ANALYSIS OF MECHANICAL PROPERTIES AND MICROSTRUCTURE OF MULTIPLE DIE CAVITY PRODUCTS PRODUCED IN VERTICAL AND HORIZONTAL ARRANGEMENT BY GRAVITY DIE CASTING

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ABSTRACT

Multiple cavities die casting (Permanent die casting) in vertical arrangement and horizontal arrangement moulds are widely used in industry. However, manufacturers assume that each product produced in either arrangement would have the same quality. Manufacturers do not have enough information about the properties of each product, i.e. strength, internal defect and the microstructure. Furthermore, in actuality the quality of each product might be affected. It is the problem that we found within the market now (pinholes, cracks, misruns and etc.), that is the reason investigation and comparison of the multi product in vertical and horizontal arrangement is needed. This investigation is needed to choose which arrangement is preferred to maintain the quality of the product. The methodology used are vickers microhardness test, izod test, ensile test, density and porosity test and optical microscope inspection for all produced sample. Results of this research show that castings produced at vertical arrangement mould have higher mechanical and properties than castings produced in horizontal arrangement mould. Vertical arrangement castings obtained higher density exceeds %1.6117 than horizontal arrangement castings that ranges between (1.156 and 4.8707 percent). However, vertical arrangement castings obtained higher porosity exceeds %13.3885 than horizontal arrangement castings that ranges between (0.0809 and 7.4629 percent). The hardness values for vertical castings ranges between (115HV and 78.9HV), while ranges between (110HV and 79.1HV) for horizontal castings. Castings in vertical arrangement hardness are %7.5442 higher than hardness for castings in horizontal arrangement. Impact strength values of vertical arrangement casting impact values that ranges between(6J and 19J) positions are %118.4615 higher than casting at horizontal arrangement casting positions that range between (2J and 11J). Ultimate tensile strength for castings produced at vertical arrangement mould ranges between (122-182 MPa) are %11.81 higher than castings produced at horizontal arrangement castings (101-178 MPa). The microporosity at vertical arrangement positions are %35 lower than microporoity at horizontal arrangement positions.

ABSTRAK

Penuangan beracuan kekal dalam acuan yang menegak dan melintang banyak digunakan dalam industri perkilangan. Kebanyakkan pengusaha kilang menanggap bahawa semua produk yang dihasilkan mempunyai kualiti yang sama meskipun berlainan susun aturnya. Hai ini menyebabkan pihak kilang tersebut tidak mendapat maklumat yang mencukupi mengenai ciri-ciri setiap produk. Antaranya ialah kekuatan produk, kecacatan dalaman dan mikrostruktur. Hal ini akan menyebabkan kualiti produk tersebut akan terjejas. Jesteru itu, permasalahan ini akan mendorong kepada masalah-masalah yang timbul dalam penjualan produk dari semasa ke semasa. Antara masalah-masalah yang timbul ialah keretakan produk, produk yang berlubang dan sebagainya. Oleh itu , pemeriksaan dan pembandingan di antara produk sama ada bersusunan menegak atau melintang adalah diperlukan. Pemeriksaan ini adalah bertujuan untuk mengekalkan kualiti produk tersebut. Kaedah-kaedah yang digunakan dalam pemeriksaan produk ini adalah ujikaji Vickers microhardness, ujikaji izod, ujikaji tensile, ketumpatan dan pemeriksaan mikroskop optik. Hasil kajian yang diperolehi menunjukkan bahawa produk yang dihasilkan melalui acuan menegak mempunyai tahap mekanikal dan ciri-ciri lebih tinggi daripada produk yang dibuat daripada acuan mendatar. Penuangan melalui acuan menegak memperolehi ketumpatan yang lebih tinggi daripada acuan mendatar iaitu sehingga mencapai 1.6117% dan berada dalam lingkungan (1.156 dan 4.8707 peratus). Penuangan acuan menegak juga memperolehi nilai keliangan lebih tinggi daripada acuan mendatar iaitu 13.3885% dan berada dalam lingkungan (0.0809 dan 7.4629 peratus). Manakala nilai kekuatan untuk penuangan acuan menegak ialah dalam lingkungan (115HV dan 78.9HV) dan untuk penuangan acuan mendatar pula ialah (110HV dan 79.1HV). Nilai kekuatan penuangan acuan menegak adalah lebih tinggi daripada penuangan acuan mendatar sebanyak 7.5442% . Nilai untuk kekuatan impak bagi acuan menegak adalah dari (6J hingga 19J) dan lebih tinggi daripada acuan mendatar iaitu sebanyak 118.4615% yang mempunyai kekuatan impak sebanyak (2J hingga 11J). Kekuatan ketegangan utama untuk acuan susunan menegak mempunyai nilai dari (122-182 MPa) dan lebih tinggi daripada acuan susunan mendatar sebanyak 11.81% . Microporosity pada kedudukan susunan menegak adalah lebih rendah daripada microporosity pada kedudukan susunan mendatar sebanyak 35%.

CONTENTS

LIST OF TABLES

LIST OF GRAPHS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

GDC	-	Gravity die casting
HPDC	-	High pressure die casting
CNC	-	Computer numerical control
CAM	-	Computer added manufacturing
Kg	-	Kilogram
g	-	Gram
SEM	-	Secondary Electron Microscope
EDM	-	Electrical discharge machining
OM	-	Optical microscope
KW/h	-	Kilowatt/hour
J	-	Joul
mm	-	Millimeter
m	-	meter
cm	-	Centimeter
Al	-	Aluminum
Cu	-	Copper
Si	-	Silicon
Mg	-	Magnesium
Mn	-	*Manganese*
Sn	-	Tin
Zn	-	Zinc

B	-	Boron
Be	-	Beryllium
Cr	-	Chromium
P	-	Phosphorus
Ni	-	Nickel
Ti	-	Titanium
Fe	-	Ferrite
$T6$	-	Heat treated aluminum alloy
t_s	-	Total Solidification time
A	-	Surface area
V	-	Volume of casting
B	-	Mold constant
fcc	-	Face center cubic
^oC	-	Celsius grade
$\%$	-	Percentage
m^3	-	Meter cubic
hcp	-	Hexagonal center cubic
356.0	-	Aluminum alloy
D, d	-	Diameter
F	-	Force
G	-	Gravity = 9.81 m/s
L	-	Length
m	-	Mass
P	-	Pressure
Q	-	Rate of Flow
r	-	Radius

T	-	Torque
Re	-	Reynold Number
Kgf	-	Kilo gram force
F	-	Force
d	-	Arithmetic mean of the two diagonals, d1 and d2 in mm
HV	-	Vickers hardness
P_A	-	Apparent porosity
P_s	-	Bulk density
W_d	-	Weight of dried sample
W_s	-	Weight of suspended sample
W_w	-	Weight of wetted sample
UTS	-	Ultimate tensile strength
YS	-	Yield strength
BSE	-	Back scattered electrons
SEI	-	Secondary electron image
SSM	-	Semi-solid aluminum
GISS	-	Gass induced semi-solid
ASTM	-	American Society for Testing and Materials
UTHM	-	Universiti Tun Hussein Onn Malaysi

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

This chapter will generally present the process, type, problems, and purpose of study. The following area of discussion in this chapter will introduce the problem background, problem statement, objectives, scope of study, and significant of study, hypothesis, expected results and synopsis.

1.1 Introduction

One of the most popular methods of producing parts in metal is by casting [1]. Casting is a manufacturing process by which a molten material such as metal or plastic is introduced into a mold, allowed to solidify within the mold, and then ejected or broken out to make a fabricated part. Casting produced should an exact replica of the mold [1]. Casting is used for making parts of complex shape that would be difficult or uneconomical to make by other methods, such as cutting from solid material [2].

Gravity die casting is a process wherein the liquid metal is poured into metallic moulds without application of any external pressure. The liquid metal enters the cavity by gravity. Gravity die casting (GDC) is different from High Pressure Die Casting (HPDC), where the liquid metal is injected into the metal mould under very high pressures for production of thin walled smaller castings with better dimensional accuracy and surface finish [3]. Like Low Pressure Die Casting (LPDC) dies, the dies used for permanent mold casting are typically coated with a refractory material. Cores can be used and made from high alloy steels or resin bonded sands. Permanent mould casting is typically used for high-volume production of sample metal parts with uniform wall thickness. The minimum wall thickness that can be permanent mould cast is approximately 4 mm because of the limited ability of metal to run into thin sections. The process is used for the volume production ranging from 1000 to more than 100 000 per year. Common permanent mould parts include gears, automotive pistons and car wheels. The alloys commonly cast by permanent mould casting include 319 (AlSi5Cu3), 413 (ALSi12) and A356 (AlSi7Mg). The casting operation ranges from manually-operated die sets) to automatically operated (carousel machines having several dies around 4-10 minutes before the casting can be taken out from the die so the process is relatively slow. If higher production rates are required, multiple die sets have to be employed [4]. Gravity die casting accounts about %30 of all light alloy casting production while high pressure die casting is the most widely used, representing about 50%. and Low pressure die casting currently accounts for about %20 [2].

Gravity die casting is a manufacturing process for producing accurately dimensioned, sharply defined, smooth or textured-surface metal parts. It is accomplished by gently pouring molten metal into reusable metal dies under the force of gravity. The term, "die casting," is also used to describe the finished part.

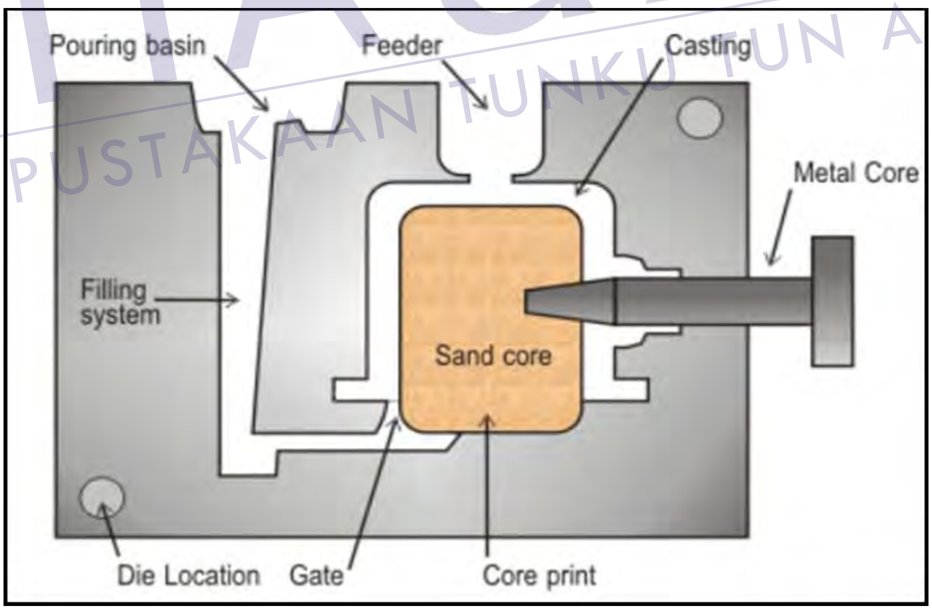

Figure 1.1: Gravity die mold [3].

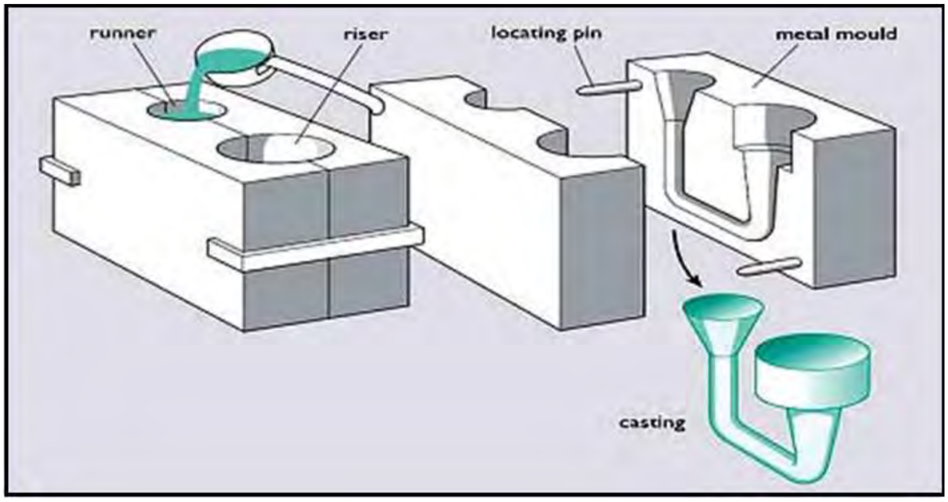

Figure 1.2: principle of gravity die casting [3].

To begin the process, a cast iron mould capable of producing tens of thousands of castings must be made in at least two sections to permit removal of castings. These sections are mounted securely to a solid base and are arranged so that one is stationary (fixed die half) while the other is moveable (ejector die half).

To begin the casting cycle, the die caster clamps the two die halves tightly together. Molten metal is poured into the die cavity where it solidifies quickly. The die halves are drawn apart and the casting is ejected. Die casting dies can be simple or complex, having moveable slides, cores, or other sections depending on the complexity of the casting.

The main advantage of gravity die casting over sand casting is the high speed of production. The reusable die tooling allows for many hundreds of castings to be produced in a day. High definition parts reduce machining costs and superior surface finish reduces finishing costs.

Although die-castings are in most cases cheaper than sand castings, die tooling is considerably more expensive than sand tooling so an optimum number of castings need to be produced to make the process cost effective in the long run [3].

1.1.1 Advantages of Gravity Die Casting

(i) The process is suitable for mass production with better reproduction; dimensional accuracy and surface finish than conventional sand castings. A minimum wall thickness of 3.0 mm can be cast. Exceptionally, 2mm wall thickness is cast over small areas.

(ii) Castings ranging from few grams to 100 Kgs of Aluminum alloy can be cast. There are reports of some foundries producing cylinder blocks of around 300 Kgs by GDC. As the component size and complexity increases the process becomes more expensive and becomes uneconomical. It will also cause difficulty in handling the die and in extracting the casting from the die with reduction in dimensional accuracy and soundness of the casting.

(iii) The GDC process is capable of achieving %20 higher mechanical properties than that of a sand casting because of faster rate of solidification imparting better grain size. The process can be automated and also can produce semi-gravity die-castings employing sand or plaster of paris cores for production of interior details [3].

1.2 Problem Statements

Generally, die casting associated many disadvantages includes porosity, limited mechanical properties, poor dimensional accuracy. Both the casting equipment required and the dies and related components are very costly, as compared to most other casting processes. Therefore to make die casting an economic process a large production volume is needed. Other disadvantages include: the process is limited to high-fluidity metals and casting weights must be between 30 grams and 10 kg [4].

In this research aluminum A365 alloy will be chosen as the specimen to be studied for the mechanical properties and microstructure analysis. Multiple die cavities will be included as a mold to fabricate products in horizontal and vertical arrangement. This research will compare each specimen fabricated in multiple die cavity, as in manufacturing industries will assume the products fabricated in multiple die cavity are identical.

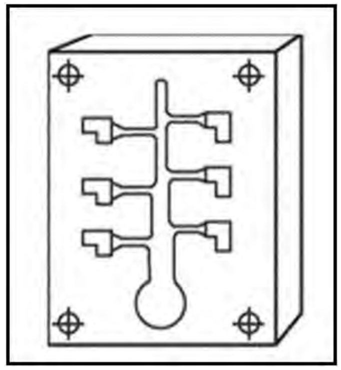

Figure 1.3: Example of multiple die cavities

1.3 Objective

The objective of this research is to study the mechanical properties of the samples produced by gravity die casting (GDC) in vertical and horizontal arrangement.

1.4 Scope Of Study

The scope of this research is as follow:

i. To study the mechanical properties and microstructure of each specimen in casting.
ii. To make comparison between each specimen produced.
iii. Tensile test will be included to test each specimen.
iv. Aluminum 356 will be the material to be casted.
v. The mold will be used is made from the mild steel.

1.5 Hypothesis

In this research, Gravity die casting (GDC) will be used to investigate each specimen produced. Each specimen will be compared for mechanical properties, produced in vertical and horizontal cavities arrangement. Izod impact test will be included to test the hardness for each specimen, also microstructure test: OM, SEM, density porosity tests.

1.6 Significant Of Study

Among all assumptions, in industry the products that been fabricated by the same mold will be identical. Such thoughts will be critical to the performance of the products during application. This research is on the potential occurrence of differences in mechanical properties if the cavities arrangements are different. Further industry can produce products more high accurate according this analysis and results, depends what of the minimum requirement they needed. Furthermore, comparison what type of arrangement has better mechanical properties. This knowledge can be applied into industry, and better quality products can be produced. To avoid poor quality of products fabricated by wrong orientation and arrangement of multiple cavities.

CHAPTER 2

LITERATURE REVIEW

This chapter is focusing on the foundry technology specially die casting. In this chapter gravity die casting (GDC), furnace processes, single cavity, multiple cavity and gating system. Also related researches in the same area of study will be covered.

2.1 Furnaces

Here you will find a general overview of foundry furnace technology most commonly used in the metal casting industry. Energy is a major cost in all foundries. The majority of energy used is in the melting and metal holding processes.

2.1.1 Electric Induction Furnaces

Electric induction furnaces are the highly used furnaces for melting iron and non ferrous alloys. As compared to other cupola furnaces, these furnaces are pollution free and have outstanding metallurgical control. They are available in capacity ranging from a few kilograms to 75 tones.

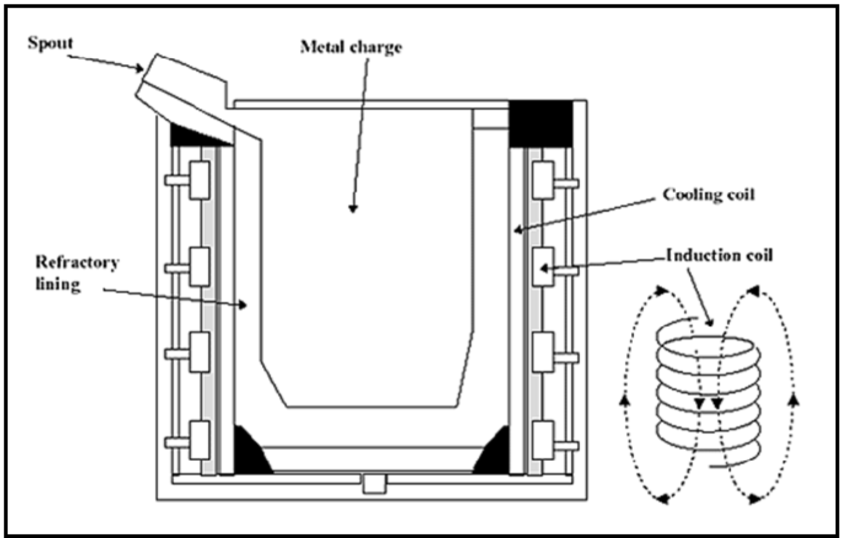

Figure 2.1: Electric Induction Furnace (Coreless)

Firstly the high voltage is passed in the primary coil, which induces low voltage and high current across the metal charge which acts as a secondary coil. Due to electrical resistance, electrical energy is converted into heat which fuses the charge. Once the metal is in its molten state the magnetic field yields a stirring motion. The stirring rate is determined by the applicable power and frequency. This rate is controlled to lower the temperature gradients in the charge and to assure entire melting of charge and adequate mixing of alloy and fluxing materials. On the other side, excess stirring can raise lining damage, oxidation of the alloys, and high amount of slag, inclusions and gas pick-up.

i. The two most common electric induction furnaces are :

a. Coreless furnace: In this furnace, the refractory-lined crucible is entirely surrounded by a water-cooled copper coil which deters the primary coil from overheating. These furnaces are available in the range of 5 tones to 10 tones.

b. Channel furnace: Also used as holding furnace, in channel furnace, the coil is surrounded by an inductor. This furnace can have a capacity of over 200 tones.

ii. Electric induction furnaces are available in varied sizes. Efficient as well as durable, these furnaces are capable to melt a vast range of metals, still little refining of the metal is possible. Due to reduced refractory wear, the operating costs of them are very less. The melting time of metal is very small thus metal is delivered at small and regular intervals. Along with ease of simplicity, they need very small quantities of metal composition which can be easily melted in very less time. Around %60 of the energy supplied to the furnace is transferred to the charge. The efficiency of an induction furnace installation is determined by the ratio of the load useful power to the input power drawn from the utility. The overall fuel consumption in the furnace is over 2000 $kw.h/tonne$ [5].

2.1.2 Cupola Furnaces

The use of cupola furnaces is one of the oldest process for making cast iron and is still among the dominant technologies in the world. In Queensland, most of the larger foundries have replaced their cupola furnaces with more efficient electric furnaces. Some of these foundries still maintain a cupola furnace for specific melts or for reserve capacity.

A typical cupola melting furnace consists of a water-cooled vertical cylinder which is lined with refractory material. The process is as follows:

i. The charge, consisting of metal, alloying ingredients, limestone, and coal coke for fuel and carbonization (%8-16 of the metal charge), is fed in alternating layers through an opening in the cylinder.

ii. Air enters the bottom through tuyeres extending a short distance into the interior of the cylinder. The air inflow often contains enhanced oxygen levels.

iii. Coke is consumed. The hot exhaust gases rise up through the charge, preheating it. This increases the energy efficiency of the furnace. The charge drops and is melted.

iv. Although air is fed into the furnace, the environment is a reducing one. Burning of coke under reducing conditions raises the carbon content of the metal charge to the casting specifications.

v. As the material is consumed, additional charges can be added to the furnace.

vi. A continuous flow of iron emerges from the bottom of the furnace.

vii. Depending on the size of the furnace, the flow rate can be as high as 100 tonnes per hour. At the metal melts it is refined to some extent, which removes contaminants. This makes this process more suitable than electric furnaces for dirty charges.

viii. A hole higher than the tap allows slag to be drawn off.

ix. The exhaust gases emerge from the top of the cupola. Emission control technology is used to treat the emissions to meet environmental standards.

x. Hinged doors at the bottom allow the furnace to be emptied when not in use [5].

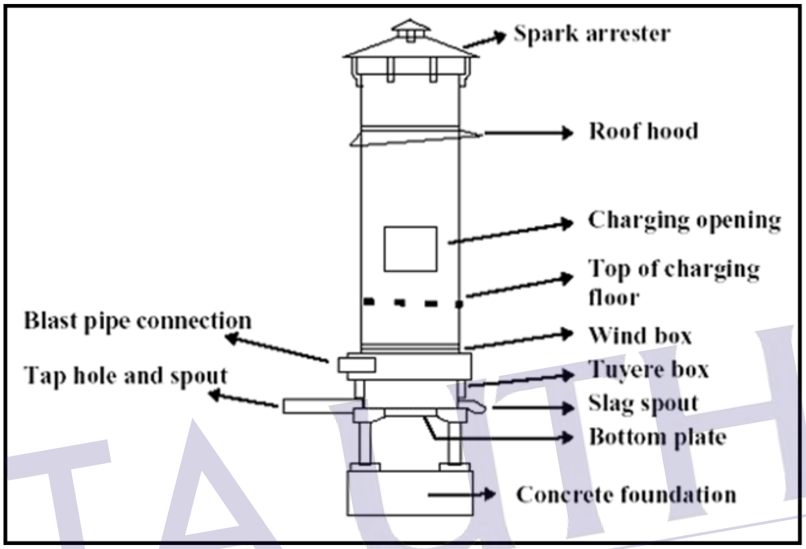

Figure 2.2: Typical Cupola Furnace.

2.1.3 Electric Arc Furnaces

Electric arc furnaces are used for melting high-melting-point alloys such as steels. The furnace consists of a saucer-shaped hearth of refractory material for collecting the molten metal, with refractory material lining the sides and top of the furnace. The roof can normally swing away to facilitate charging of the furnace. Two or three carbon electrodes penetrate the furnace from the roof or the sides. Doors in the side of the furnace allow removal of alloys, removal of slag and oxygen lancing.

The scrap metal charge is placed on the hearth and melted by the heat from an electric arc formed between the electrodes. In a direct-arc furnace, the electric arc comes into contact with the metal; in an indirect-arc furnace the electric arc does not actually touch the metal. Molten metal is typically drawn off through a spout by tipping the furnace.

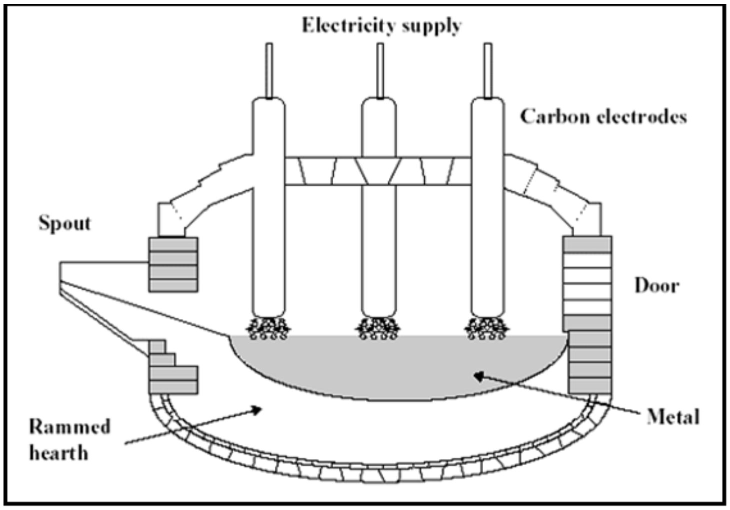

Figure 2.3: Direct Arc Furnace.

As the refractories deteriorate, slag is generated. Fluxes such as calcium fluoride may be added to make the slag more fluid and easier to remove from the melt. Refractory life can also be extended by forming protective slag layers in the furnace, by intentional addition of silica and lime. The slag protects the molten metal from the air and extracts certain impurities.

Electric arc melting furnaces are more tolerant of dirty scrap that induction furnaces and can be used to refine metals, allowing steel to be refined from an iron charge. Direct electric-arc furnaces have a very high thermal efficiency - around 70% - and can function at as little as 450-550 $kw.h/tonne$ of metal melted. Indirect electric arc furnaces typically achieve closer to 700-1000 $kw.h/tonne$ of steel [5].

2.1.4 Crucible Furnaces

Crucible furnaces are among the oldest and simplest furnaces used in the foundry industry. They are primarily used to melt smaller amounts of nonferrous metals but can also be used for ferrous metals. They are mostly used by smaller foundries or for specialty alloy lines. The crucible or refractory container is heated in a furnace, typically fired with natural gas or liquid propane, although coke, oil or electricity have been used. There are three common crucible furnaces: bale-out furnaces, where molten metal is ladled from the crucible; tilting furnaces, where the metal is poured directly from the furnace; and lift-out furnaces, where the crucible can be removed from the furnace and used as a ladle [5].

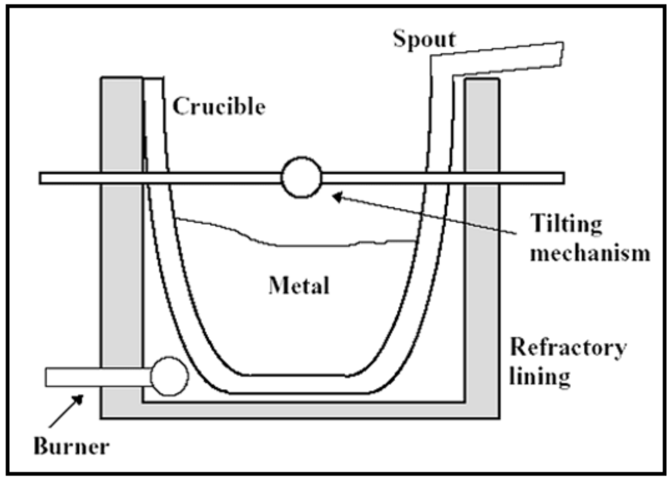

Figure 2.4: Crucible Furnace.

2.1.5 Rotating Furnaces

Rotating furnaces consist of a refractory-lined cylinder that rotates slowly around a horizontal axis. The charge is heated directly from an open flame, typically fed by either gas or oil. Exhaust gases are extracted from the opposite end of the chamber. Rotating the furnace helps to mix the charge and utilizes heat from the whole refractory surface.

Immediately after melting, the melt is covered with a layer of salt. This reduces slag formation by protecting the melt from oxidization. Rotating melting furnaces are relatively inefficient, at around 990-1080 $kw.h/tonne$ of metal melted, but the lower cost of fuel offsets this disadvantage to some extent [5].

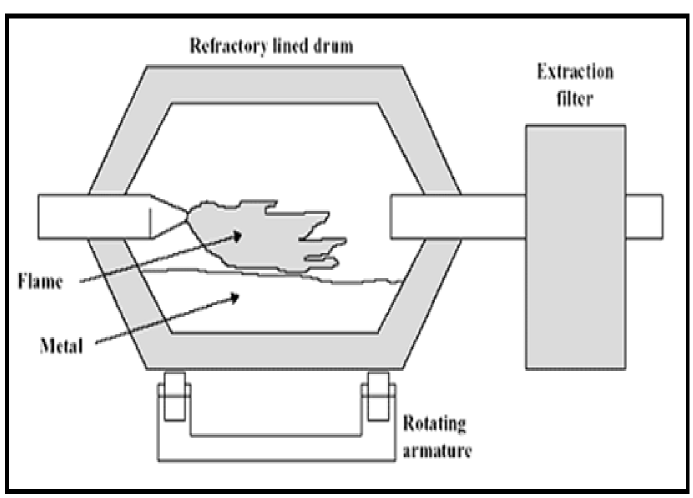

Figure 2.5: Rotating Furnace [5].

2.2 Defects of Die Casting and their Causes

i. Shrinkage porosity: Also known as closed shrinkage defects, are defects that form within the casting. Isolated pools of liquid form inside solidified metal, which are called hot spots. The shrinkage defect usually forms at the top of the hot spots. They require a nucleation point, so impurities and dissolved gas can induce closed shrinkage defects. The defects are broken up into macroporosity and microporosity (or micro shrinkage), where macroporosity can be seen by the naked eye and microporosity cannot.

ii. Gas porosity: Is the formation of bubbles within the casting after it has cooled. This occurs because most liquid materials can hold a large amount of dissolved gas, but the solid form of the same material cannot, so the gas forms bubbles within the material as it cools. Gas porosity may present itself on the surface of the casting as porosity or the pore may be trapped inside the metal, which reduces strength in that vicinity. Nitrogen, oxygen and hydrogen are the most encountered gases in cases of gas porosity. In aluminum castings, hydrogen is the only gas that dissolves in significant quantity, which can result in hydrogen gas porosity. For castings that are a few kilograms in weight the pores are usually 0.01 to 0.5 mm (0.00039 to 0.020 in) in size. In larger casting they can be up to a millimeter (0.040 in) in diameter [7].

iii. Misrun, it appears when incomplete casting with rounded edges where casting is not completely filled. Probable cause of this phenomenon: 1. Low shell or metal pour temperature. 2. Lack of fluidity. 3. Interrupted pour. 4. Rate of pour too slow. 5. Thin sections. 6. Low shell permeability and absence of vents [8].

iv. Cold Shuts, discontinuities within the casting-look like stratified lava flow. Caused by pouring process too slow or metal too cool when poured. Either of these causes can result in thin section solidifying before the mold is totally filled and/or two molten metal streams meeting at too low a temperature for them to fuse together properly. Both the misrun and cold shuts can also be caused by cold dies, low metal temperature, dirty metal, lack of venting, or too much lubricant. [9].

v. Hot tears, Appears when intergranular crack exhibiting oxidized fracture interface. Probable cause of this phenomenon: 1. Restrained by gating. 2. Shell too strong.3. Sharp inside corners 4.Bad casting Design. 5. Movement of shell before alloy solidified. 6. Improper metal or shell temperature. 7. Faster cooling rate after pouring (during solidification). 8. Improper chemistry of alloy [8].

vi. Shrinkage can appears in gate area by observing large internal irregular cavities usually exposed on removal or gate. The probable cause of this defect might be improper gate design and/or inadequate feeding. Also Shrinkage can appears on surface as a surface depression or irregular cavities exhibiting oxidized surfaces. The probable cause of this defect can be either localized mold hot spot and /or metal and/or shell temperature too high.

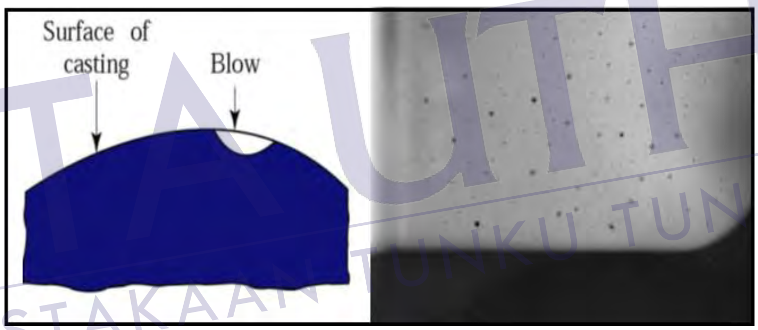

Figure 2.6: Example of gas porosity defect [10].

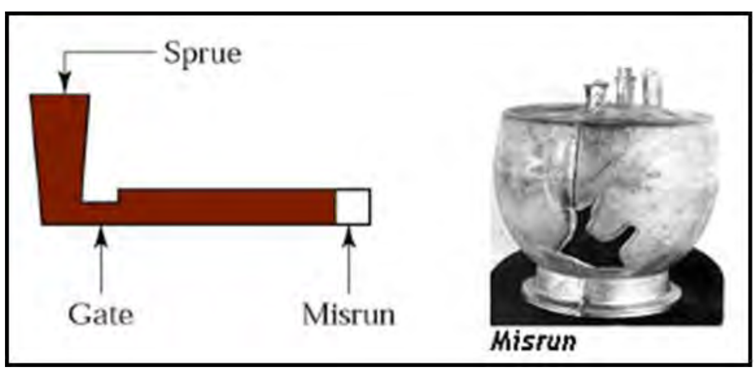

Figure 2.7: Example of misrun defect [10].

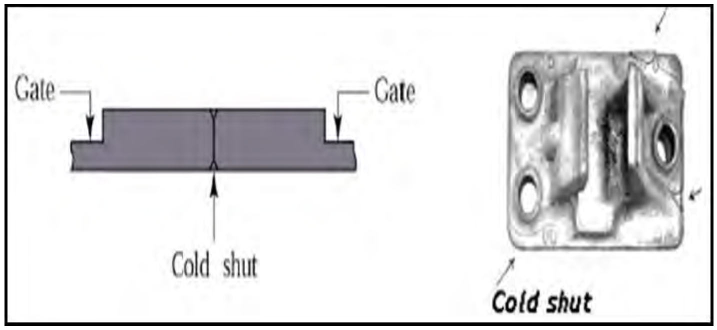

Figure 2.8: Example of cold shut defect [10].

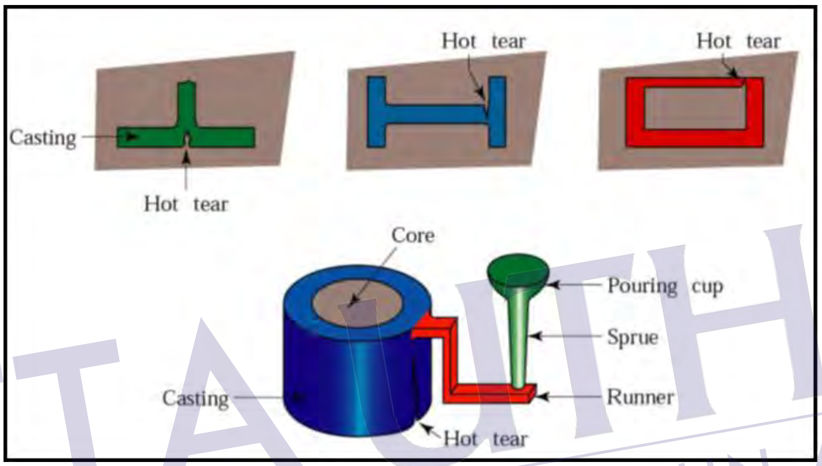

Figure 2.9: Example of hot tear defect [10].

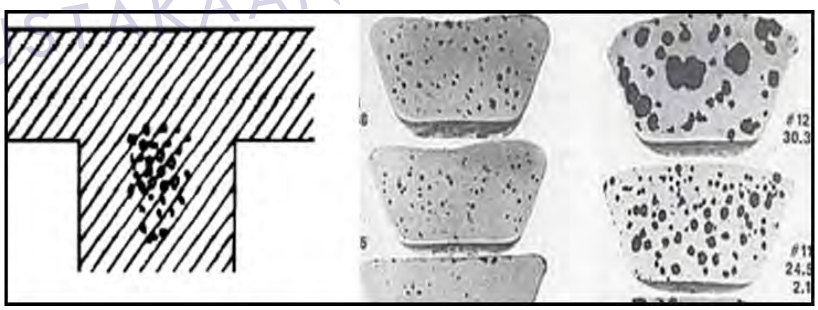

Figure 2.10: Example of shrinkage porosity [10].

2.3 Aluminum Casting Alloy

Although its low melting temperature tends to make it suitable for casting, pure aluminum is seldom cast. Its high shrinkage and susceptibility to hot cracking cause considerable difficulty, and scrap is high. By adding small amount of alloying elements, however, very suitable casting characteristics can be obtained and strength can be increased. Aluminum alloys are cast in considerable quantity by a variety of processes. Many of the most popular alloys contain enough silicon to produce the eutectic reaction, which is characterized by a low melting and high as-cast strength. Silicon also improves the fluidity of the metal, making it easier to produce complex shapes or thin sections, but high silicon also produces an abrasive, difficult-to-cut material. Copper, zinc and magnesium are other popular alloy additions that permit the formation of age-hardening precipitates.

Table 2.1 list some of the commercial aluminum casting alloy and uses the three digit designation system of the Aluminum Association. The first digit indicates the alloy group as follows:

Table 2.1: Major Alloying Elements

1XX.X	99.0% minimum aluminum content
2XX.X	Al + Cu
3XX.X	Al + Si & Mg, or Al + Si & Cu, or Al + Si & Mg & Cu
4XX.X	Al + Si
5XX.X	Al + Mg
7XX.X	Al + Zn
8XX.X	Al + Sn
9XX.X	Other elements

The second and third digits identify the particular alloy or aluminum purity, and the last digit, separated by a decimal point, indicates the product form (e.g., casting or ingot).

Aluminum casting alloys have been designed for both properties and process. When the strength requirements are low, as-cast properties are usually adequate. High-strength castings usually require the use of alloys that can subsequently be heat treated. Sand casting has the fewest process restrictions. The aluminum alloys used for permanent mold casting are designed to have lower coefficients of thermal expansion (or contraction) because the molds offer restraint to the dimensional changes that occur upon cooling. Die-casting alloys require high degrees of fluidity because they are often cast in thin sections. Most of the die-casting alloys are also designed to produce high "as-cast" strength without heat treatment, using the rapid cooling conditions of the die-casting process to promote a fine grain size and fine eutectic structure. Tensile strengths of the aluminum permanent mold and die casting alloys can be in excess of 275 MPa [1].

For purposes of understanding their effects and importance, alloying elements for the majority of alloys are probably best classified as major, minor, microstructure modifiers or impurities; understanding, however, that impurity elements in some alloys might be major elements in others:

1. Major elements typically include silicon (Si), copper (Cu) and magnesium (Mg)
2. Minor elements include nickel (Ni) and tin (Sn) -- found largely in alloys that likely would not be used in high integrity die castings
3. Microstructure modifying elements include titanium (Ti), boron (B), strontium (Sr), phosphorus (P), beryllium (Be), manganese (Mn) and chromium (Cr)
4. Impurity elements would typically include iron (Fe), chromium (Cr) and zinc (Zn) [11].

Table 2.2: Composition, Properties, and Uses of Some Aluminum Casting Alloys

Alloy Designation [a]	process [b]	Composition (%) (Major Alloys ≥1%)						Temper	Tensile strength		Elongation in 2 in.(%)
		Cu	Si	Mg	Zn	Fe	Other		Ksi^c	Mpa	
208	S	4.0	3.0		1.0	1.2		F	19	131	1.5
242	S,P	4.0		1.6		1.0	2.0Ni	T61	40	276	__
295	S	4.5	1.0			1.0		T6	32	221	3.0
296	P	4.5	2.5			1.2		T6	35	241	2.0
308	P	4.5	5.5		1.0	1.0		F	24	166	__
319	S,P	3.5	6.0		1.0	1.0		T6	31	214	1.5
354	P	1.8	9.0					__	__	__	__
355	S,P	1.3	5.0					T6	32	221	2.0
C355	S,P	1.3	5.0					T61	40	276	3.0
356	S,P		7.0					T6	30	207	3.0
A356	S,P		7.0					T61	37	255	5.0
357	S,P		7.0					T6	45	310	3.0

Table 2.2: Continued

Alloy Designation[a]	process[b]	Composition (%) (Major Alloys ≥1%)						Temper	Tensile strength		Elongation in 2 in.(%)
		Cu	Si	Mg	Zn	Fe	Other				
359	S,P		9.0					—	—	—	—
360	D		9.5			2.0		F	44^{d}	303	44^{d}
A360	D		9.5			2.0		F	46^{d}	317	3.5^{d}
380	D	3.5	8.5		3.0	2.0		F	46^{d}	317	2.5^{d}
A380	D	3.5	8.5		3.0	1.3		F	47^{d}	324	3.5^{d}
383	D	1.5	10.5		3.0	1.3		F	45^{d}	310	3.5^{d}
284	D	3.75	11.3		1.0	1.3		F	48^{d}	331	2.5
413	D	1.0	12.0			2.0		F	43^{d}	297	2.5^{d}
A413	D	1.0	12.0			1.3		F	42^{d}	290	3.5^{d}
443	D	5.25				2.0		F	33^{d}	228	9.0^{d}
B443	S,P	5.25				2.0		F	17	117	3.0
514	S			4.0				F	22	152	6.0
518	D			8.0		1.8		F	45^{d}	310	5.0^{d}
520	S			10.0				T4	42	290	12.0
535	S			6.9				F	35	241	9.0
712	S				5.8			F	34	234	4.0
713	S,P				7.5	1.1		F	32	221	3.0
771	S				7.0			T6	42	290	5.0
850	S,P	1.0					6.3 Sn, 1.0 Ni	T5	16	110	5.0

Notifications:

^{b}S, sand cast; P, permanent-mold-cast: D, die cast.

^{a}, Aluminum Association.

^{d}, Typical values.

^{c}Minimum figures unless noted [1].

2.4 The Solidification Process

Casing is a solidification process where the molten material is poured into a mold and then allowed to freeze into the desired final shape. Many of the structural features that ultimately control product properties are set during solidification. Furthermore, many casting defects, such as gas porosity and solidification shrinkage, are solidification phenomena, and they can be reduced or eliminated by controlling the solidification process.

Solidification occurs in two stages, nucleation and growth, and it is important to control both of these processes. Nucleation occurs when a stable particles of solid forms from within the molten liquid. As the material changes state, its internal energy is reduced since at lower temperatures the solid phase is more stable that the liquid . At the same time, however, interface surfaces are created between the new solid and the parent liquid. Formation of these surfaces requires a positive contribution of energy. As a result, nucleation generally occurs at a temperature somewhat below the equilibrium melting point (the temperature where the internal energies of the liquid and solid are equal). The difference between the melting point and the actual temperature of nucleation is known as the amount of undercooling.

The second step in the solidification process is growth which occurs as the heat of fusion is extracted from the liquid material. The direction rate and type of growth can be controlled by the way in which the heat is removed. Directional solidification, in which the solidification interface sweeps continuously through the material, can be used to assure the production of a sound casting. The molten material on the liquid side of the interface can flow into the mold to continuously compensate for the shrinkage that occurs as the material changes from liquid to solid. Faster rates of cooling generally produce products with finer grain size and superior mechanical properties [1].

2.4.1 Cooling Curve

Figure 2.7 shows a typical cooling curve for a pure or eutectic-composition material (one with a distinct melting point) and is useful for depicting many of the principle features and terms. The pouring temperature is the temperature of the liquid metal when it first enters the mold cavity. Superheat is the difference between the pouring temperature and the freezing temperature of the material. The higher the superheat, the more time is given for the material to flow into the intricate details of the mold cavity before to begin to freeze. The cooling rate is the rate at which the liquid or solid is cooling and can be viewed as the slope of the cooling curve at any given point. A thermal arrest is the plateau in the cooling curve that occurs during the solidification of a material with fixed melting point. At this temperature, the heat being removed from the mold comes from the latent heat of fusion that is released during solidification is known as the total solidification time. The time from the start of solidification to the end of solidification is called the local solidification time.

If undercooling was required to induce the initial nucleation the subsequent solidification may release enough heat to cause an increase in temperature back to the melting point. This increase in temperature, known as recalescence, is shown in figure 2.8.

The specific form of cooling curve depends on the type of material being poured, the nature of the nucleation process and the rate and means of heat removal from the mold. Fast cooling rates and short solidification times lead to finer structure and improved mechanical properties [1].

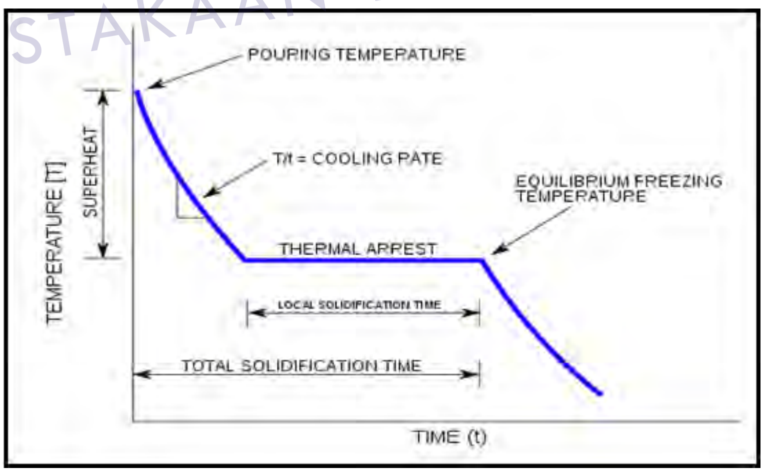

Figure 2.11: Cooling curve for a pure metal of eutectic-composition [1].

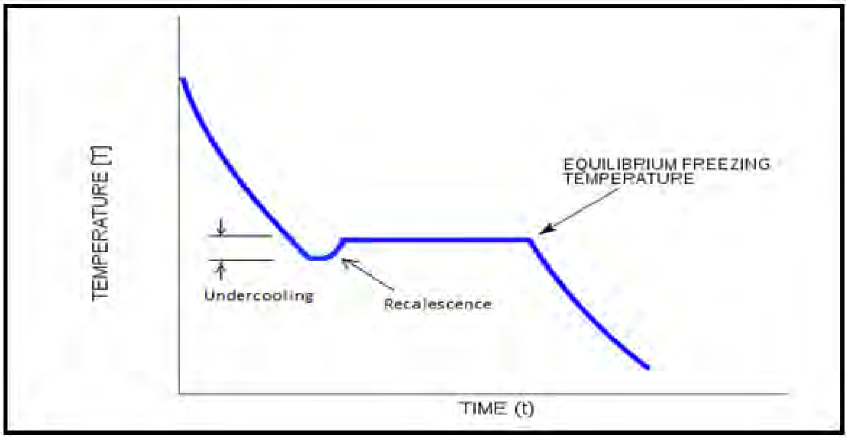

Figure 2.12: Cooling curve depicting undercooling and subsequent recalescence [1].

2.4.2 Chvorinov's Rule

The amount of heat that must be removed from a casting to cause it to solidify is dependent upon both the amount of superheating and the volume of metal in the casting.

$$t_s = B(V/A)^n \qquad \text{Where } n=1.5 \text{ to } 2.0 \qquad (2.1)$$

The total solidification time t_s, is the time from pouring to the completion of solidification; V is the volume of the casting; A is the surface area; and the B is the mold constant, which incorporates the characteristics if the metal being cast (its density, heat capacity. And heat of fusion), the mold material (its density, thermal conductivity, and heat capacity), the mold thickness and the amount of superheat [1].

2.4.3 Solidification Shrinkage

The molten in the furnace occupies considerably more volume than the solidified castings that are eventually produced, giving rise to a number of problems for the founder.

There are three quite different contractions to be dealt with when cooling from the liquid state to room temperature, as figure 2.9 illustrates.

i. As the temperature reduces, the contraction to be experienced is that in the liquid state. This is the normal thermal contraction observed by everyone as a mercury thermometer cools; the volume of the liquid metal reduces almost exactly linearly with failing temperature.

In the casting situation the shrinkage of the liquid metal is usually not troublesome; the extra liquid metal required to compensate for this small reduction in volume is provided without difficulty. It is usually not even noticed, being merely a slight extension to the pouring time if the freezing is occurring while the mold is being filled. Alternatively, it is met by a slight fall in level in the feeder.

ii. The contraction on solidification is quite another matter, however. This contraction occurs at the freezing point, because (in general) of the greater density of the solid compared to that of the liquid. Contraction associated with freezing for the aluminum is given in Table 2.3. The contraction causes a number of problems. These include (i) The requirement for 'feeding', which is defined here as any process that will allow for the compensation of solidification contraction by the movement of either liquid or solid, and (ii) 'shrinkage porosity', which is the result of failure of feeding to operate effectively. These issues are dealt with at length in this chapter.

iii. The final stages of shrinkage in the solid state can cause a separate series of problems. As cooling progresses, and the casting attempt to reduce its size in consequence, it is rarely free to contract as it wishes. It usually finds itself constrained to some extent either by the mold, or often by other parts of the casting that have solidified and cooled already. These constrains always lead to the casting being somewhat larger than would be expected from free contraction alone. This is because of a certain amount of plastic stretching that the casting necessarily suffers. It leads to difficulties in predicting the size of the pattern since the degree to which the pattern is made oversize (the 'contraction allowance' or 'patternmaker's allowance') is not easy to quantify. The mold constraint during the solid-state contraction can also lead to more localized problems such as hot tearing or cracking of the casting.

Table 2.3: Solidification shrinkage of aluminum.

Metal	Crystal Structure	Melting Point C	Liquid Density(kgm^{-3})	Solid density(kgm^{-3})	Volume Change(%)
Al	fcc	660	2368	2550	7.14

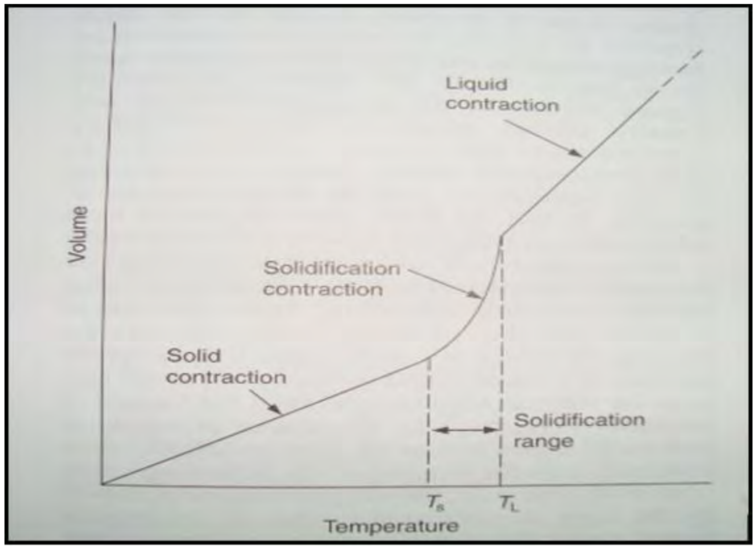

Figure 2.13: Schematic illustration of three shrinkage regimes.

In general liquid contracts on freezing, because of the rearrangement of atoms from a rather random (open-packed) arrangement to a regular crystalline array of significantly denser packing.

The densest solids are those that have cubic close-packed (face-centered-cubic, fcc, and hexagonal close-packed, hcp) symmetric, as shown in table 2.2 in case of aluminum.

For the majority of materials that do contract on freezing it is important to have a clear idea of what happens in a poorly fed casting. As an idea case of an unfed casting, it is instructive to consider the freezing of a sphere. We shall assume that the sphere has been fed via an ingate of negligibly small size up to stage at which a solid shell has formed of thickness x (figure 2.10). The source of supply of feed metal is then frozen off. Now as solidification continues with the freezing of the following onion layer of thickness d_x, the reduced volume occupied by the layer dx compared to that of original liquid means that either a pore has to form, or the liquid has to expand a little, and the surrounding solid correspondingly has to contract a little.

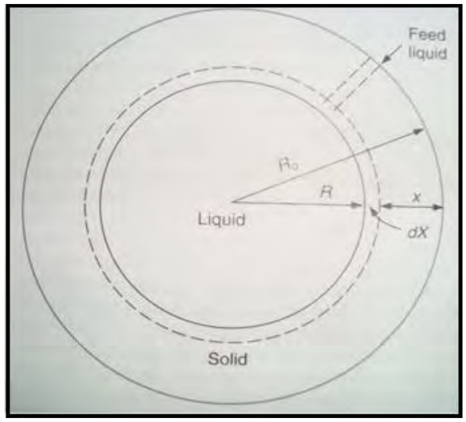

Figure 2.14: Solidification model for an unfed sphere [12].

2.4.4 Patternmaker's Shrink

Shrinkage after solidification can be dealt with by using an oversized pattern designed specifically for the alloy used. Contraction rules, or shrink rules, are used to make the patterns oversized to compensate for this type of shrinkage. These rulers are up to %2.5 oversize, depending on the material being cast. These rulers are mainly referred to by their percentage change. A pattern made to match an existing part would be made as follows: First, the existing part would be measured using a standard ruler, then when constructing the pattern, the pattern maker would use a contraction rule, ensuring that the casting would contract to the correct size.

Note that patternmaker's shrinkage does not take phase change transformations into account. For example, eutectic reactions, martensitic reactions, and graphitization can cause expansions or contractions [1].

Table 2.4: Typical patternmaker's shrinkage of various metals

Metal	Percentage	in/ft
Aluminium	1.0–1.3	$\frac{1}{8}$–$\frac{5}{32}$
Brass	1.5	$\frac{3}{16}$
Magnesium	1.0–1.3	$\frac{1}{8}$–$\frac{5}{32}$
Cast iron	0.8–1.0	$\frac{1}{10}$–$\frac{1}{8}$
Steel	1.5–2.0	$\frac{3}{16}$–$\frac{1}{4}$

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