical simulation programs were able to simulate the behavior of molten metal close to reality, obtaining the better final design, but still not the optimum design[42].

Up to now, there are the following optimization method applying to the gating system design:

- the gradient search method,
- the FEM neural network method,
- genetic algorithm(GA)[40, 43], and

- the Taguchi method.

Taguchi[36, 47, 48] has introduced several new statistical tools and concepts of quality improvement that depend heavily on the statistical theory of experimental design. Some applications of Taguchi's methods in the foundry industry have shown that the variation in casting quality caused by uncontrollable process variables can be minimized[35, 49-51]. Therefore, the Taguchi method shows certain advantages over other optimization methods when applying to casting design.

2.4 Summary

A large number of experimental investigations linking gating parameters with casting quality have been carried out by researchers and foundry engineers over the past few decades. Since all liquid melt required filling up the casting cavity needs to be introduced through the gating system, it has been long recognized that gating system design plays one of the key elements in casting quality. Although there are general casting design guidelines and empirical equations for the gating ratio, pouring time, and gating system dimensions, the variations in casting parameters chosen by different researchers have led to significant variations in empirical guidelines. This also forces foundries to carry out a number of trial and error runs and create guidelines based on their own experience. Traditionally, gating system design is performed by casting process engineers based on their individual knowledge and experience. In many cases, the gating system design is not optimal and often based on trial and error practice. This leads to not only a long casting development cycle but also a low reliability of casting design due to variation of individual knowledge and experience.

The casting process has a large number of parameters that may affect the quality of castings. Some of these parameters are controllable while others are noise factors. Therefore, the optimization of casting parameters provides a cost-effective and time-efficient approach for rapid casting quality improvement.

Chapter III
OPTIMIZATION OF GATING SYSTEM USING THE TAGUCHI METHOD

The objective of this work is to demonstrate how the application of numerical optimization techniques can be used to develop an effective optimization process for gating system design. Based on a plate aluminium casting and a cylindrical magnesium casting, a technique for optimizing gating system parameters using the Taguchi method with multiple performance characteristics is proposed. The Signal to Noise(S/N) ratio and Analysis of Variance(ANOVA) are employed for the gating parameters with multiple characteristics.

3.1 S/N ratio with multiple performance characteristics

The Taguchi method uses signal-to-noise (S/N) ratio instead of the average value to interpret the trial results data into a value for the evaluation characteristic in the optimum setting analysis. This is because signal-to-noise (S/N) ratio can reflect both the average and the variation of the quality characteristics. If the S/N ratio η is expressed in dB units, it can be defined as Equation (1) by a logarithmic function based on the Mean Square Deviation (MSD) around the target:

$$\eta = -10\log(MSD) \quad (1)$$

where MSD is the mean-square deviation for the output characteristic.

To obtain optimal casting cost, the higher-the-better quality characteristic for product yield must be taken. The MSD for the higher-the-better quality characteristic can be expressed as Equation (2):

$$MSD = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{T_i^2} \tag{2}$$

where n is the total number of tests in a trial and T_i ,is the value of product yield at the ith test.

On the other hand, the lower-the-better quality characteristic for filling velocity and shrinkage porosity also be taken for obtaining the optimal casting quality. The MSD for the lower-the-better quality characteristic can be expressed as Equation (3):

$$MSD = \frac{1}{n}\sum_{i=1}^{n} S_i^2 \tag{3}$$

where S_i is the value of filling velocity and shrinkage porosity at the ith test.

The proposition for the optimization of a gating system with multiple performance characteristics (three objectives) using a weighting method is defined as the Equations (4) to (6):

$$X = Y \times Z \tag{4}$$

Where,

$$X = \begin{bmatrix} \eta_{1c} \\ \eta_{2c} \\ \vdots \\ \eta_{9c} \end{bmatrix},\ Y = \begin{bmatrix} \eta_{11} & \eta_{12} & \eta_{13} \\ \eta_{21} & \eta_{22} & \eta_{23} \\ \vdots & \vdots & \vdots \\ \eta_{91} & \eta_{92} & \eta_{93} \end{bmatrix},\ Z = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} \tag{5}$$

And

$$\sum_{i=1}^{3} \omega_i = 1 \tag{6}$$

where ω_1 is the factor of product yield, ω_2 is the factor of shrinkage porosity, ω_3 is the factor of filling velocity, η_{jc} is the multiresponse S/N ratio in the jth test, η_{ji} is the ith

single response S/N ratio for the jth test, and ω_i is the weighting factor in the ith performance characteristics.

3.2 Analysis of Variance (ANOVA)

The purpose of employing the analysis of variance is to investigate the gating system parameters (factors) with multiple characteristics that significantly affect the quality characteristic. The ANOVA was established based on the sum of the square (SS), the degree of freedom (D), the variance (V), and the percentage of the contribution to the total variation (P). The total sum of square(SS_T) for S/N ratio and the sum of square for the tested factors(SS_p) can be calculated by Equations (7) and (8):

$$SS_T = \sum_{i=1}^{m} \eta_{ic}^2 - \frac{1}{m}\left[\sum_{i=1}^{m} \eta_{ic}\right]^2 \tag{7}$$

$$SSp = \sum_{i=1}^{m} \frac{(S\eta_{jc})^2}{t} - \frac{1}{m}\left[\sum_{i=1}^{m} \eta_{ic}\right]^2 \tag{8}$$

where m is the number of the tests, p represents one of the tested parameters, j is the level number of this parameter p, t is the repetition of each level of the parameter p, and $S\eta_{jc}$ is sum of the multiresponse S/N ratio involving this parameter p and level j.

In this study, the employment of L_9 orthogonal array indicates that the number of the tests(m) is 9. The total degree of freedom is D_T=m-1, for the tested parameter, D_p= t-1. As shown in Equations (9) to (11), the variance (V_p) is defined as the sum of squares of each trial sum result involved the factor, divided by the degrees of freedom of the factor. The corrected sum of squares (SS_p') is defined as sum of squares (SS_p) of factors minus the error variance times the degree of freedom of each factor. The contribution (P_p) denotes the percentage of the total variance of each individual factor.

$$V_p(\%) = \frac{SS_p}{D_p} \times 100 \tag{9}$$

$$SS_p^{'} = SS_p - D_p V_e \tag{10}$$

$$P_p(\%) = \frac{SS_p^{'}}{SS_T} \times 100 \tag{11}$$

where SS_T is the total sum of squares including all trials.

3.3 Evaluating Criteria

To evaluate the sound casting comprehensively, the optimization criteria for the plate and housing casting samples were defined as: (1) casting quality, and (2) casting cost. The molten metal filling velocity and casting shrinkage porosity can demonstrate the casting quality; and the casting cost characteristic can be indicated by product yield. These three characteristics acting as multiple performance objectives for evaluating different gating system designs are defined by Equations (12) to (14):

$$Velocity = \sqrt{V_x^2 + V_y^2 + V_z^2} \tag{12}$$

$$Yield\% = \frac{Weight_{cast}}{Weight_{cast} + Weight_{gating+riser}} \% \tag{13}$$

$$Porosity\% = \frac{Vol_{pores}}{Vol_{cast}} \% \tag{14}$$

where V_x, V_y, V_z are three component of vector velocity, the product yield is defined by the weight of casting divided by the total weight including the gating and riser system, and porosity is the ratio of the volume of all the pores in the casting to the volume of the whole casting.

3.4 Objective function

The design objective (design requirement) for the castings is to maximize Product Yield, minimize Shrinkage Porosity, and minimize Filling Velocity, simultaneously. But it is impossible to combine the maximum and minimum values together. In order to achieve the design target, the experiment data need to be transferred to the same Maximum requirement by the S/N ratio.

Regardless of the lower-the-better or the higher-the-better performance characteristics described by Equations (2) and (3). The larger the signal to noise ratio is, the smaller the variance of performance around the objective value. This indicates that, to obtain the optimal design of gating systems, the S/N ratio values of the three performance objectives, the Yield, Porosity and Velocity, must be maximized.

In actual casting process, since each evaluating factor needs to be considered by different weighting index, the objective function should be formulated by integration of the three optimization criteria, which is given by Equation (15):

$$Maximize \quad f(X) = \omega_1 \eta_{yield} + \omega_2 \eta_{porosity} + \omega_3 \eta_{velocity} \tag{15}$$

where ω_1, ω_2, ω_3 are the weighting factors of S/N ratio for yield, porosity and velocity, respectively.

The above objective function is presented in an analytical form as a function of input parameters since increased productivity, smooth cavity filling with minimized oxidation and reduced porosity play the important roles during casting manufacturing. However, in actual manufacturing process, for different components, the three characteristics should be considered as different critical roles by weighting factors. When defect elimination becomes critical, high weighting factors of porosity and velocity need to be considered. However, for certain casting products, high yield factor may require due to low cost demand. As an example, for aluminum plate casting, case 1(532), case 2(262) and case 3(118) with three different combinations of weighting factors were selected to demonstrate various plate casting requirements. Three digits in the brackets stand for the three individual performance objectives, i.e., the Yield, Porosity and Velocity, which are further interpreted below. For magnesium housing casting, case 1(523), case 2(352) and case 3(127) with three different combinations of weighing factors were selected to show various housing casting requirements.

For example, case1(532) means the weighting factor of S/N ratio for yield ω_1 = 50%, the weighting factor of S/N ratio for porosity ω_2 = 30%, and the weighting factor of S/N ratio for velocity ω_3 = 20%. Therefore, the multiresponse S/N ratio for case 1 can be calculated with Equation (16):

$$\eta_{Multiresponse} = 0.5 \times \eta_{yield} + 0.3 \times \eta_{porosity} + 0.2 \times \eta_{velocity} \quad (16)$$

3.5 Proposed Optimization Framework

In this optimization framework, MAGMASOFT® as a simulation tool on top of the Taguchi method was employed for the numerical simulation of different casting gating system designs. Here the optimization strategy has to be connected to the simulation environment. The optimization framework and its process flow are illustrated in Figure 3.1.

The coupling of the optimization and the simulation software is done by programming in C++ program and mainly involved the execution of system commands, reading and writing to external data files. The structure of the casting design optimization implementation is divided into four main parts: pre-processing, simulation, post-processing and optimization which are described in the following sections.

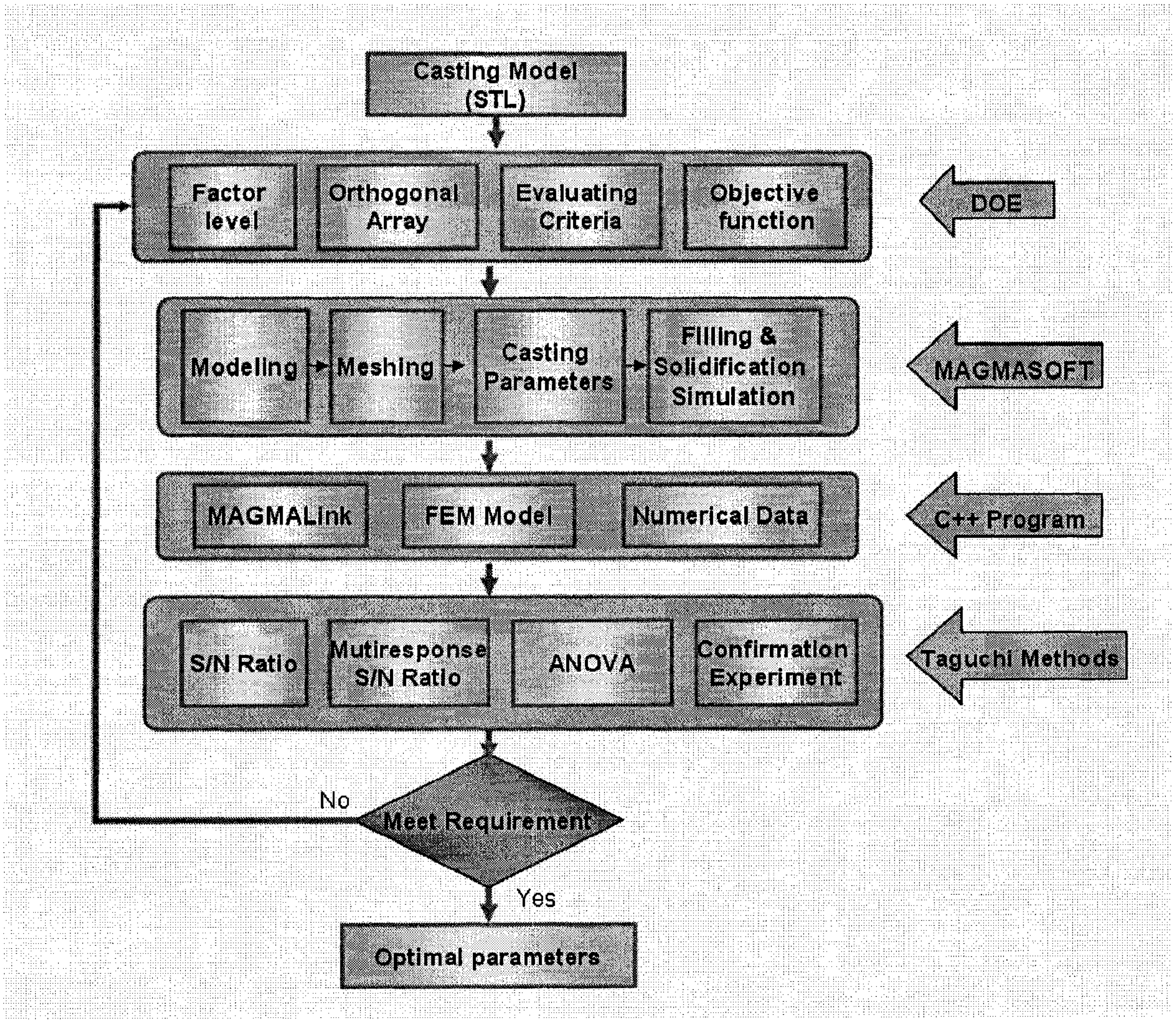


Figure 3.1 Optimization process flowchart of the casting design using MAGMASOFT® and Taguchi methods

CHAPTER IV
SIMULATION EXPERIMENT

In the engineering environment, an experiment is a series of tests or trials which produce quantifiable outcomes. Engineers conduct experiments to improve the quality of products or processes.

In the sand casting process, the main concern for quality engineers is to study the parts shrinkage problem. It is not possible to observe directly what causes the shrinkage. Experience may tell us that several factors such as metal filling velocity, filling time, gating system design, pouring temperature, and type of sand being used, etc. may be responsible for this shrinkage problem. An experiment often helps engineers under these circumstances to determine which of these factors affect shrinkage the most. During the experiment, a process or product can be characterized by collected data, the effects of different factors can be determined, and the predicted results can be verified. For the casting shrinkage problem, it is important to know at what level each factor should be kept to minimize the shrinkage. Therefore, properly designing the experiment is essential to determine the best combination of factor levels which can meet this requirement.

4.1 Design of Experiments

Design of experiments(DOE) is a scientific approach that allows the experimenter to understand a process and to determine how the input variables(factors) affect the output or quality characteristic. In other words, it is a systematic approach to process optimization. Up to now, the Taguchi method is widely used for improving product and process quality[53].

4.1.1 Taguchi method

In the early 1950s, Taguchi[53] introduced the concept of online and offline quality control techniques known as the Taguchi method. On-line quality control are those actives during the actual production or manufacturing, whereas off-line quality control are those activities during the product or process design and development phases. Taguchi developed both a philosophy and methodology for the process of quality improvement which was heavily dependent on statistical concepts and tools, especially experiments. His method emphasizes the importance of using experimental design in the following four key areas: (1) Making products and manufacturing processes insensitive to components variation; (2) Making products and processes insensitive to manufacturing and environmental variations; (3) Minimizing variation around a target value of the response; and (4) Life test of products.

The applications of Taguchi method can solve various industrial problems as follows:

- Determining the critical process parameters affecting the adhesion of surface mount devices to printed circuit boards;
- Reducing part-shrinkage variability in an injection moulding process;
- Investigating the factors affecting the variation in the surface roughness of an engine part; and
- Optimizing die casting process parameters affecting the final casting quality.

4.1.2 Orthogonal Array

Taguchi not only conducted experimental designs from process application, but also introduced the concept of using designed experiments to make products and processes robust, i.e. to make them insensitive to environmental and manufacturing variations. Taguchi has greatly added to the understanding of the role of designed experiments in quality improvement, and has provided a structured approach to designing quality into products and processes. This work is mainly focused on the experimental design approach recommended by Taguchi. The numbers of levels for each control parameter defines the experimental region. For the experiments in this project, L_9 orthogonal array with four columns and nine rows was used. The experimental layout for four gating system factors using L_9 orthogonal array is shown in Table 4-1.

Table 4-1. Experimental plan using L_9 orthogonal array

Experiment Number	Parameter/level			
	(A)Ingate Parameter 1	**(B)Ingate Parameter 2**	**(C) Runner Parameter 1**	**(D) Runner Parameter 2**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

4.2 Simulation Process

Mold filling and solidification processes of the castings in this study were simulated with the MAGMASOFT® (Version 4.4)[55]. The simulation was carried out on the COMPAQ Presario Window XP platform (2000MHz, 256MB RAM, 30GB HD). The process flow chart is shown as Figure 4.1. The simulation results indicated that gating system parameters significantly affect the casting quality. This virtual approach and optimization technique can be applied to the foundry industry, which is evidently superior to typical trial-and-error approaches.

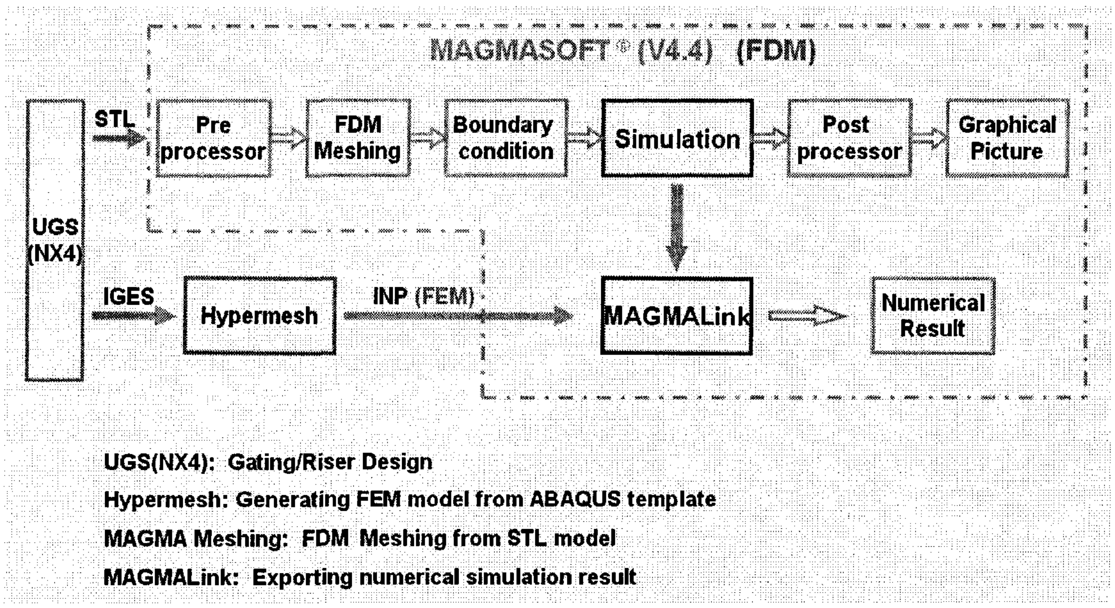


Figure 4.1. Flow chart showing integration of CAD and FE modeling software into simulation

4.2.1 Pre-processing

- ***Modeling*:** Simulation of the cavity filling and solidification process requires the geometrical information for the casting, the gating system and the mould in advance. Firstly, solid CAD models of the casting can be created using any CAD software and converted into STL files. The preprocessor module of MAGMASOFT® then reads the STL files as geometry inputs into the software. The casting shape can also be constructed using modeling functions within the MAGMASOFT® environment.

- After the casting model is established, the initial design of a gating and riser system is created using parametric geometry functions. This structured modeling of geometry is done with the aid of command files. By modifying the parameter values in the geometric functions, the design can be varied accordingly. This is an essential part of the strategy to explore different gating and riser designs in an autonomous fashion.
- ***Meshing***: Since MAGMASOFT® is a numerical simulation tool that employs the finite-difference (FD) method, the modeled geometry of the full casting system needs to be further divided into individual control volumes prior to the simulation. This subdividing of the geometry into meshed elements is described as the meshing process and can be performed using the enmeshment module in MAGMASOFT®. Depending on the complexity of the model and resolution of the mesh generation, the number of meshed elements can be adjusted accordingly for the desired accuracy.

4.2.2 Simulation

After the pre-processing, the STL models can be imported to the simulation software for calculating the mesh. Then, the casting parameters, filling and solidification process would be conducted as per parameter values selected.

When the filling and solidification simulation process completed, the post-processor can illustrated the simulation result graphically. If the numerical simulation result in numerical format needs to be obtained, the MAGMALink module has to be applied. With the correspondent FE model node number, the numerical simulation results can be calculated in the specific area of the castings. The whole simulation flow chart is illustrated in Figure 4.2.

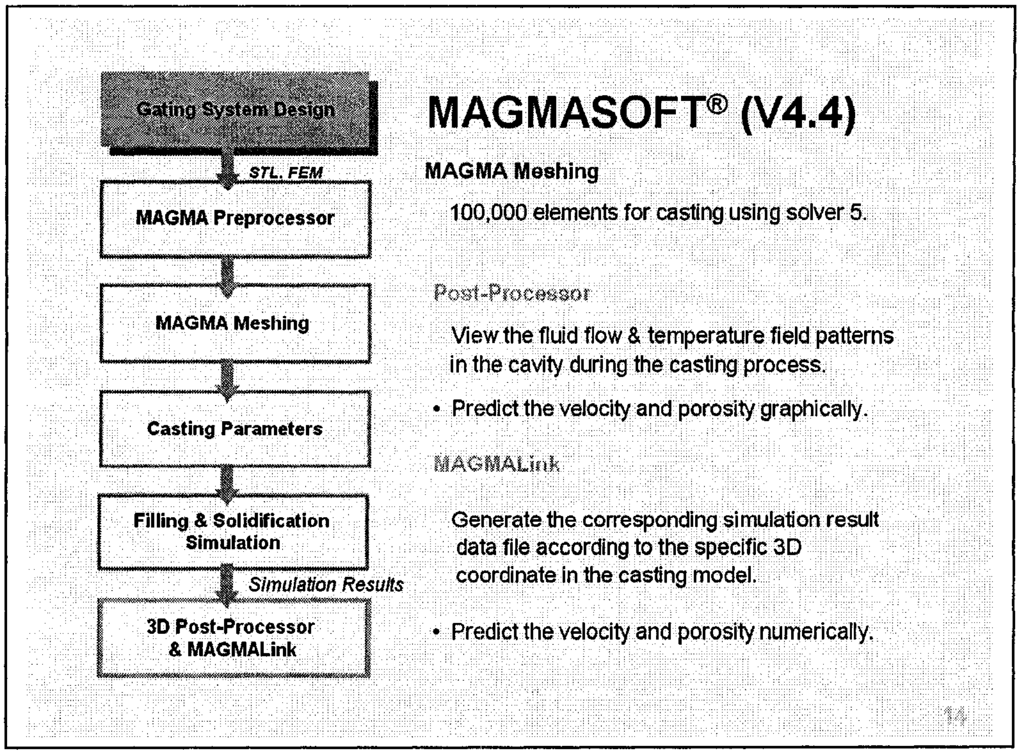


Figure 4.2 Flow chart of simulation process

4.2.2.1 Casting Parameter Specification

Before the simulation can be run, casting process information must be defined. This includes the thermophysical properties of the cast and mould materials and their initial temperature conditions. The heat transfer coefficients also have to be defined for the boundary condition of the materials. Specifications for the filling and solidification process include the filling time or pouring rate, the filling direction, the feeding effectivity, criterion temperatures and the solver types. The feeding effectivity defines the maximum ratio of the volume available for feeding and the actual volume of the riser. The filling time varies from one problem to the other, depending on the casting size. The fill direction indicates the flow of metal into the mold and is defined here in the negative Z direction to match the orientation of the gating and riser system. The filling and solidification simulation parameters used in this study are listed in Tables 4-2 and 4-3.

Table 4-2 Filling simulation parameters

Filling Definition	
Parameter	**Value**
Solver	Solver 4
Filling Depends on	Time
Filling Time	5 s
Storing Data	10% increments of % Filled
Fill Direction-X	0
Fill Direction-Y	0
Fill Direction-Z	-1

Table 4-3 Solidification simulation parameters

Solidification Definition	
Parameter	**Value**
Temperature from Filling	Yes
Solver	Solver 4
Stop Simulation	Automatic
Stop Value	425°C
Calculate Feeding	Yes
Feeding Effectivity	70%
Criterion Temperature	442.6°C
Criterion Temperature	603.0°C
Storing Data	10% increments of % Solidified

4.2.2.2 Filling and Solidification Simulation

Once the meshed geometries and the necessary process parameters have been established, the actual filling and solidification simulation can be carried out. The type of numerical calculations employed is based on the algorithm (Solver) type chosen. Solver 4 is used for speed and accuracy. For both the filling and solidification simulation, results can bextracted in 10% increments of the process completion for further analysis.

4.2.2.3 Post-Processing

- ***Export Results***: With the 3-D post processor module in MAGMASOFT®, the visualization of the fluid flow and temperature field patterns in the cavity during the casting process can be graphically analyzed. However, to formalize the casting design optimization process, these results have to be converted to a proper format that can be routinely handled. Here, the MAGMALink module of MAGMASOFT® is employed to export the graphical results into text format. Using the MAGMALink, customized subroutines can be applied to access the MAGMASOFT® files and data structures, which extracts the desired results from each control volume and convert them into the appropriate format for further processing.
- ***Result Processing***: Since the exported results contain vast amounts of values corresponding to the large number of control volumes used in the simulation, additional computations are performed to analyze the results. Then the processed results are further organized to form the appropriate performance measures required for the optimization performance evaluation process.

4.2.3 Finite Element Model Generation

The Finite Element(FE) Models of castings can be generated by HyperMesh software. The entire progress can be illustrated with the following procedures:

1. Select Profile in the ABAQUS 3D template as shown in Figure 4.3.

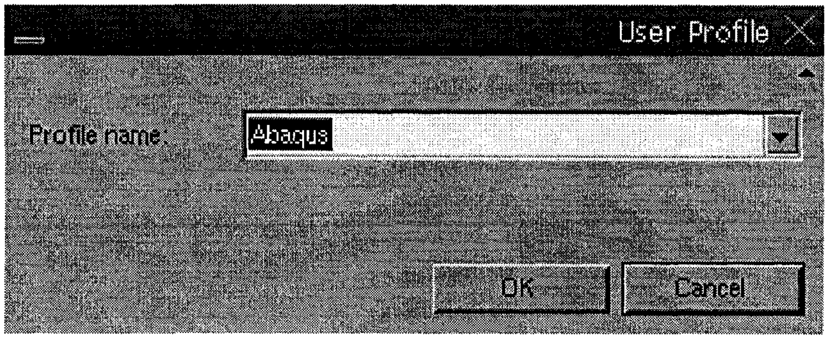


Figure 4.3 Slect Profile interface in Hypermesh

2. Import Geometry as IGES file as shown in Figure 4.4.

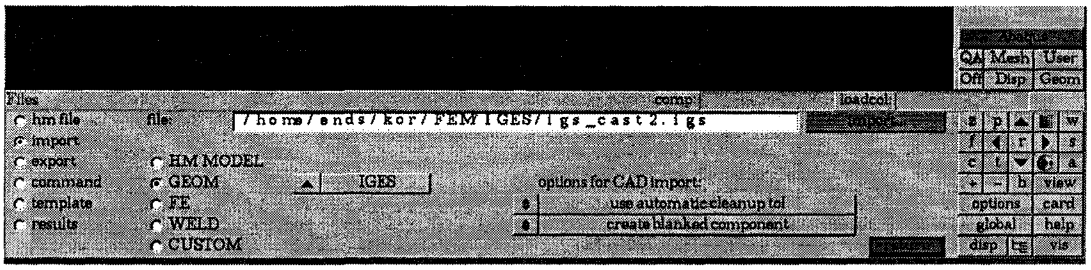


Figure 4.4 Geometry import window in HyperMesh software

3. Define Component including Material, Type, Properties as shown in Figure 4.5.

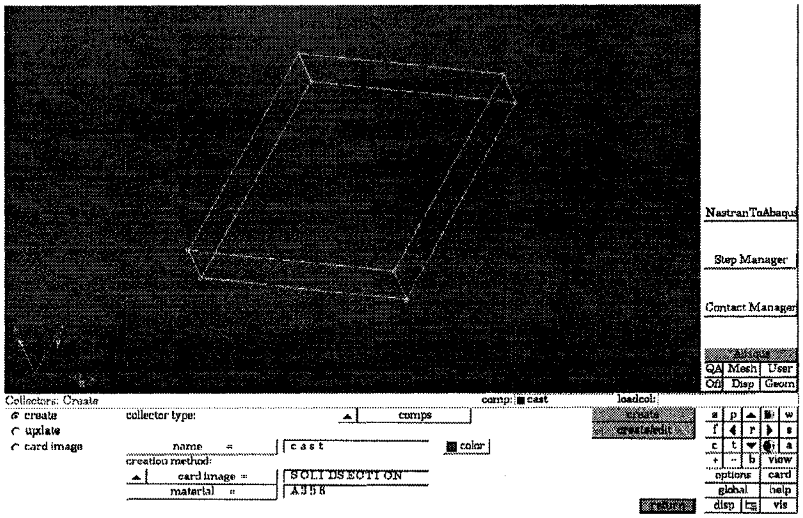


Figure 4.5 Component definition window in HyperMesh

4. Define Meshing Properties – e.g. Mesh Type, Mesh Size

5. Mesh the Component as shown in Figure 4.6.

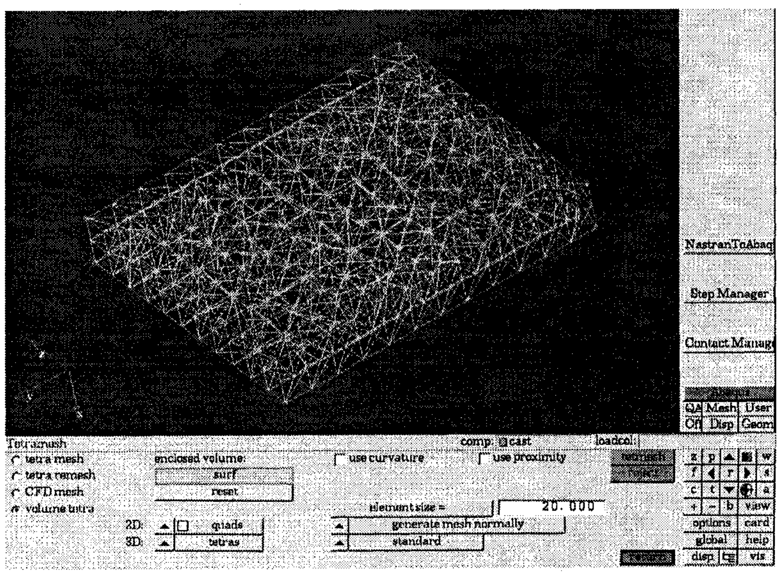


Figure 4.6 Component meshing window in HyperMesh

6. Export FEM to preferred ABAQUS template (*.inp File) as shown in Figure 4.7.

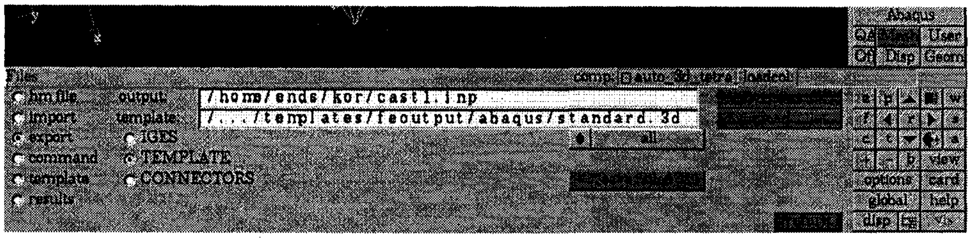


Figure 4.7 File export window in HyperMesh

The final format of the FEM model file is *.INP, the content of the INP file is showed as the Figure 4.8.

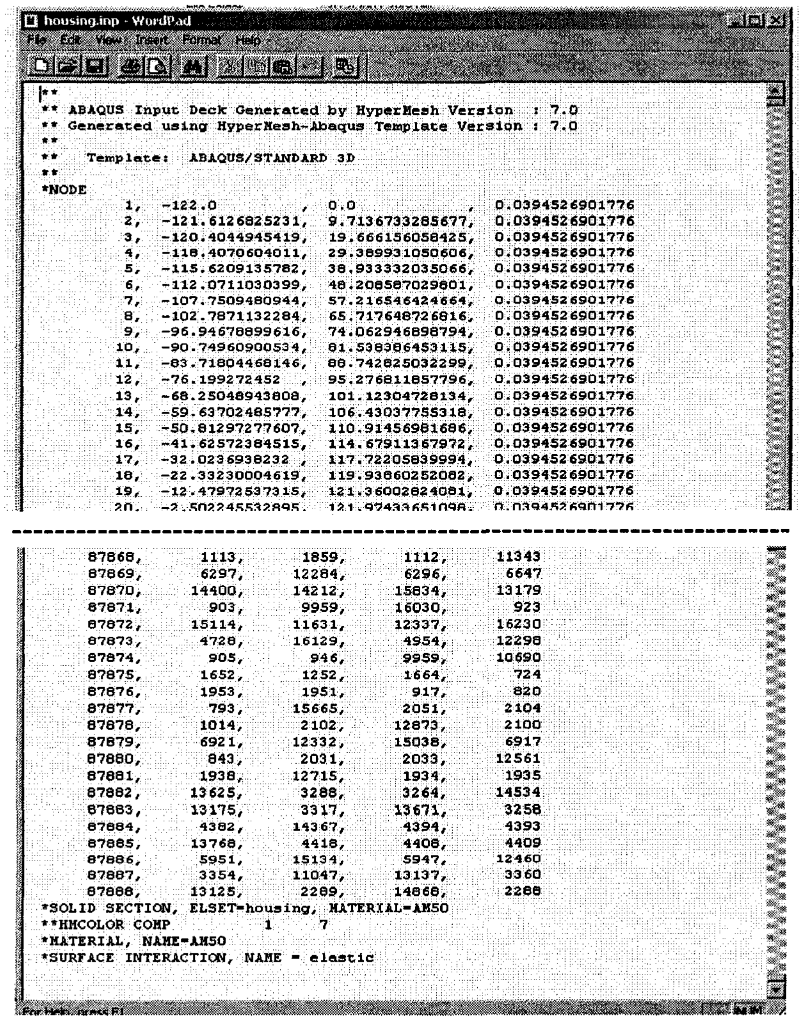


Figure 4.8 Numerical data in INP file exported by HyperMesh

4.2.4 MAGMALink

After simulation completion, MAGMALink is required to export the MAGMASOFT simulation results into text format. Figure 4.9 shows the MAGMALink position during numerical simulation process.

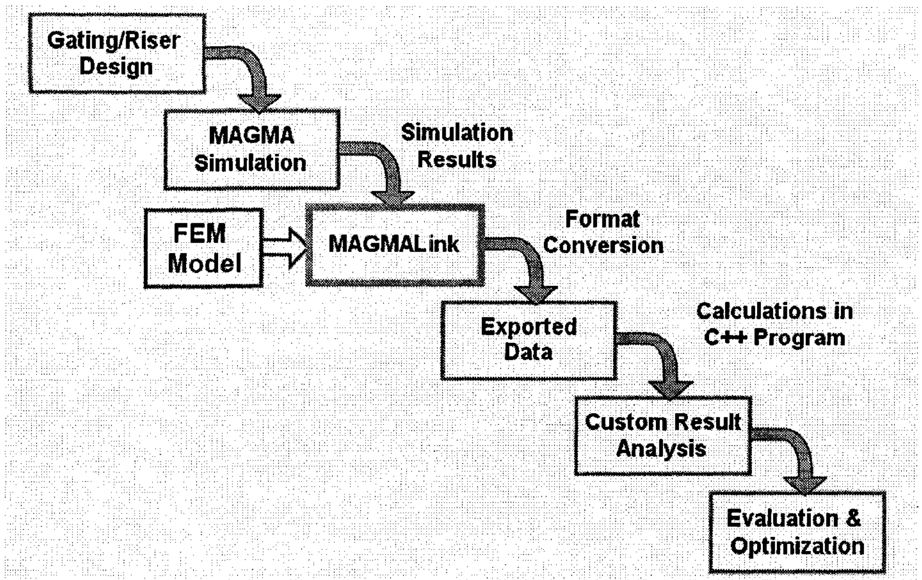


Figure 4.9 MAGMALink in Numerical Simulation Process

The Purpose of MAGMALink is to convert the simulation results into text format for further processing. The functions of MAGMALink are :

- Import FE meshed model into the MAGMA preprocessor (for simulation)
- Export MAGMA simulation results to the FE meshed elements
- Connect with ABAQUS, I-DEAS, PATRAN, ANSYS.

The Progress of MAGMALink execution include:

1. Select matching FE meshed model
2. Define material groups

3. Select desired results

4. Export results

In order to achieve the above functions, several steps have to be followed:

1. A Finite Element Meshed(FEM) model of the casting has to be available (generated from commercial software like ABAQUS, LS-DYNA, HYPERMESH etc.)
2. In the MAGMASOFT GUI, click on Export button.
3. Then select the matching FE meshed model file & select the FEM Input and Output format as shown in Figure 4.10.

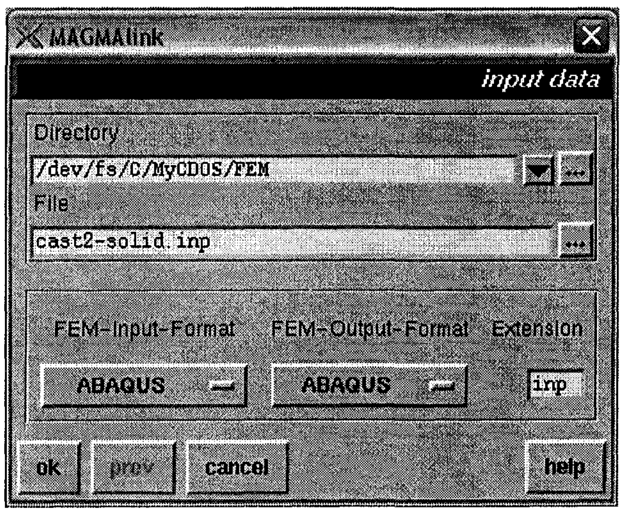


Figure 4.10 FEM model selection window in MAGMALink

4. After a Material Definition window appears, click on the FEM-Material list, then click on Select Data. Select the desired matching data in a Material Definitions window and click OK as shown in Figure 4.11.

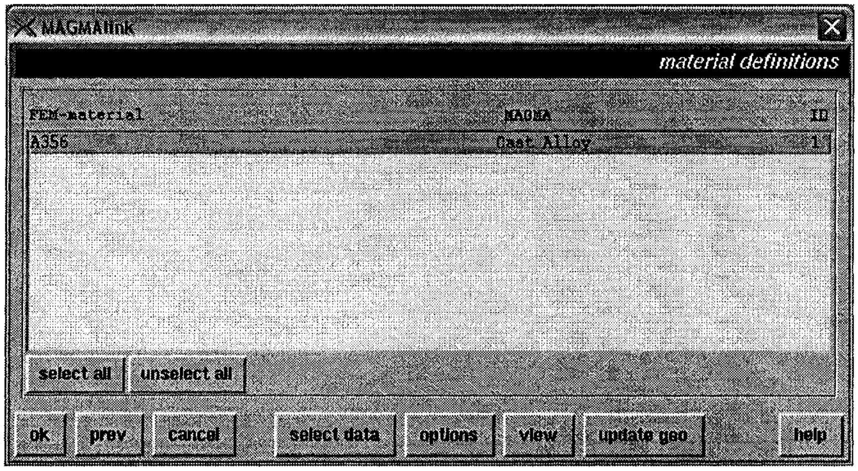


Figure 4.11 Material definition window in MAGMALink

5. Once the MAGMA materials are defined, a result selection window appears as shown in Figure 4.12. The export process can be starts after selecting the desired results.

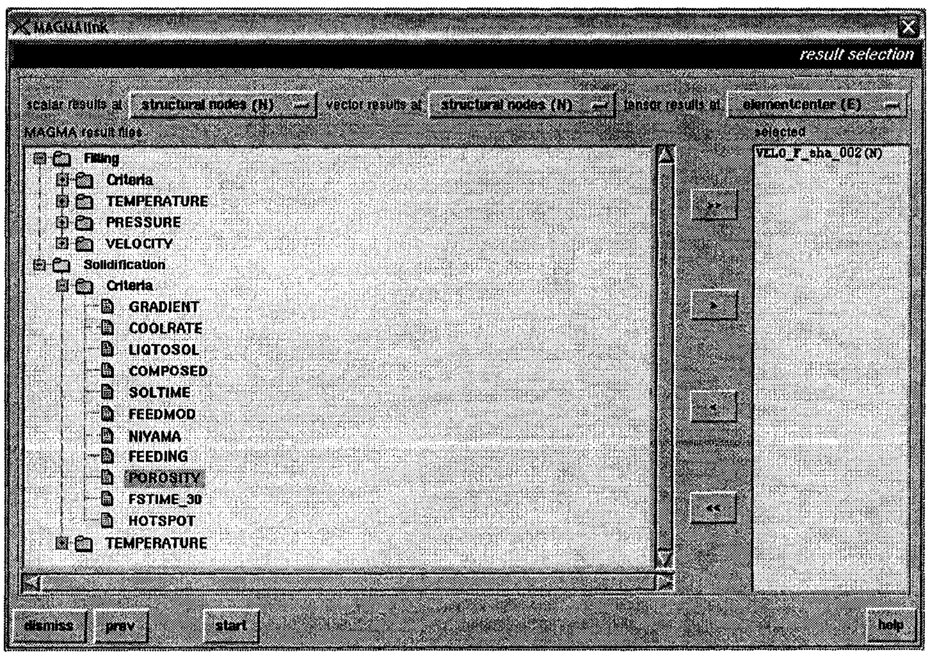


Figure 4.12 Result selection window in MAGMALink

6. A Conversion Process window appears as shown in Figure 4.13 to show the export progress. Once the export process is completed, click on Dismiss to exit the MAGMALink windows.

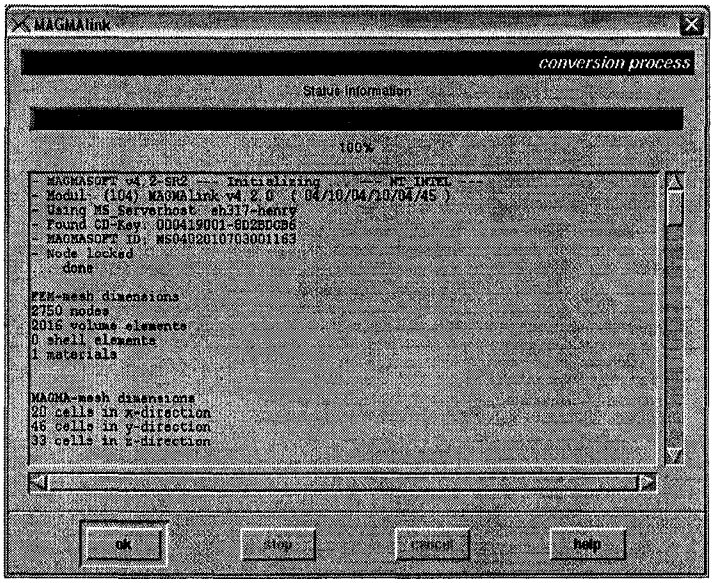


Figure 4.13 Conversion process window in MAGMALink

The C++ programs are developed to automate the interaction of evaluating equations with MAGMA simulation results. The flow chart of the program is shown in Figure 4.14.

The program exports the simulation results into text format using MAGMALink and performs calculations on the exported results. Thereafter the data files are generated for further optimization calculation. A sample of the exported MAGMASOFT porosity and velocity results using MAGMALink for further processing is shown in Figure 4.15.

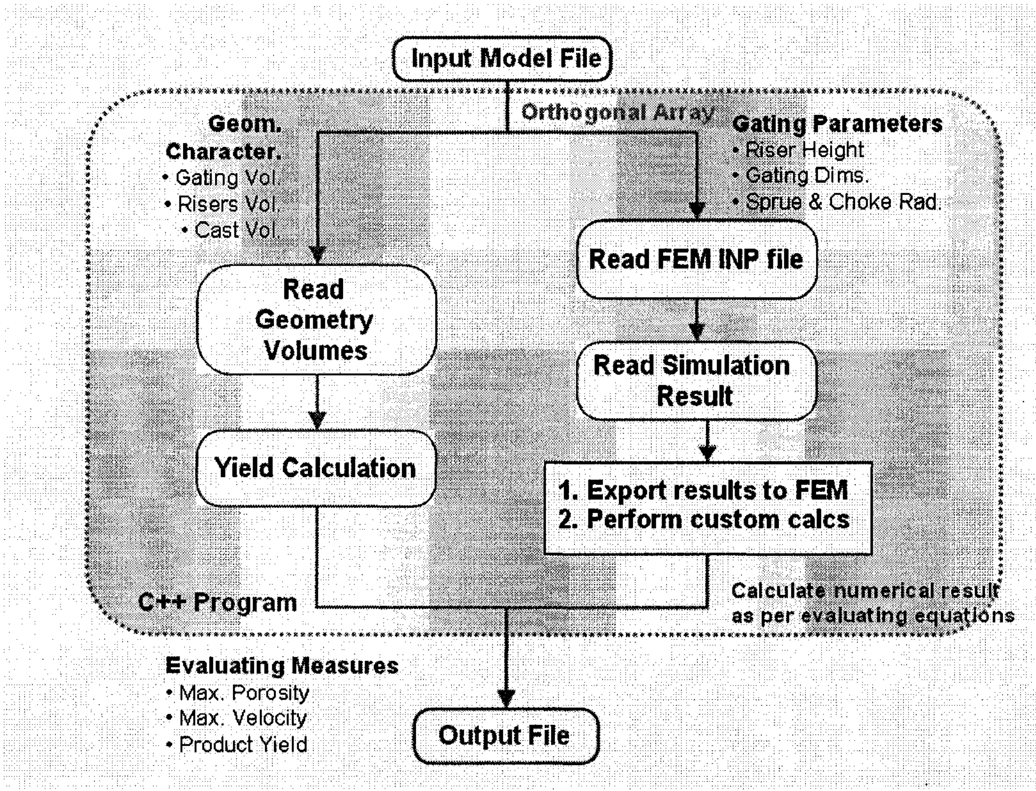


Figure 4.14 Flow chart of the C++ program

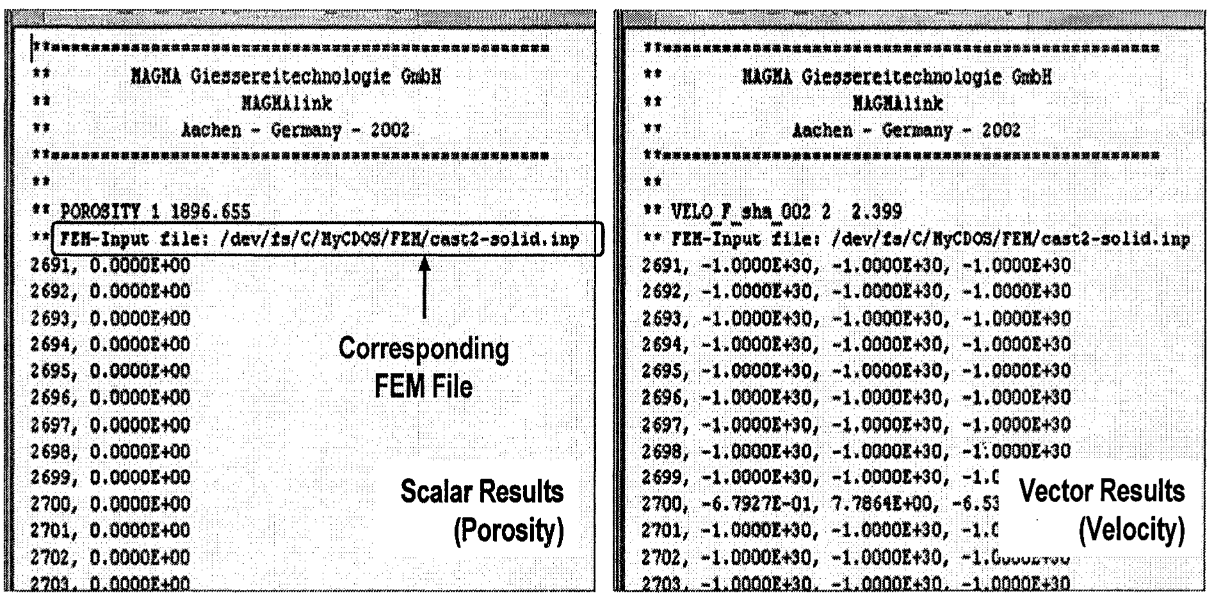


Figure 4.15 Numerical results exported by MAGMALink

The use of MAGMALink requires manual interaction with the user to input a FE model and to select the desired simulation results for export. A FE model is required by MAGMALink to map and export the simulation results to the correspondent meshed elements of the FE model. In exception to MAGMALink, the optimization capability is fully automatically calculated using the Taguchi method.

4.2.5 Exported Data

As per the FEM 3D coordinate node number of the specific area of the casting in this work, the program executes the calculation with cast evaluating equations. The final numerical results(data files) of the casting model are shown as Figures 4.16 to 4.18.

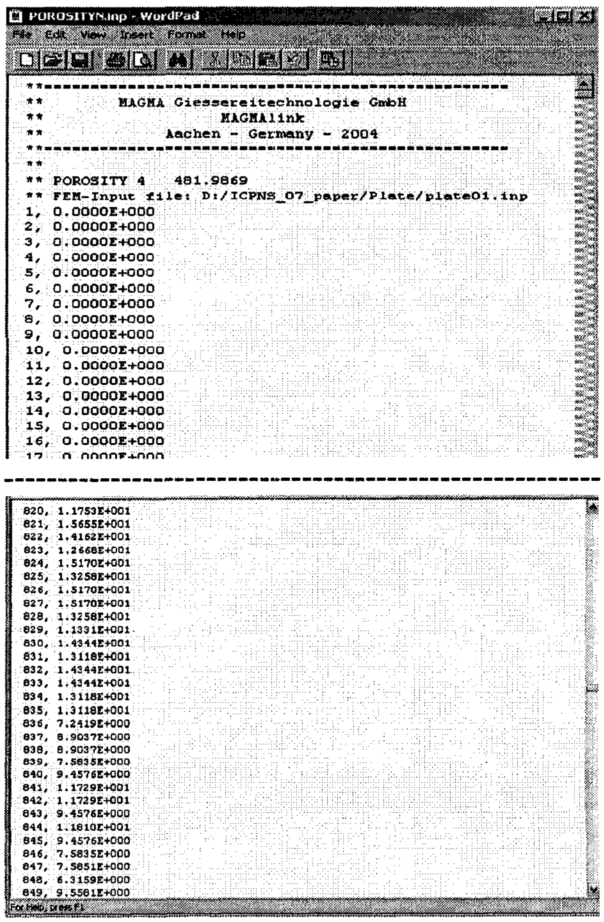
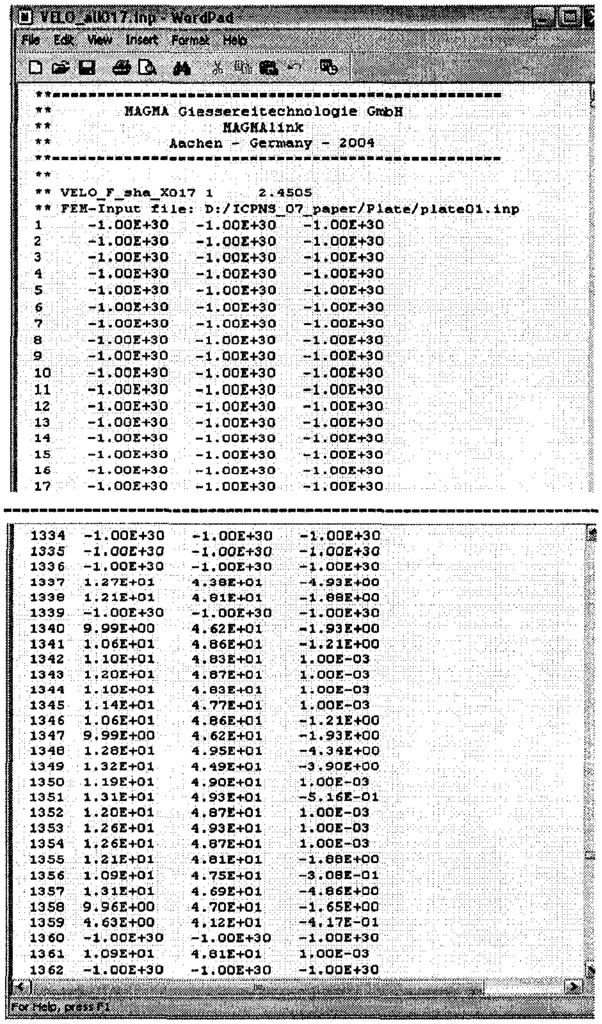
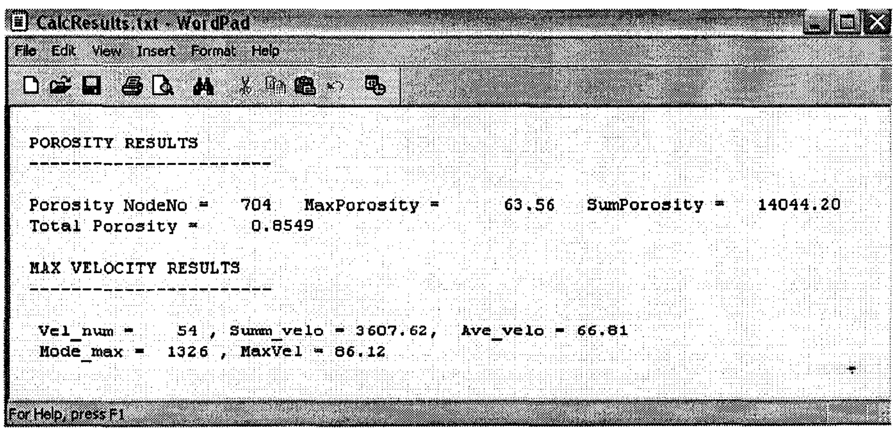


Figure 4.16 Shrinkage porosity result of the plate casting



```
VELO_al017.inp - WordPad
**=====================================================
**          MAGMA Giessereitechnologie GmbH
**                     MAGMAlink
**               Aachen - Germany - 2004
**=====================================================
**
** VELO_F_sha_X017 1       2.4505
** FEM-Input file: D:/ICPNS_07_paper/Plate/plate01.inp
1      -1.00E+30   -1.00E+30   -1.00E+30
2      -1.00E+30   -1.00E+30   -1.00E+30
3      -1.00E+30   -1.00E+30   -1.00E+30
4      -1.00E+30   -1.00E+30   -1.00E+30
5      -1.00E+30   -1.00E+30   -1.00E+30
6      -1.00E+30   -1.00E+30   -1.00E+30
7      -1.00E+30   -1.00E+30   -1.00E+30
8      -1.00E+30   -1.00E+30   -1.00E+30
9      -1.00E+30   -1.00E+30   -1.00E+30
10     -1.00E+30   -1.00E+30   -1.00E+30
11     -1.00E+30   -1.00E+30   -1.00E+30
12     -1.00E+30   -1.00E+30   -1.00E+30
13     -1.00E+30   -1.00E+30   -1.00E+30
14     -1.00E+30   -1.00E+30   -1.00E+30
15     -1.00E+30   -1.00E+30   -1.00E+30
16     -1.00E+30   -1.00E+30   -1.00E+30
17     -1.00E+30   -1.00E+30   -1.00E+30
-------------------------------------------------------
1334  -1.00E+30   -1.00E+30   -1.00E+30
1335  -1.00E+30   -1.00E+30   -1.00E+30
1336  -1.00E+30   -1.00E+30   -1.00E+30
1337  1.27E+01    4.38E+01    -4.93E+00
1338  1.21E+01    4.81E+01    -1.88E+00
1339  -1.00E+30   -1.00E+30   -1.00E+30
1340  9.99E+00    4.62E+01    -1.93E+00
1341  1.06E+01    4.86E+01    -1.21E+00
1342  1.10E+01    4.83E+01    1.00E-03
1343  1.20E+01    4.87E+01    1.00E-03
1344  1.10E+01    4.83E+01    1.00E-03
1345  1.14E+01    4.77E+01    1.00E-03
1346  1.06E+01    4.86E+01    -1.21E+00
1347  9.99E+00    4.62E+01    -1.93E+00
1348  1.28E+01    4.95E+01    -4.34E+00
1349  1.32E+01    4.49E+01    -3.90E+00
1350  1.19E+01    4.90E+01    1.00E-03
1351  1.31E+01    4.93E+01    -5.16E-01
1352  1.20E+01    4.87E+01    1.00E-03
1353  1.26E+01    4.93E+01    1.00E-03
1354  1.26E+01    4.87E+01    1.00E-03
1355  1.21E+01    4.81E+01    -1.88E+00
1356  1.09E+01    4.75E+01    -3.08E-01
1357  1.31E+01    4.69E+01    -4.86E+00
1358  9.96E+00    4.70E+01    -1.65E+00
1359  4.63E+00    4.12E+01    -4.17E-01
1360  -1.00E+30   -1.00E+30   -1.00E+30
1361  1.09E+01    4.81E+01    1.00E-03
1362  -1.00E+30   -1.00E+30   -1.00E+30
For Help, press F1
```

Figure 4.17 Filling velocity result of the plate casting



```
CalcResults.txt - WordPad
POROSITY RESULTS
----------------------

Porosity NodeNo =   704   MaxPorosity =       63.56   SumPorosity =    14044.20
Total Porosity =     0.8549

MAX VELOCITY RESULTS
----------------------

 Vel_num =     54 , Summ_velo = 3607.62,  Ave_velo = 66.81
 Node_max =  1326 , MaxVel = 86.12
For Help, press F1
```

Figure 4.18 Maximum porosity and velocity in the plate casting

4.3 Numerical Optimization Case Study(1)----Plate

4.3.1 Plate model preparation

- ***Plate Casting***: A plate model was used as the test casting to demonstrate the numerical optimization strategy. The three-dimensional CAD model of the test casting is shown in Figure 4.19. The dimension of casting plate model were 18x18x2 cm and the material was defined as A356(AlSi7Mag) for simulation.

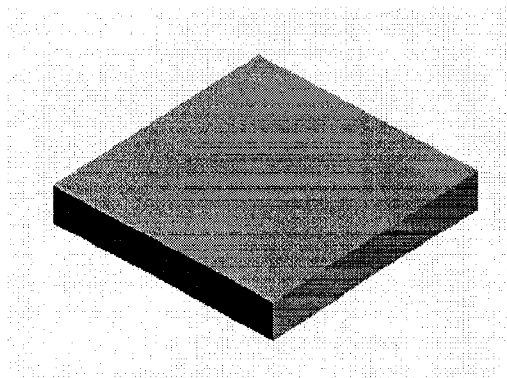


Figure 4.19 3-D model of a plate casting.

- Solid CAD models were created using the Unigraphics NX4.0 of UGS Corp. The STL models of the various gating designs were converted from 3-D models by the assembly method. As shown in Figure 4.20, the plate aluminum model was used as the test sand casting to demonstrate the numerical optimization. The sprue was designed as a tapered column to prevent the gas entrainment. A pouring basin and tapered sprue were used and metal was introduced into the casting cavity through one runner and one ingate located at the center of plate.

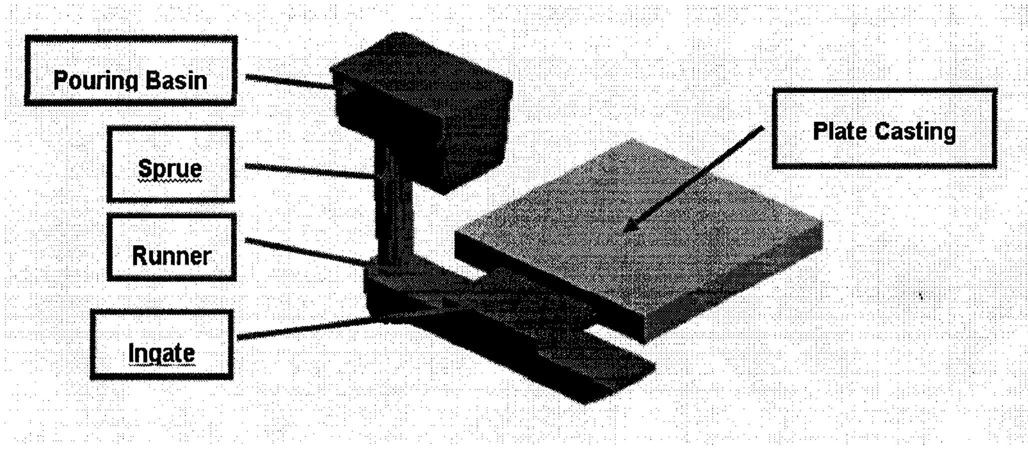


Fig 4.20 3-D model of the full plate casting with the gating system

4.3.2 Gating parameters and levels

Both pressurized and non-pressurized gating designs were applied to the plate casting. The parameter ranges of the four design variables are given in the Table 4-4. Based on the casting design rules in Chapter II and the computational ability, the factors, gating system dimensions, and levels were selected accordingly. In this experiment, 9 sets gating system dimensions were designed using the Taguchi L_9 orthogonal array.

Table 4-4. Gating System Parameters and their levels for plate casting

Level	Factor			
	(A)Chock diameter (mm)	(B)Runner area (mm^2)	(C) Ingate height (mm)	(D) Ingate width (mm)
1	19	702 (39x18)	10	50
2	21	900 (45x20)	15	70
3	23	1104 (46x24)	20	90

Note: The runner area 702 mm^2 = runner width 39mm and runner height 18mm.

4.3.3 Computer Simulation:

Simulation of the mold filling and solidification process requires geometrical models of the casting, the gating system and the sand mould. After the establishment of the full casting models, the whole geometry was enmeshed automatically with about

200,000 elements using Solver 5. The resolution of the meshed model could be refined using a larger number of elements. However, this would lead to an exponential increase in the time required for design analysis. Therefore, the number of elements chosen for this study was of an amount that could sufficiently maintain the mesh quality of the model without causing any error or warning messages during the enmeshment procedure.

The Heat Transfer Coefficient (HTC) was defined as C800. The thermophysical properties of the aluminum alloy A356(AlSi7Mg) was selected from the database of simulation software. The selected initial and boundary conditions for simulation and the chemical composition of Aluminum Alloy A356 are shown in Table 4-5 and 4-6.

Table 4-5. Initial and boundary conditions for simulation for the plate casting

1	**Material definitions (Initial Temperature) [^{0}C]**	**Cast Alloy (A356)**	750
		Mould (Furan)	20
2	**Boundary definitions (Heat Transfer Coefficient) [W/ m^2 K]**	**Casting – Mould**	C800
3	**Filling definitions (pouring time) (s)**	**Use solver 5**	5

Table 4-6. The Chemical composition of aluminum alloy A356

Al Alloy	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Others**
A356	7%	0.12%	0.1%	0.05%	0.4%	0.15%

4.4 Numerical Optimization Case Study(2)----Housing

4.4.1 Housing model preparation

- **Housing Casting**: A cylindrical housing model was used as the test casting to further demonstrate the numerical optimization strategy. The three-dimensional CAD model of the test casting is shown in Figure 4.21. It has an outer radius of 26 cm and 16 cm at the largest and narrowest part, an inner radius of 12 cm and 18 cm at the upper half and bottom part respectively and a height of 24.5 cm. This casting material was defined as magnesium alloy AM50 and AM60B for two sets of simulation runs and the weight of housing casting model was approximately 30 kg.

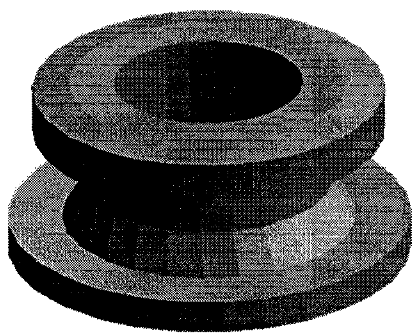


Figure 4.21. 3-D model of a cylindrical housing casting.

- Based on the casting rules summarized in chapter II, for this casting, bottom filling of the mold was employed with the consideration of the Compbell's casting rules. A tapered sprue was used and metal was introduced into the casting cavity through two ingates. Two equal risers were added to the top of the housing model. The detail gating system design were shown in Figures 4.22 and 4.23.

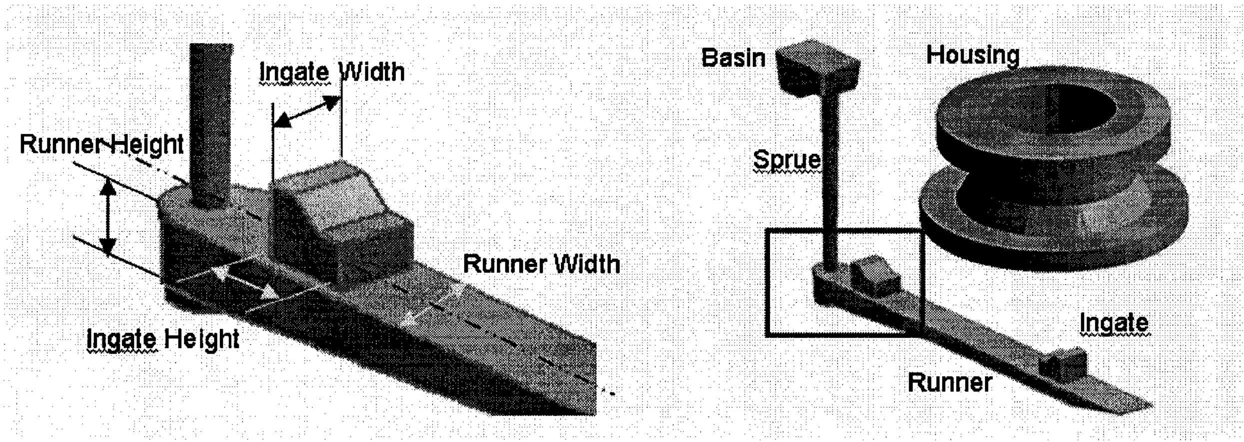
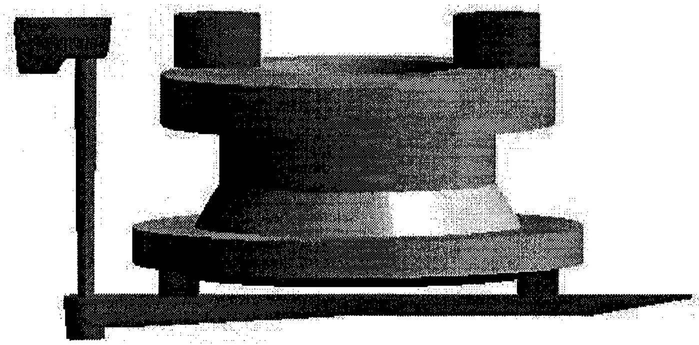


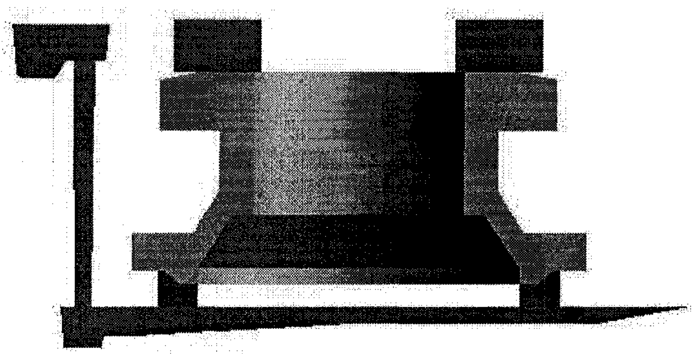
Fig 4.22. 3-D models of the housing sample and the gating system

4.4.2 Gating parameters and levels

In this case study, bottom filling of the mold was employed on the housing casting. A pouring basin and tapered sprue were used and metal was introduced into the casting cavity through one runner and two ingates which were symmetrical to the center line. Two equal risers were added to the top of the housing model. The gating system of housing is controlled by four independent parameters, namely, ingate height, ingate width, runner height, runner width, as showed in Figure 4.22. Changing these parameters can modifying gating system geometry and cross section area separately. Since the lower and wide geometry runner helps reduce the metal velocity and achieve a smooth flow into mold, the parameter ranges of the design variables are given in the Table 4-7. The STL models with the various gating designs were converted from 3-D models by the assembly method. Figure 4.23 shows models of the full housing with gating and riser system for simulation.



(a)



(b)

Figure 4.23 Models of the full housing with gating and riser system for simulation (a) front view, and (b) section view

Table 4-7. Gating System Parameters and their levels for the housing casting

Level	Factor (unit: mm)			
	(A)Ingate height	(B)Ingate width	(C) Runner height	(D) Runner width
1	45	40	30	50
2	50	45	35	55
3	55	50	40	60

4.4.3 Computer Simulation

Simulation of the mold filling and solidification process required geometrical information for the casting, the gating system and the sand mould. Solid CAD models were created using the Unigraphics NX4.0 software of UGS Corp. and converted into STL files. The preprocessor module of simulation software then read the STL files as geometry. Following the establishment of the full casting system, the geometry was enmeshed automatically by the enmeshment module prior to the simulation. The test casting required the enmeshment with about 100,000 elements using Solver 5.

Once the meshed geometries were established, the casting process design parameters, the thermophysical properties of the cast metal along with initial and boundary conditions were defined according to the actual experiment condition. Magnesium alloy AM50 & AM60 was used as the casting material and dry silica was used for the sand mould. The thermophysical properties of the cast magnesium alloy AM50 and AM60B(the test samples) and boundary conditions were selected from the database module of simulation software and are listed in Table 4-8. The chemical composition of magnesium alloys AM50 and AM60B is shown in Table 4-9. With the 3-D post processor module, the fluid flow in the cavity and solidification during the casting process can be analyzed and potential defects will be discussed in the next chapter.

Table 4-8. Initial and boundary conditions for simulation for housing

1	**Material definitions (Initial Temperature) [^{0}C]**	Cast Alloy (AM50) Cast Alloy (AM60B) Mould (Furan)	770 769 20
2	**Boundary definitions (Heat Transfer Coefficient) [W/ m^2 K]**	Casting – Mould	C500
3	**Filling definitions (pouring time) (s)**	Use solver 5	10

Table 4-9. Chemical composition of magnesium alloys AM50 and AM60B (wt.%)

Mg Alloy	**Al**	**Zn**	**Mn**	**Si**	**Others**
AM50	5%	0.4%	<0.01%	<0.01%	<0.01%
AM60B	7%	0.4%	>0.25%	<0.01%	<0.01%

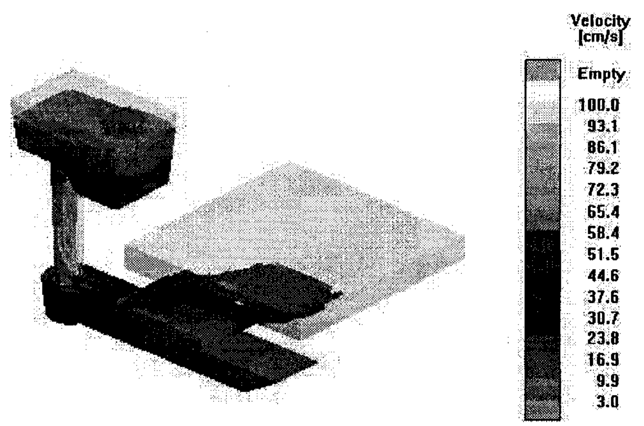
CHAPTER V

RESULTS AND DISCUSSION

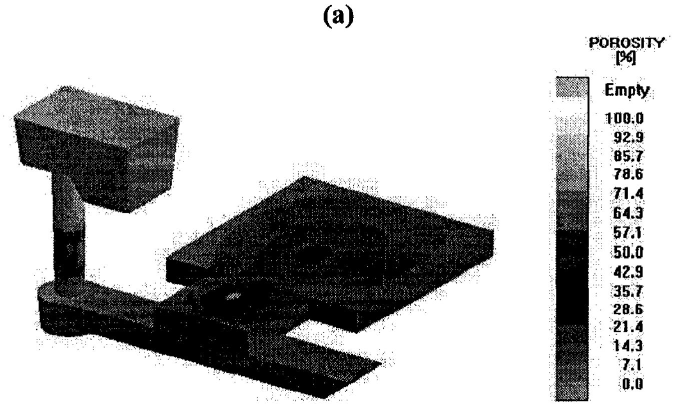
5.1 Aluminum Plate Casting Simulation Result

5.1.1 Graphical Simulation Results

With the 3-D post processor module, the fluid flow in the cavity and solidification during the casting process were analyzed, and potential defects were predicted as shown in Figure 5.1. The 3-D post-processor can only view the fluid flow & temperature field patterns in the cavity during the casting process and predict the potential defects graphically.



(a)



(b)

Figure 5.1 (a)Filling velocity as 48% cavity was filled and (b)shrinkage porosity upon complete solidification for the plate casting

5.1.2 Numerical Simulation

In order to generate the corresponding simulation result data file according to the specific 3D coordinate in the casting model, based on the FEM model node number, MagmaLink module was employed in this study to predict the filling velocity and shrinkage porosity numerically. The numerical simulation results of shrinkage porosity and filling velocity with 9 sets of gating parameters are given in Table 5-1.

Table 5-1. Numerical simulation result for product yield, shrinkage porosity, and filling velocity

Experiment Number	(A) Chock diameter	(B) Runner area	(C) Ingate height	(D) Ingate width	Product Yield (%)	Shrinkage Porosity (%)	Filling Velocity (cm/s)
1	1	1	1	1	67.4588	0.7694	68.32
2	1	2	2	2	61.4934	0.9780	55.03
3	1	3	3	3	55.7556	0.4555	49.28
4	2	1	2	3	62.7665	0.8889	50.95
5	2	2	3	1	61.5043	0.4389	60.81
6	2	3	1	2	60.1098	0.8549	66.81
7	3	1	3	2	62.2813	0.7928	59.42
8	3	2	1	3	61.7362	0.4109	52.5
9	3	3	2	1	59.6646	0.8445	64.32

5.1.3 Multiresponse S/N ratios with different combination of weighting factors

For the multiple performance characteristics, the value of the weighting factor is dependent on the engineering requirement. As shown in Table 5-2, three combinations of weighting factors were selected in this study for the multiresponse S/N ratio calculated from Equations (4) to (6) given in Chapter III. The response of each factor to its individual level was calculated by averaging the S/N ratios of all experiments at each level for each factor. With three combinations of weighting factors, the factor's mean multiresponse S/N ratios for each level are summarized in Table 5-3, respecfively.

Table 5-2. S/N Ratio of objectives and Multiresponse S/N Ratio with three weighting factors (dB).

Experiment number	S/N Ratio (Yield)	S/N Ratio (Porosity)	S/N Ratio (Velocity)	Multiresponse S/N Ratio		
				Case 1 ($\omega_1 = 0.5$, $\omega2 = 0.3$, $\omega3 = 0.2$)	Case 2 ($\omega1 = 0.2$, $\omega2 = 0.6$, $\omega3 = 0.2$)	Case 3 ($\omega1 = 0.1$, $\omega2 = 0.1$, $\omega3 = 0.8$)
1	36.5808	2.2770	-36.6910	11.635	1.344	-25.467
2	35.7766	0.1932	-34.8120	10.984	0.309	-24.253
3	34.9258	6.8302	-33.8534	12.741	4.313	-22.907
4	35.9546	1.0229	-34.1429	11.456	0.976	-23.617
5	35.7781	7.1527	-35.6795	12.899	4.311	-24.251
6	35.5789	1.3617	-36.4968	10.899	0.633	-25.503
7	35.8872	2.0167	-35.4787	11.453	1.292	-24.593
8	35.8108	7.7253	-34.4032	13.342	4.917	-23.169
9	35.5143	1.4680	-36.1669	10.964	0.750	-25.235

Table 5-3. Factor's Mean multiresponse S/N ratio(dB) for each level with three weighting factors.

Level	Mean S/N for Case 1				Mean S/N for Case 2				Mean S/N for Case 3			
	(A)	(B)	(C)	(D)	(A)	(B)	(C)	(D)	(A)	(B)	(C)	(D)
1	11.79	11.51	11.96	11.83	1.99	1.20	2.30	2.14	-24.21	-24.56	-24.71	-24.98
2	11.75	12.41	11.13	11.11	1.97	3.18	0.68	0.74	-24.46	-23.89	-24.37	-24.78
3	11.92	11.53	12.36	12.51	2.32	1.90	3.31	3.40	-24.33	-24.55	-23.92	-23.23

5.1.4 Determination of optimal gating parameters

For case 1, the order of the performance characteristics is the product yield (ω_1 = 0.5), the shrinkage porosity (ω_2 = 0.3), and the filling velocity (ω_3 = 0.2). For case 2, the order of the performance characteristics is the product yield (ω_1 = 0.2), the shrinkage porosity (ω_2 = 0.6), and the filling velocity (ω_3 = 0.2). Finally, for case 3, the order of the performance characteristics is the product yield (ω_1 = 0.1), the shrinkage porosity (ω_2 =

0.1), and the filling velocity (ω_3 = 0.8). Figures 5.2 to 5.4 show the multiresponse S/N ratio for cases 1 to 3, respectively.

The multiresponse S/N ratio for each level of the gating system parameter is calculated based on Equations (4) to (6) given in Chapter III. As discussed in preceding section, regardless of the lower-the-better or the higher-the-better performance characteristics, the larger the multiresponse S/N ratio, the smaller the variance of performance around the objective value.

For case 1 and case 2, the A3B2C3D3 is the maximum multiresponse S/N ratio. The section area ratio of sprue to runner to ingate of optimal gating system is As:Ar:Ag = 1:2.17:4.33. For case 3, the A1B2C3D3 is the maximum multiresponse S/N ratio. The optimal gating system section ratio for case 3 is As:Ar:Ag = 1:3.18:6.36 with a relatively small chock area which could lower the ingate filling velocity.

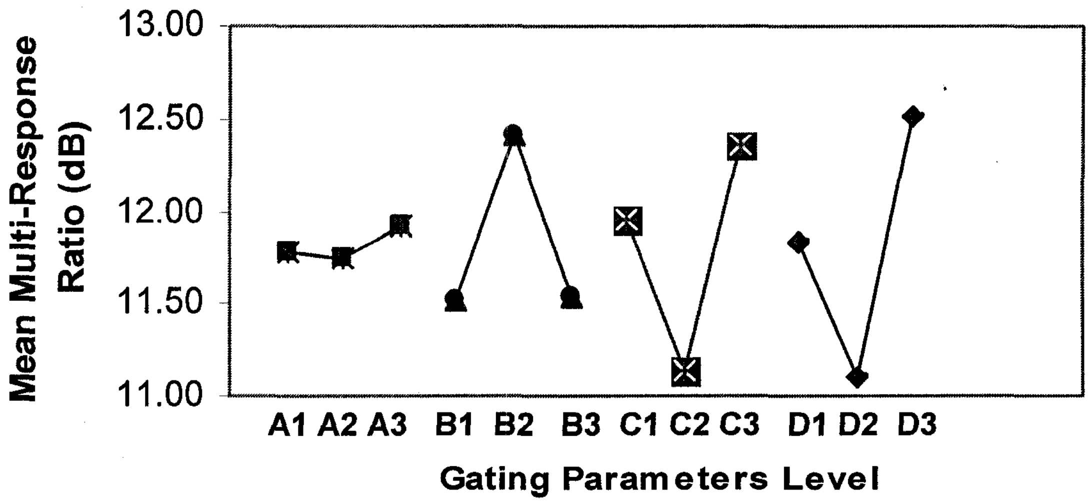


Figure 5.2. Multiresponse signal-to-noise graph for case 1(ω_1 = 0.5, ω_2 = 0.3, ω_3 = 0.2)

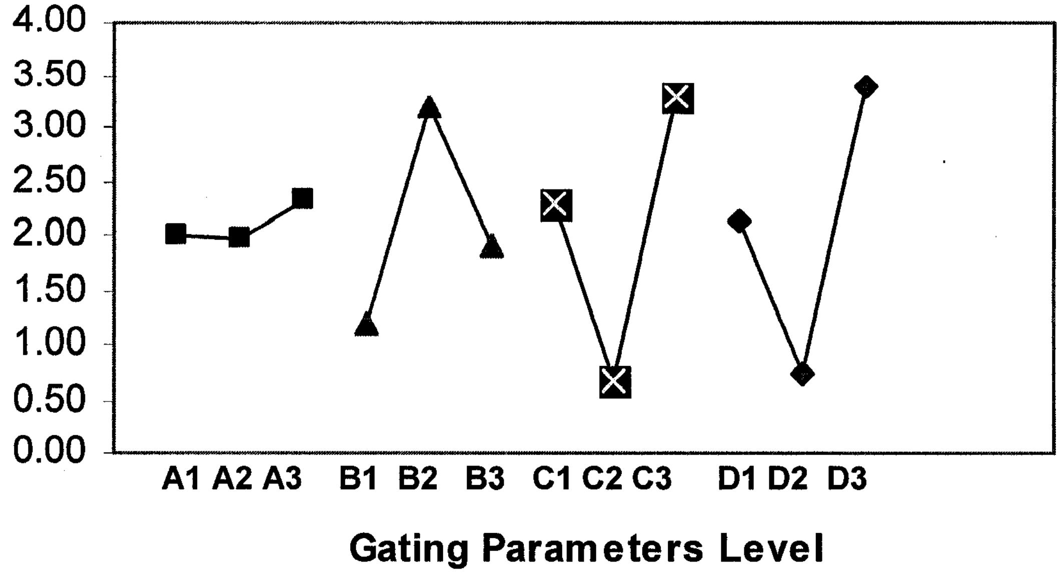


Figure 5.3. Multiresponse signal-to-noise graph for case 2 ($\omega_1 = 0.2$, $\omega_2 = 0.6$, $\omega_3 = 0.2$)

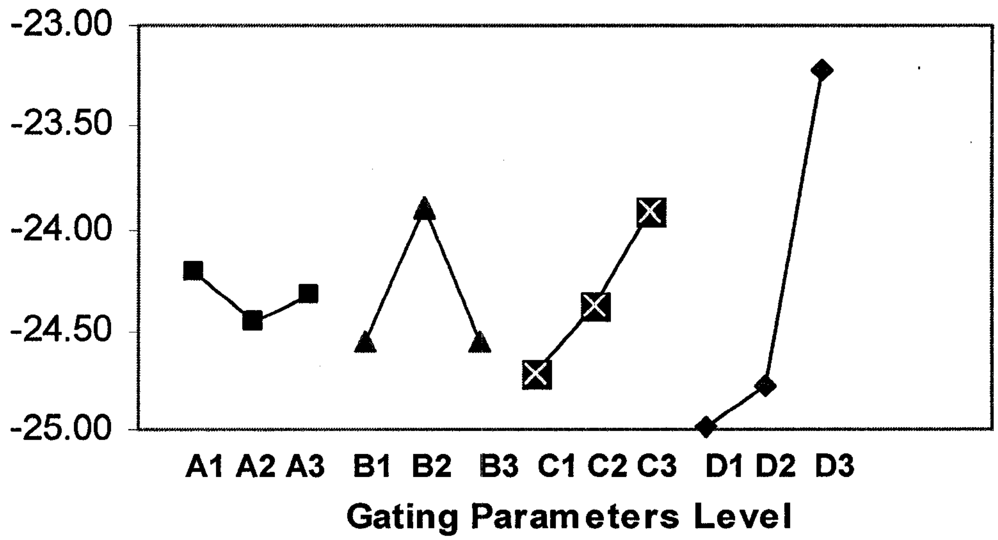


Figure 5.4. Multiresponse signal-to-noise graph for case 3 ($\omega_1 = 0.1$, $\omega_2 = 0.1$, $\omega_3 = 0.8$)

5.1.5 Factor contributions with different combination of weighting factors

The contribution of each gating parameter to the quality objectives with the multiple characteristics is determined by performing analysis of variance based on Equations 7 to 11 given in Chapter III. Tables 5-4 to 5-6 show the results of ANOVA for cases 1 to 3, respectively. From cases 1 to 3, the contribution of ingate width and ingate height is 76.7%,77.18% and 86.96% respectively. It is evident that the sprue choke diameters have insignificant effects on the three cases quality objectives and the ingate width has the major influence on cases 1 and 3.

5.1.6 Confirmation experiment

The confirmation experiment is the final step in verifying the conclusions from the previous round of experimentation. The estimated S/N ratio (η_{opt}) using the optimal level of gating parameters was calculated by Equation (17):

$$\eta_{opt} = \eta_{tm} + \sum_{j=1}^{n} (\eta_{om} - \eta_{tm}) \tag{17}$$

where η_{tm} is total mean of the multiresponse S/N ratio, η_{om} is mean of the multiresponse S/N ratio at the optimal level, and n is the number of the main design parameters that affect the quality characteristics. Tables 5-7 to 5-9 list the confirmation experiments using the optimal gating parameters of case 1 to case 3.

As presented in Table 5-7, the increase of the multiresponse S/N ratio from the initial gating parameters to the optimal gating parameters is 1.593 dB. Although the product yield has decreased by 14.36%, the shrinkage porosity is decreased by 49.36% and the filling velocity is decreased by 24.69%. For the case 2, the increase of the multiresponse S/N ratio from the initial gating parameters to the optimal gating parameters is 3.77 dB as given in Table 5-8. For the case 3, the increase of the multiresponse S/N ratio from the initial gating parameters to the optimal gating parameters is 3.03 dB. As shown in Table 5-9, the product yield has decreased by 13.75%, the shrinkage porosity is decreased by 44.62% and the filling velocity is decreased by 31.66%.

Table 5-4. Results of the ANOVA for case 1 ($\omega_1 = 0.5$, $\omega_2 = 0.3$, $\omega_3 = 0.2$).

Symbol	Gating Parameters	Degree of freedom(D)	Sum of squares (SS)	Variance (V)	Corrected sums of squares (SS')	Contribution (P, %)	Rank
A	Choke_Dia	2	0.0474	0.0237	0.0474	0.7	4
B	Runner_Area	2	1.5627	0.7813	1.5627	22.6	3
C	Ingate_height	2	2.3563	1.1781	2.3563	34.1	2
D	Ingate_width	2	2.9463	1.4731	2.9463	42.6	1
Error			0.0000	0		0	
Total			6.9127			100	

Table 5-5 Results of the ANOVA for case 2 ($\omega_1 = 0.2$, $\omega_2 = 0.6$, $\omega_3 = 0.2$).

Symbol	Gating Parameters	Degree of freedom(D)	Sum of squares (SS)	Variance (V)	Corrected sums of squares (SS')	Contribution (P, %)	Rank
A	Choke_Dia	2	0.2295	0.1147	0.2295	0.84	4
B	Runner_Area	2	6.0221	3.011	6.0221	21.99	3
C	Ingate_height	2	10.5378	5.2689	10.5378	38.48	2
D	Ingate_width	2	10.5982	5.2981	10.5982	38.70	1
Error			0.0000	0		0	
Total			27.3876			100	

Table 5-6. Results of the ANOVA for case 3 ($\omega_1 = 0.1$, $\omega_2 = 0.1$, $\omega_3 = 0.8$).

Symbol	Gating Parameters	Degree of freedom(D)	Sum of squares (SS)	Variance (V)	Corrected sums of squares (SS')	Contribution (P, %)	Rank
A	Choke_Dia	2	0.0922	0.0461	0.0922	1.24	4
B	Runner_Area	2	0.8792	0.4396	0.8792	11.80	3
C	Ingate_height	2	0.9570	0.4785	0.9570	12.84	2
D	Ingate_width	2	5.5236	2.7618	5.5236	74.12	1
Error			0.0000	0		0	
Total			7.4520			100	

Table 5-7. Results of the confirmation experiment for case 1 ($\omega_1 = 0.5$, $\omega_2 = 0.3$, $\omega_3 = 0.2$).

	Initial Gating Parameters	Optimal Gating Parameters	
		Prediction	Experiment
Level	A1B1C1D1	A3B2C3D3	A3B2C3D3
Product Yield (%)	67.46		57.77
Shrinkage Porosity (%)	0.7694		0.3896
Filling Velocity (cm/s)	68.32		51.45
Multiresponse S/N Ratio (dB)	11.635	13.74	13.228
Improved multiresponse S/N ratio (dB)			1.593

Table 5-8. Results of the confirmation experiment for case 2 ($\omega_1 = 0.2$, $\omega_2 = 0.6$, $\omega_3 = 0.2$).

	Initial Gating Parameters	Optimal Gating Parameters	
		Prediction	Experiment
Level	A1B1C1D1	A3B2C3D3	A3B2C3D3
Product Yield (%)	67.46		57.77
Shrinkage Porosity (%)	0.7694		0.3896
Filling Velocity (cm/s)	68.32		51.45
Multiresponse S/N Ratio (dB)	1.344	5.92	5.114
Improved multiresponse S/N ratio (dB)			3.77

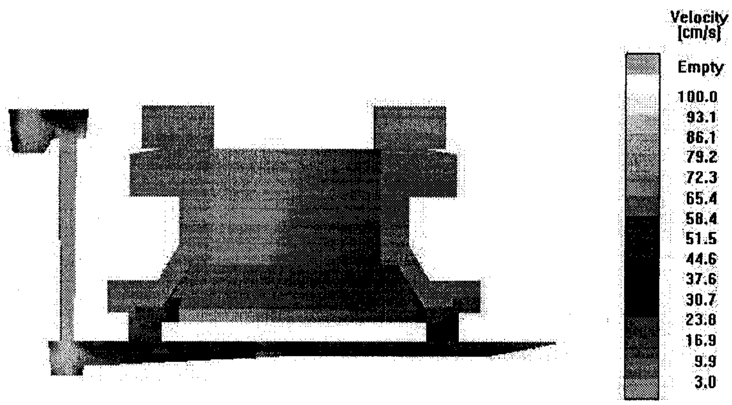
Table 5-9. Results of the confirmation experiment for case3 ($\omega_1 = 0.1$, $\omega_2 = 0.1$, $\omega_3 = 0.8$).

	Initial Gating Parameters	Optimal Gating Parameters	
		Prediction	Experiment
Level	A1B1C1D1	A1B2C3D3	A1B2C3D3
Product Yield (%)	67.46		58.18
Shrinkage Porosity (%)	0.7694		0.4261
Filling Velocity (cm/s)	68.32		46.69
Multiresponse S/N Ratio (dB)	-25.467	-22.37	-22.437
Improved multiresponse S/N ratio (dB)			3.03

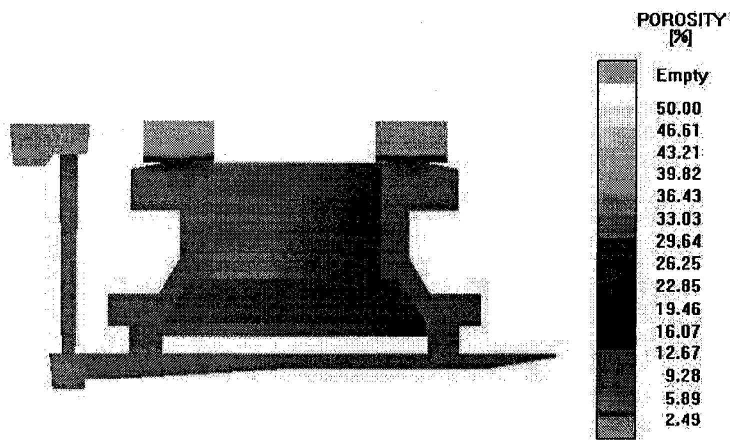
5.2 Magnesium Housing Casting Simulation Result

5.2.1 Graphical Simulation

After executing simulation program, with the 3-D post processor module, the fluid flow in the cavity and solidification during the casting process were analyzed and potential defects were predicted as shown in Figure 5.5. The 3-D post-processor allows to visualize the fluid flow & temperature field patterns in the cavity during the casting process and predict the potential defects graphically.



(a)



(b)

Figure 5.5. (a) Filling velocity as 10% cavity is filled, and
(b) shrinkage porosity upon complete solidification for housing

5.2.2 Numerical Simulation

In order to generate the corresponding simulation result data file according to the specific 3D coordinate in the casting model, based on the FEM model node number, MagmaLink module was utilized to output the computed filling velocity and shrinkage porosity profiles numerically. The numerical simulation results of shrinkage porosity and filling velocity with 9 sets of gating parameters are given in Table 5-10, including the 9 sets of product yield calculated by Equation (13) in Chapter III.

Table 5-10. Numerical simulation result for product yield, shrinkage porosity, and filling velocity

Experiment Number	Product Yield (%)	Shrinkage Porosity (%)		Filling Velocity (cm/s)	
		(AM50)	(AM60B)	(AM50)	(AM60B)
1	88.4858	0.0798	0.1454	103.5	90.26
2	87.5994	0.0650	0.0972	46.57	48.33
3	86.6763	0.0504	0.0864	45.04	45.65
4	87.1393	0.0709	0.1007	48.01	49.01
5	87.7218	0.0584	0.125	56.89	66.02
6	87.7995	0.0411	0.0828	48.76	48.08
7	87.1987	0.0393	0.0668	42.02	42.92
8	87.3774	0.1568	0.2918	43.32	43.68
9	87.8704	0.0944	0.1384	44.38	54.27

5.2.3 Multiresponse S/N ratios with different combination of weighting factors

Based on the simulation results from Table 5-10, three combinations of weighting factors were selected for the multiresponse S/N ratios of the housing casting calculated from Equations (4) to (6) in Chapter III. The calculated multiresponse S/N ratios are presented in Table 5-11. The response of each factor to its individual level was calculated by averaging the S/N ratios of all experiments at each level for each factor. With three combinations of weighting factors, the factor's mean multiresponse S/N ratios for each level are summarized in Table 5-12.

Table 5-11. S/N Ratio of objectives and Multiresponse S/N Ratio with three weighting factors (dB).

Experiment number	S/N Ratio (Yield)	S/N Ratio (Porosity)	S/N Ratio (Velocity)	Multiresponse S/N Ratio		
				Case 1 $\omega_1 = 0.5$, $\omega_2 = 0.2$, $\omega_3 = 0.3$	**Case 2** $\omega_1 = 0.3$, $\omega_2 = 0.5$, $\omega_3 = 0.2$	**Case 3** $\omega_1 = 0.1$, $\omega_2 = 0.2$, $\omega_3 = 0.7$
1	38.9375	18.6155	-39.7449	11.268	13.040	-20.205
2	38.8500	21.6517	-33.5262	13.697	15.776	-15.253
3	38.7580	23.0081	-33.1308	14.041	16.505	-14.714
4	38.8043	21.2012	-33.7171	13.527	15.498	-15.481
5	38.8621	20.2146	-35.7950	12.735	14.607	-17.127
6	38.8698	23.6932	-33.7007	14.063	16.767	-14.965
7	38.8102	25.2239	-32.5621	14.681	17.743	-13.868
8	38.8280	12.6069	-32.7699	12.104	11.398	-16.535
9	38.8768	18.5285	-33.9048	12.973	14.146	-16.140

Table 5-12. Factor's Mean multiresponse S/N ratio(dB) for each level with three weighting factors.

Level	Mean S/N for Case 1(523)				Mean S/N for Case 2(352)				Mean S/N for Case 3(127)			
	Ingate width	Ingate height	Runer width	Runer height	Ingate width	Ingate height	Runer width	Runer height	Ingate width	Ingate height	Runer width	Runer height
1	13.00	13.16	12.48	12.33	15.11	15.43	13.74	13.93	16.72	16.52	17.23	17.82
2	13.44	12.85	13.40	14.15	15.62	13.93	15.14	16.76	15.86	16.31	15.62	14.70
3	13.25	13.69	13.82	13.22	14.43	15.81	16.28	14.47	15.51	15.27	15.24	15.58

5.2.4 Optimal gating systems for different combination of weighting factors

For case 1, the order of the performance characteristics is the product yield (ω_1 = 0.5), the shrinkage porosity (ω_2 = 0.2), and the filling velocity (ω_3 = 0.3). For case 2, the weighting factors for the product yield , the shrinkage porosity , and the filling velocity are 0.3,0.5 and 0.2, respectively. Finally, for case 3 with great consideration given to casting quality, the order of the performance characteristics becomes the product yield (ω_1 = 0.1), the shrinkage porosity (ω_2 = 0.2), and the filling velocity (ω_3 = 0.7).

Figures 5.6 to 5.8 show the multiresponse S/N ratio for case 1 to 3, respectively. The multiresponse S/N ratio for each level of the gating system parameter is calculated from Equations (4) to (6) in Chapter III. As discussed in Chapter III, regardless of the lower-the-better or the higher-the-better performance characteristics, the larger the multiresponse S/N ratio, the smaller the variance of performance around the objective value is. For cases 1 and 2, the A2B3C3D2 is the maximum multiresponse S/N ratio. For case 3, the A3B3C3D2 is the maximum multiresponse S/N ratio. The large ingate width (A3) tends to reduce the ingate filling velocity characteristic which has the largest weighting factor(70%) for the multiple performance characteristics of case 3.

However, the relative important factor among the gating parameters for the multiple performance characteristics still need to be investigated by using the analysis of variance (ANOVA) method which can take into account the factor contribution somewhat accurately.

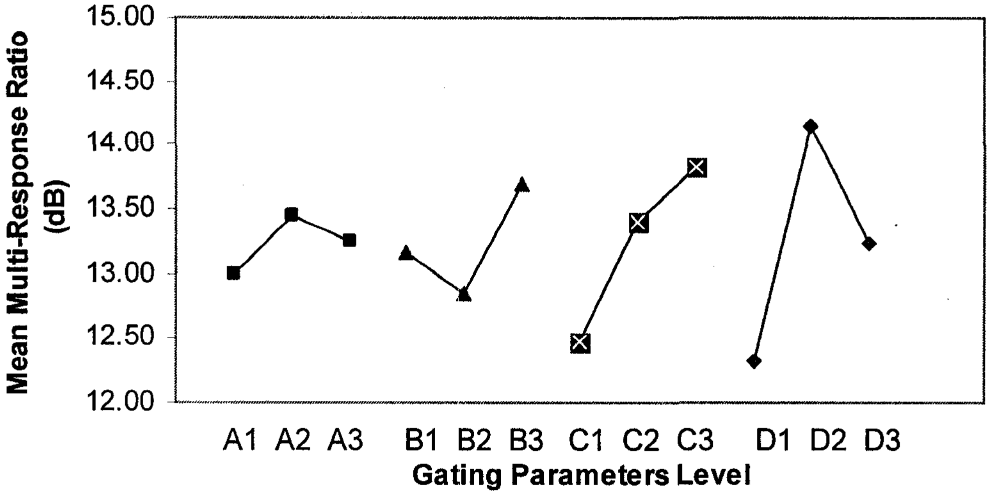


Figure 5.6. Multiresponse signal-to-noise graph for case 1($\omega_1 = 0.5$, $\omega_2 = 0.2$, $\omega_3 = 0.3$).

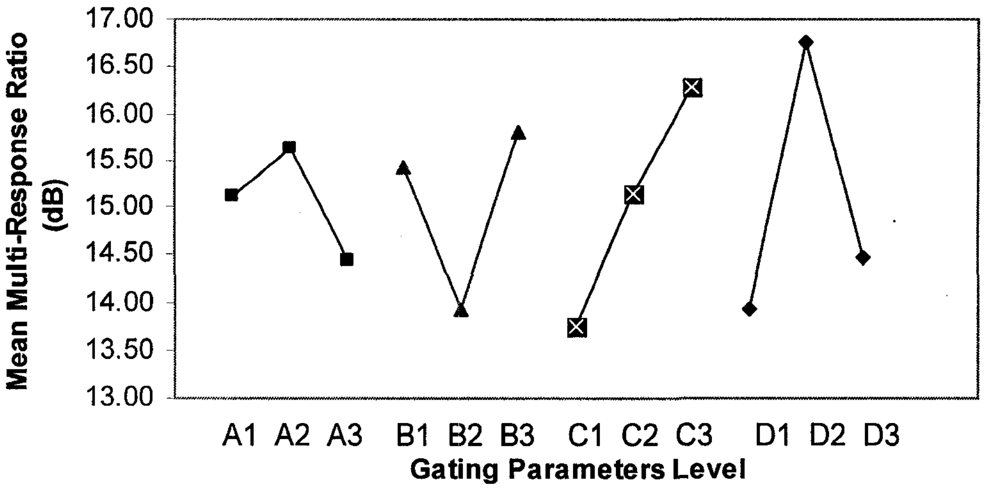


Figure 5.7. Multiresponse signal-to-noise graph for case 2 ($\omega_1 = 0.3$, $\omega_2 = 0.5$, $\omega_3 = 0.2$).

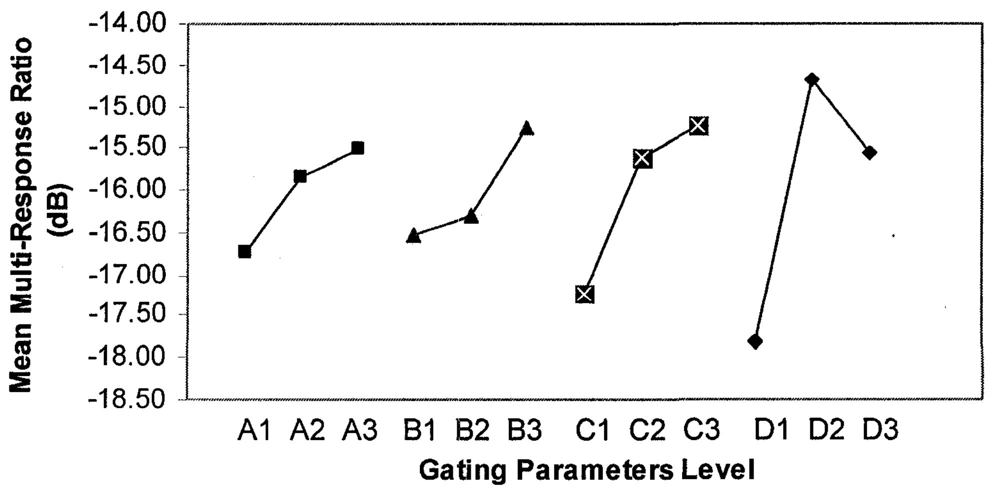


Figure 5.8. Multiresponse signal-to-noise graph for case 3 ($\omega_1 = 0.1$, $\omega_2 = 0.2$, $\omega_3 = 0.7$).

5.2.5 Factor contributions with different combination of weighting factors

The contribution of each gating parameter to the objectives with the multiple characteristics can be determined by performing analysis of variance based on Equations (7) to (11) in Chapter III.

Tables 5-13 to 5-15 summarized the results of ANOVA for case 1, 2 and 3, respectively. It can be found that the contributions of runner height and runner width are greater than other two ingate factors. Based on this housing gating system design, it is evident that the runner height has the major influence on the casting quality objectives.

The sequence of the four factors affecting the casting quality is the runner height, the runner width, the ingate height, and the ingate width. For case 1 and case 3, the contribution of two runner parameters is more than 80%. Therefore, the ingate parameters have insignificant effects on the three quality objectives.

5.2.6 Confirmation experiment

The confirmation experiment is the final step in verifying the conclusions from the previous round of experimentation. The estimated S/N ratio η_{opt} using the optimal level of gating parameters can be calculated by Equation (17). The detailed results of the confirmation experiment using the optimal gating parameters of cases 1, 2 and 3 are presented in Tables 5-16 to 5-18.

Table 5-13. Results of the ANOVA for case 1 ($\omega_1 = 0.5$, $\omega_2 = 0.2$, $\omega_3 = 0.3$).

Symbol	Gating Parameters	Degree of freedom(D)	Sum of squares (SS_p)	Variance (V_p)	Corrected sums of squares (SS'_p)	Contribution (P_p, %)	Rank
A	Ingate_wid	2	0.2918	0.1459	0.2918	3.17	4
B	Ingate_hgt	2	1.0996	0.5498	1.0996	11.96	3
C	Runn_wid	2	2.8212	1.4106	2.8212	30.69	2
D	Runn_hgt	2	4.9789	2.4895	4.9789	54.17	1
Error			0.0000	0		0	
Total			9.1915			100	

Table 5-14. Results of the ANOVA for case 2 ($\omega_1 = 0.3$, $\omega_2 = 0.5$, $\omega_3 = 0.2$).

Symbol	Gating Parameters	Degree of freedom(D)	Sum of squares (SS_p)	Variance (V_p)	Corrected sums of squares (SS'_p)	Contribution (P_p, %)	Rank
A	Ingate_wid	2	2.1561	1.07805	2.1561	6.86	4
B	Ingate_hgt	2	5.9271	2.96355	5.9271	18.85	3
C	Runn_wid	2	9.7865	4.89325	9.7865	31.13	2
D	Runn_hgt	2	13.5660	6.783	13.5660	43.15	1
Error			0.0000	0		0	
Total			31.4357			100	

Table 5-15. Results of the ANOVA for case 3 ($\omega_1 = 0.1$, $\omega_2 = 0.2$, $\omega_3 = 0.7$).

Symbol	Gating Parameters	Degree of freedom(D)	Sum of squares (SS_p)	Variance (V_p)	Corrected sums of squares (SS'_p)	Contribution (P_p, %)	Rank
A	Ingate_wid	2	2.3318	1.1659	2.3318	8.53	4
B	Ingate_hgt	2	2.6601	1.33005	2.6601	9.73	3
C	Runn_wid	2	6.7362	3.3681	6.7362	24.63	2
D	Runn_hgt	2	15.6166	7.8083	15.6166	57.11	1
Error			0.0000	0		0	
Total			27.3447			100	

Table 5-16. Results of the confirmation experiment for case 1

($\omega_1 = 0.5$, $\omega_2 = 0.2$, $\omega_3 = 0.3$).

	Initial Gating Parameters	Optimal Gating Parameters	
		Prediction	Experiment
Level	A1B1C1D1	A2B3C3D2	A2B3C3D2
Product Yield (%)	88.49		87.10
Shrinkage Porosity (%)	0.1126		0.0489
Filling Velocity (cm/s)	96.88		40.64
Multiresponse S/N Ratio (dB)	11.27	14.79	14.93
Improved multiresponse S/N ratio (dB)			3.66

Table 5-17. Results of the confirmation experiment for case 2

($\omega_1 = 0.3$, $\omega_2 = 0.5$, $\omega_3 = 0.2$).

	Initial Gating Parameters	Optimal Gating Parameters	
		Prediction	Experiment
Level	A1B1C1D1	A2B3C3D2	A2B3C3D2
Product Yield (%)	88.49		87.10
Shrinkage Porosity (%)	0.1126		0.0489
Filling Velocity (cm/s)	96.88		40.64
Multiresponse S/N Ratio (dB)	13.04	16.98	18.18
Improved multiresponse S/N ratio (dB)			5.14

Table 5-18. Results of the confirmation experiment for case3

($\omega_1 = 0.1$, $\omega_2 = 0.2$, $\omega_3 = 0.7$).

	Initial Gating Parameters	Optimal Gating Parameters	
		Prediction	Experiment
Level	A1B1C1D1	A3B3C3D2	A3B3C3D2
Product Yield (%)	88.49		87.02
Shrinkage Porosity (%)	0.1126		0.077
Filling Velocity (cm/s)	96.88		35.21
Multiresponse S/N Ratio (dB)	-20.21	-13.01	-13.35
Improved multiresponse S/N ratio (dB)			6.86

Table 5-16 shows the increase of the multiresponse S/N ratio from the initial gating parameters to the optimal gating parameters is 3.66 dB. Despite that the product yield has decreased by 1.57%, the shrinkage porosity is decreased by 56.57% and the filling velocity is decreased by 58.05%. For the case 2, the increase of the multiresponse S/N ratio from the initial gating parameters to the optimal gating parameters is 5.14 dB as presented in Table 5-17. For the case 3, the increase of the multiresponse S/N ratio from the initial gating parameters to the optimal gating parameters is 6.86 dB. The product yield has decreased by 1.66%, the shrinkage porosity is decreased by 31.62% and the filling velocity is decreased by 63.66% as listed in Table 5-18.

CHAPTER VI
CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

This study has presented an application of the gating system parameter optimization design using the Taguchi method in combination with advanced numerical simulation. The Taguchi method with multiple performance characteristics has been demonstrated for obtaining a set of optimal gating system parameters based on the defined objectives. The following conclusions can be drawn based on the experimental results of this study:

1. Taguchi's orthogonal array provides a suitable and efficient methodology for the optimization of gating system parameters.
2. The multiple performance characteristics such as product yield, shrinkage porosity, and filling velocity can be simultaneously considered and improved through this optimization technique.
3. For case 1 and case 2 of the magnesium housing casting, the combination of A2B3C3D2 is the optimal gating design with the maximum multiresponse S/N ratio. For case 3, the A3B3C3D2 is the optimum level with the maximum multiresponse S/N ratio.
4. For all three study cases of the magnesium housing casting, the sequence of the four factors affecting the casting quality is the runner height, the runner width, the ingate height, and the ingate width. The runner height is the most significant factor which influences the casting quality.

5. For case 1 and case 2 of the aluminum plate casting, the A3B2C3D3 are the optimum levels with the maximum multiresponse S/N ratio. For case 3 of magnesium housing casting, the combination of A1B2C3D3 gives the optimal gating design with the maximum multiresponse S/N ratio.
6. In all three cases of aluminum plate casting, the sequence of the four factors affecting the casting quality is the ingate width, the ingate height, the runner section area, and the sprue choke diameter. The ingate width is the most significant factor which affects the casting quality.
7. With the different casting quality evaluating criteria, the gating system optimal parameters are changed with the combinations of weighting factors. The optimal parameters for the gating system also varied with different weighing factors from case to case, in which factors and evaluating objective functions should be defined based on the real engineering requirement.

6.2 Suggestions for future work

To obtain the optimal casting design, the key point is improving the speed and robustness of the process. Some of the potential future works are proposed as follows:

- After the Taguchi method was successfully tested on light metal sand casting applications, the next step is to apply it on other casting processes such as die casting with other casting alloys.
- The technique should be applied to complicated castings incorporating with additional design variables to further validate its effectiveness. Despite of complication of computation, the effort will be worthwhile being made if design

enhancement is achieved. The complicated Orthogonal Array should be applied when designing the experiments for complicated castings.

- To improve the effectiveness of the optimization process, the valuating criteria should be set correctly based on actual casting product requirement.
- Objective functions should be open to accommodate additional design parameters. For example, extra velocity constrains may be applied to describe the occurrence of bouncing of molten metal at the end of runners while the ingate velocity has to be kept below 50 cm/s.

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