MARMARA UNIVERSITY

INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCE

ABLATION CASTING

EGE DEMİRTAŞ

MASTER THESIS

Department of Metallurgical and Materials Engineering

Thesis Supervisor

Prof. Dr. Altan TÜRKELİ

ISTANBUL, 2016

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November, 2016 **Ege DEMİRTAŞ**

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Ablation Döküm

Ablation Döküm, içi ergimiş metal alaşım ile dolu çözünebilir bağlayıcılar içeren kumdan kalıba soğutucu sıvı püskürterek kalıbı dağıtma ve katılaşan metal alaşım üzerinde oldukça hızlı yapısal aşırı soğuma oluşturma meydana getiren bir tür kum döküm yöntemidir. Meydana gelen yapısal aşırı soğuma, alaşımın katılaşırken ikincil dendrit kolları arası boşluğun azalmasını, alaşımın ince taneli yapıya sahip olmasını ve mukavemet özelliklerinin iyileştirilmesini sağlamaktadır.

Bu çalışmada amaç, çözünebilen bağlayıcılar kullanılmadan, bentonit kili içeren yaş kum kalıplar kullanılarak üretilen Al-Si esasl A356.0 alaşımın geleneksel kum kalıba döküm yöntemi ve ablation döküm yöntemi ile elde edilen mikroyapısını karşılaştırmaktır.

Yapılan deneylerde, Al-Si A356.0 alaşımının dökümü için ergitme fırını, K tipi termocuple ve bentonit kili içeren yaş kum kalıp kullanıldı. Kum kalıba döküm yöntemi ve ablation casting yöntemi için ayrı kalıplar hazırlandı. Kum döküm işleminde katılaşma sırasında hiç bir müdahele yapılmadı. Ablation döküm işleminde ise kalıp katılaşma sırasında soğuk su ile dağıtıldı ve metal alaşımı soğutuldu. Katılaşma tamamlandıktan sonra bu alaşımların, numune hazırlama yöntemleri olan kesme, bakalit alma, zımparalama, parlatma ve dağlama işlemleri uygulanarak mikroskop altında incelemesi yapıldı.

Sonuç olarak her iki üretim yöntemi kullanılarak elde edilen alaşımların mikroyapısında farklılıklar görülmüştür. Kum kalıba döküm yapılmış alaşımın mikroyapısında kaba taneli Al ve iğnesel şekilli Si ötektik gözlenirken, ablation döküm yöntemi ile üretilmiş alaşımın mikroyapısında ince taneli dendritik Al ve ince lamelli Si ötektik gözlenmiştir.

Kasım, 2016 **Ege DEMİRTAŞ**

Anahtar Kelimeler: A356.0 Al-Si alaşımı, ablation döküm, mikroyapı, ikincil dendrit boyları arası boşluk

ABSTRACT

Ablation Casting

Ablation casting is a type of sand casting method which employs soluble binder containing sand molds filled with molten metal alloy and dissipation of these sand molds by a cooling liquid to create rapid undercooling upon solidifying metal alloy inside the mold. The rapid undercooling provides reducing secondary arm spacing (SDAS), refining the microstructure and improving mechanical properties of the alloy.

The aim of this study is research and comparison of both microstructures of Al-Si based A356.0 alloy produced by conventional sand casting and ablation casting method, which the molds are in greensand condition containing bentonite instead of soluble binders.

In the experiments, bentonite containing sand molds, melting furnace, K type thermocouple were utilized for casting A356.0 Al-Si alloy. The molds are individually prepared for both conventional sand casting and ablation casting. No interference applied throughout solidification of sand cast alloy. In case of ablation casting, the molds are dissipated and solidifying alloy is cooled via cold water during solidification. After solidification completed sample preparation methods; cutting, mounting, grinding, polishing and etching were implemented to be able to investigate microstructure of the metal alloy under microscope.

In conclusion, differences observed upon the products of both casting methods. The microstructure of sand cast alloy consist of coarse Al-matrix and needle-like shaped Si eutectic whereas the microstructure of ablation cast alloy consist fine-dendritic Al and lamellar Si eutectic.

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Keywords: A356.0 Al-Si alloy, ablation casting, microstructure, secondary dendrite arm spacing

SYMBOLS

Ag: Silver

Al: Aluminum

Al_3^+: Trivalent aluminum

$Al(OH)_3$: Gibbsite

Al_2O_3: Alumina

AlO_2^-, AlO^+: Aluminum oxide

$Al_2O_3.2SiO_2.2H_2O$: Kaolinite

Al-Cu: Aluminum-Copper

Al-Cu-Mg: Aluminum-Copper-Magnesium

Al-Fe-Si: Aluminum-Iron-Silicon

Al-Mg: Aluminum-Magnesium

Al-Mg-Zn: Aluminum-Magnesium-Zinc

Al-Mg-Zn-Cu: Aluminum-Magnesium-Zinc-Copper

Al-Ni-Fe: Aluminum-Nickel-Iron

Al-Si-Mg: Aluminum-Silicon-Magnesium

Al-Zn: Aluminum-Zinc

Bi: Bismuth

Ca: Calsium

$CaSO_4.1/2H_2O$: Gypsum

Cd: Cadmium

Cr-Mo: Chromium-Molybdenum

Cu: Copper

Cu-As: Copper-Arsenic

d: Average grain diameter

e^-: Electron

Fe: Iron

Fe_2SiO_4: Fayalite

$FeSiO_3$: Grunerite

$FeCr_2O_4$: Chromite

Fe_2O_3: Haematite

H_2O: Water

In: Indium

H_V: Hardness Vickers

Li: Lithium

Mg: Magnesium

Mg_2SiO_4: Forsterite

Mn: Manganese

Na: Sodium

NaOH: Sodium hydroxide

$NaAlO_2$: Sodium aluminate

Ni: Nickel

O_2^-: Ionic oxygen gas

P: Phosphorus

Pb: Lead

Si: Silicon

Sn: Tin

Sr: Strontium

Ti: Titanium

TiO_2: Anatase

V: Vanadium

Zn: Zinc

Zr: Zirconium

$ZrSiO_4$: Zircon silicate

σ_y: Yield stress (MPa)

σ_0: Dislocation movement starting constant

k_y: Strengthening coefficient

ABBREVIATIONS

AA: North American Aluminum Association

ANSI: American National Standarts Institute

CLA: Counter gravity low pressure of air melted alloys

CLV: Counter gravity low pressure of vacuum melted alloys

CV: Check Valve Casting

CLAS: Counter gravity low pressure air melted sand casting

DAS: Dendrite arm spacing

SDAS: Secondary dendrite arm spacing

FCC: Face centered cubic

PS: Polystyrene

TS: Tensile Strength

UTS: Ultimate Tensile Stress

YS: Yield Strength

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CHAPTER 1

1. INTRODUCTION AND AIM

Casting is one of the earliest production method founded by mankind in the aim of fulfilling the needings on weapons, useful tools, accesorizes. It is the easiest method for producing three-dimensional parts with changing shapes from basic to complex. Various casting methods were developed during the history of production for different purposes[1]. Nowadays there are countless types of casting methods actively used for catering material demands of many existing industries (food, automative, buildings, aerospace, chemical etc)[2]. Altough the dynamics of the processes differs from each other, the objective of all of them is similar; eliminating harmful defects and improving quality of beneficial properties.

Sand casting methods more preferable for low to medium number production than permeable mold casting and die casting. Complex shaped parts are can be produced with high surface quality. The equipments of sand casting is relatively cheaper so redeem of costs for capital investment is much easier[2]. Also it is possible to produce multiple parts at the same time by employing multiple disposable patterns[1]. However, formation of coarse particles and porosities are more likely due to lower cooling rates. Besides, molds are prone to erosion after repeatedly used and the liquid metal can be contaminated by eroded particles[3,4]. Moreover, since pouring mostly managed by manually by foundrymen, formation of pouring defects are highly possible[5]. For this reasons, sand casting is not favorable for high-strength material casting.

To overcome most of these main problems, ablation casting method was developed. A process that employs cooling liquid to dissipate the sand mold and achieve high cooling rates for solidification at the same time. Therefore, the growth of both porosity and grain size is restricted and secondary dendrite arm spacing is reduced, resulting with better mechanical properties which any other sand casting method yet to achieve so far[5,6]. Ablation casting firstly applied for low melting point alloys i.e. aluminum and magnesium alloys successfully. The first products of ablation casting manufactured for automative industry components.

The aim of this study is to produce a 356.0 Al-Si alloy with fine eutectic structure and small secondary dendrite arm spacing by ablation casting which the sand molds are clay-water-sand mixture (greensand) instead of chemical bonded dry molds. The elimination of chemical binders improves dissipation characteristics of the mold and provide longer mold material life.

1.1 Aluminum

Aluminum, is a chemical element belongs to 3A boron group on the periodic table with a symbol **Al** and has an atomic number 13. Aluminum has an atomic weight 26,981 gr/mole and 2,7 g/cm^3 density which is comperasively lower than other metals such as iron, copper which has a 7,83 g/cm^3 and 8,96 g/cm^3 density values respectively. It is the most abundant metal on the earth's crust (approximately 8% by mass) and third most abundant element on the earth after oxigen and silicon. Aluminum has a face centered cubic (FCC) lattice in solid state. Each cell contains 4 atoms therefore the coordination number is 12[7].

Aluminum generally can be found as oxides or sulfides on the earth rather than native state since its reactive nature and reducing properties upon other elements. The most common ore of the aluminum is bauxite, a mineral consist of gibbsite [$Al(OH)_3$] , boehmite [(γ-AlO(OH)] and diaspore [α-AlO(OH)] mixed with the two iron-oxides, goethite [FeO(OH)] and haematite (Fe_2O_3), the clay mineral kaolinite ($Al_2O_3.2SiO_2.2H_2O$) and anatase TiO_2[8]. The purification of aluminum managed with chemical reduction of bauxite according to following reactions[7];

Bayer Process

$Al(OH)_{3(sol)} + NaOH_{(liq)} \Leftrightarrow NaAlO_{2(liq)} + H_2O$

$2NaAlO_2 + 4H_2O + 2NaOH + Al_2O_3 \,.\, 3H_2O$

Electrolysis of Aluminum Oxide

$Al_2O_3 <=> AlO_2^- + AlO^+$

$AlO_2^- \Leftrightarrow Al_3^+ + 2O_2^-$

$AlO^+ \Leftrightarrow Al_3^+ + O_2^-$

$Al_3^+ + 3e^- \Rightarrow Al$

Pure aluminum is more resistant to surface oxidation whereas iron is more susceptible to rust away unless its alloyed with elements providing stainless properties. The exposed surface of aluminum forms a transparent, very thin and stable layer with oxygen to prevent surface corrosion as this protective layer doesn't flake and fall off from the surface. Also, like certain stainless steels, heat treated aluminum alloys can be resistant to stagnant media containing chloride ions, acids and sea water[9].

Aluminum alloys are the best alternative as a structural metal, coming second only after steels, even though having approximately one third of weight. This feature is beneficial for developing lightweight and high strength structural components, especially for automative, aerospace and aircraft industries.

1.1.2 Aluminum Alloys

The main objective to produce aluminum alloys is to increase the mechanical properties to achieve high strength component for commercial use. There are two main categories of aluminum alloys according to production method; Wrought alloys and cast alloys. These categories also divide into sub-categories regarding their strengthening mechanisms as aluminum alloys belonging each class have diversified physical and chemical metallurgies. For example some elements dissolve more than other elements in aluminum to form a solid solution therefore an appropriate heat treatment process is possible strengthening mechanism for this type of alloys whereas some alloys gain strength by 'below recrystallisation temperature processes' (forming, extruding, rolling etc.) i.e cold working.

1.1.2.1 Alloying Elements

Aluminum is a soft and very ductile material in pure form (%99.999) and commercial grade(%99-%99.997) thus it has to be alloyed with certain elements to increase mechanical properties. Over 100 elements have solubility with aluminum but only nine of them have a solid solubility greater than 1 wt% and they alloyed for spesific production methods and strengthening process to reach desired mechanical properties[10].

-Silicon

-Magnesium

-Zinc

-Copper

-Manganese

-Silver

-Gallium

-Lithium

-Germanium

Within this group, germanium, silver, and gallium are comperatively expensive than the others and since lithium causes processing difficulties, they usually not combined with aluminum. The other five elements shown in Figure 1.1 are the most common elements to produce vast majority of aluminum alloys for daily use and various industries.

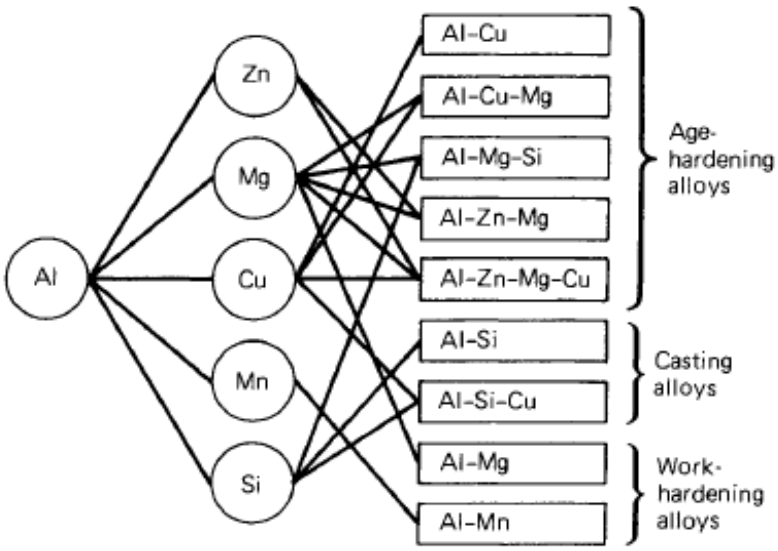

Figure 1.1 Primary alloying elements[10]

Silicon

Si is the second most abundant impurity in bauxite, an aluminum rich ore, owing to contain silica and silicate compounds. It is one of the most common alloying elements especially utilized in casting. Si addition improves fluidity of the molten metal and decreases hot tearing outstandingly. Improved fluidity allows molten metal to flow intricate and thin wall sections of complex shapes. Besides, the side effect of improved

fluidity results better feeding of casting during solidification and reduces shrinkage porosity[2].

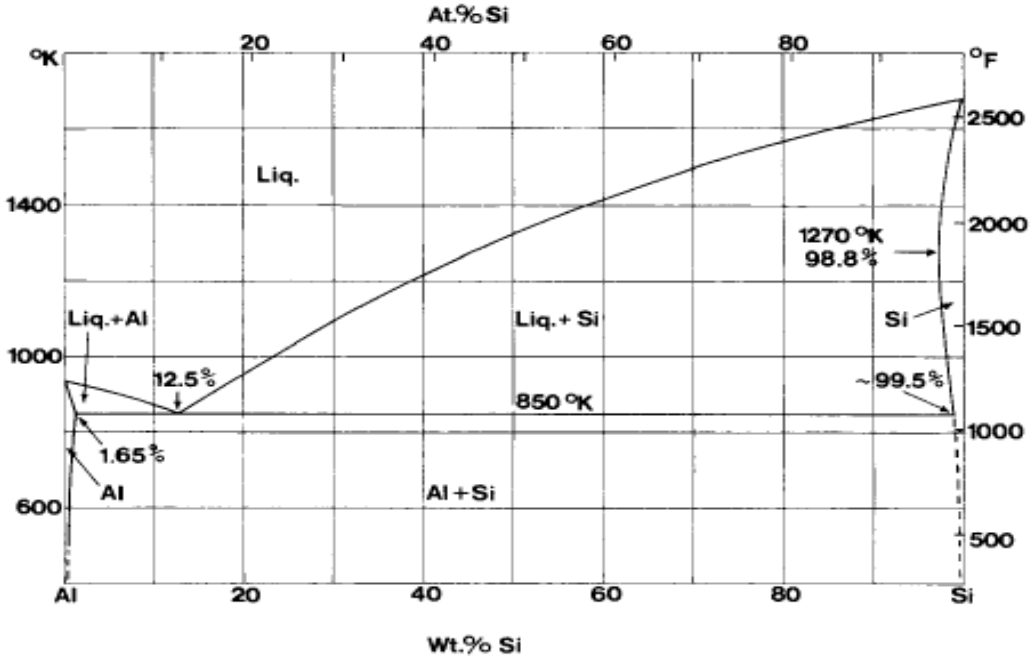

Figure 1.2 Al-Si Equilibrium Diagram[11]

Silicon content can be raised up to 30 wt% in Al-Si commercial alloys. The alloys containing less than 12.5 wt% are hypo-eutectic and alloys contain larger than this value are hyper-eutectic alloys. Hypo-eutectic Al-Si alloys exhibit good weldability and corrosion resistance with low specific gravity. Machining of these alloys are more challenging than Al-Cu and Al-Mg alloys. Hyper-eutectic alloys exhibit excellent wear resistance, low thermal expansion and better fluidity because of larger silicon content. [10]

- Silicon combines with Fe impurities in Al-Cu-Mg alloys to prevent formation of Cu_2FeAl_7 precipitates which reduces the excess Cu content and therefore heat treating response of the products. Moreover, addition of Si (0.5-4%) minimizes cracking possibility of these alloys.

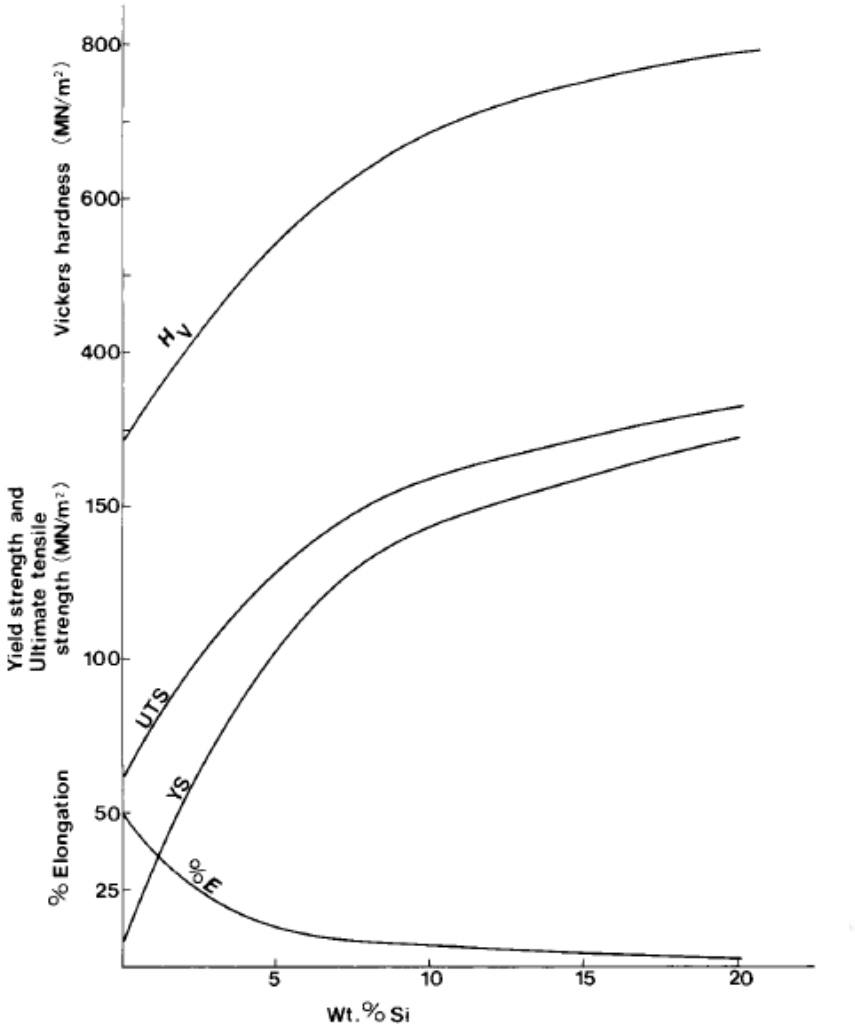

Figure 1.3 Mechanical Property changes with silicon addition[11]

Magnesium

Mg has a high solubility level up to 17.4 wt% in aluminum. High solubility provides a wide range of products between the range of 4-10 wt% Mg and compositions above 7 wt% Mg are heat treatable yet common wrought alloys contains max 5.5 wt% Mg as they have a better stability under normal conditions[10].

Solving 6 wt% Mg in Al can yields three times more strengthful alloys than those have 1 wt% Mg. Besides, Mg contributes to increase strength values with ductility by cold working and provides perfect corrosion resitance and (alloys with 3.5 wt% Mg min.) weldability[10].

Al-Mg alloys with low impurity levels especially selected for surface finished decorative products. However, highly anodic Mg_5Al_3 and Mg_5Al_8 phases can precipitate along the grain boundaries and these phases cause intergranular cracking and stress corrosion at the same time[10].

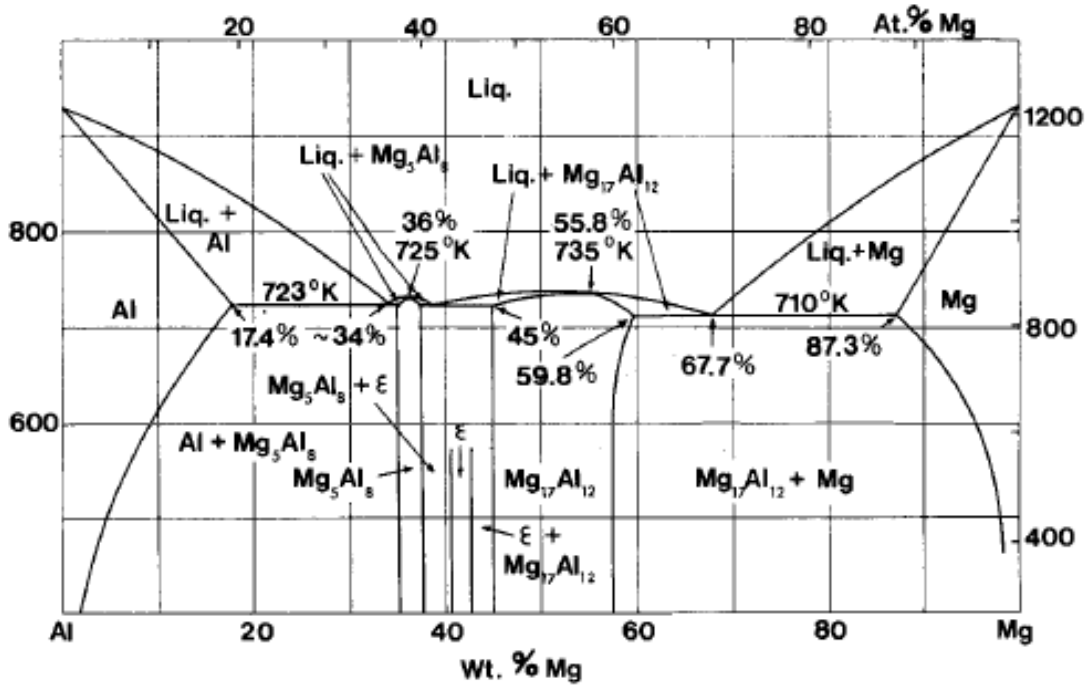

Figure 1.4 Al-Mg Equilibrium Diagram[11]

Casting of Al-Mg alloys is more challenging than Al-Si alloys as Mg increases the thermal expansion coefficient of the molten metal and thus precautions have to be taken while casting such as using proper risers and a carefully controlled cooling operation. Moreover, Mg has a high tendency to oxidization in liquid phase so melting and pouring have to be managed with caution also.

- Mg can be alloyed with other major alloying elements where different purposes necessary. Addition of Mg to Al-Si binary alloys between the range of 0.04-0.7 wt% increase the heat treatment efficiency and forms soluble Mg_2Si precipitates along the material and increase strength without compromising of ductility.

- Mg can be alloyed for increasing yield stress and UTS especially Al-7.5wt% Zn binary alloys due to formation of $MgZn_2$ particles via heat treatment processes. But increasing Mg content makes products vulnerable to corrosion[10].

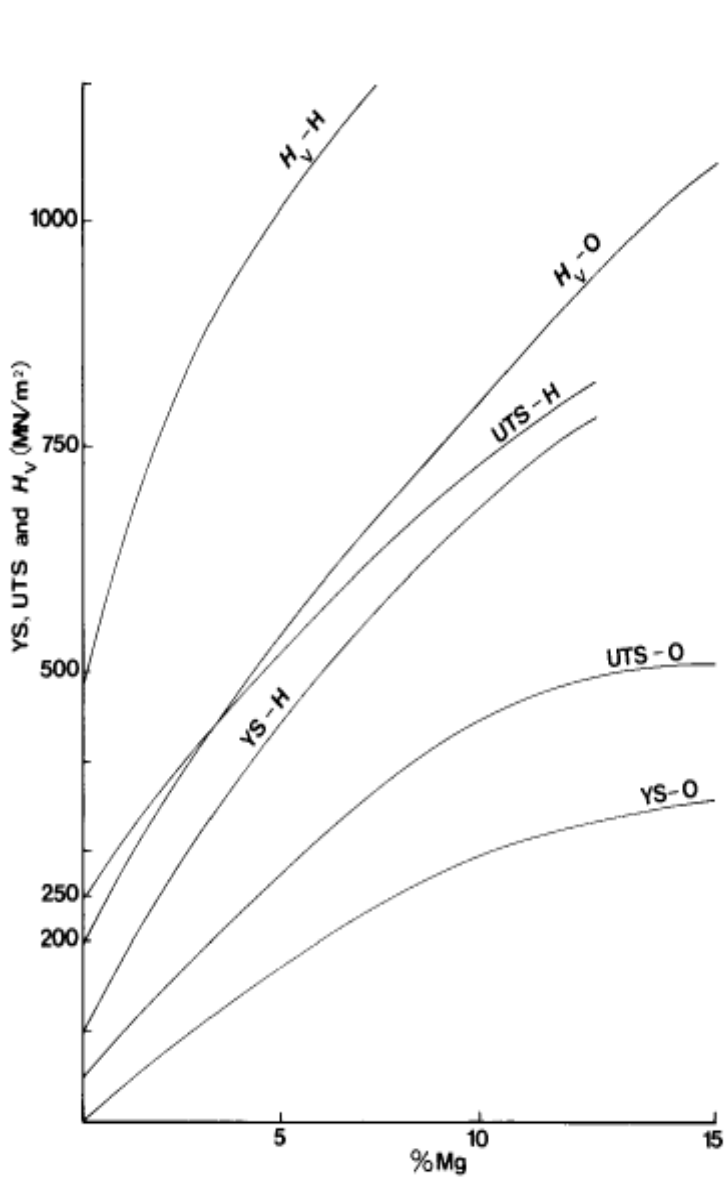

Figure 1.5 Mechanical property changes with magnesium addition[11]

The aging characteristics of wrought and cast Al-Cu alloys can be improved with just a little addition of Mg (about 0.05 wt%). High strength and ductile material production is possible by natural or artificial aging after solution heat treatment[10,11].

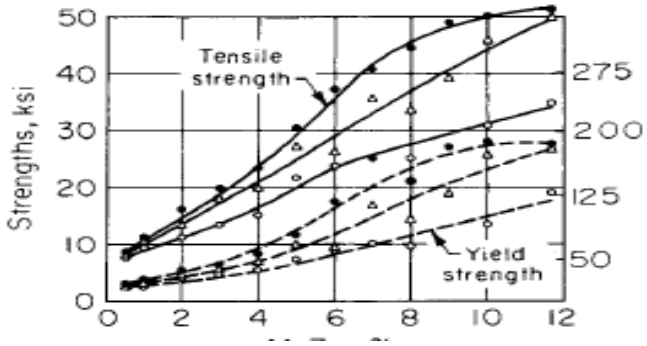

Figure 1.6 Effect of wt% MgZn2 vs. mechanical properties of %99.95 Al[10]

Copper

The main element for producing high age-hardening responsive wrought and cast Al alloys to improve strength and hardness via solution heat treatment and aging (generally T4 and T6) but reducing ductility and elongation. Cu has a solubility limit up to 10 wt% in Al but most production alloys contain Cu between 4-6 wt% as they give the best strength values among all combinations.

Formation of $CuAl_2$ intermetallic phase ease up the chip breakability during machining and improves tool life. The disadvantage of these alloys is their invulnerability to cracking while solidification since Cu promotes inter dentridic shrinkage and they exhibit less resistance to general corrosion although increasing resistance to stress corrosion[2].

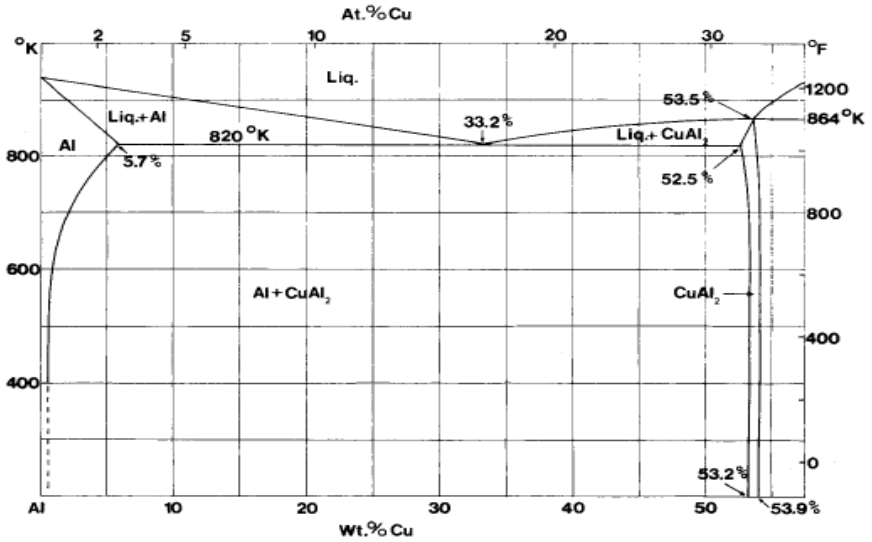

Figure 1.7 Al-Cu Equilibrium Diagram[11]

- Addition of Cu to the Al-Mg-Zn ternary alloys yields the most strengthful family of the Al alloys; 7xxx wrought and 7xx.x casting. The effect of Cu is increasing aging rate and quench sensitivity while Mg and Zn control aging process and forming $CuMgAl_2$ precipitates. As mentioned, Cu increases the stress corrosion resistance and reduces general corrosion resistance at the same time[10].

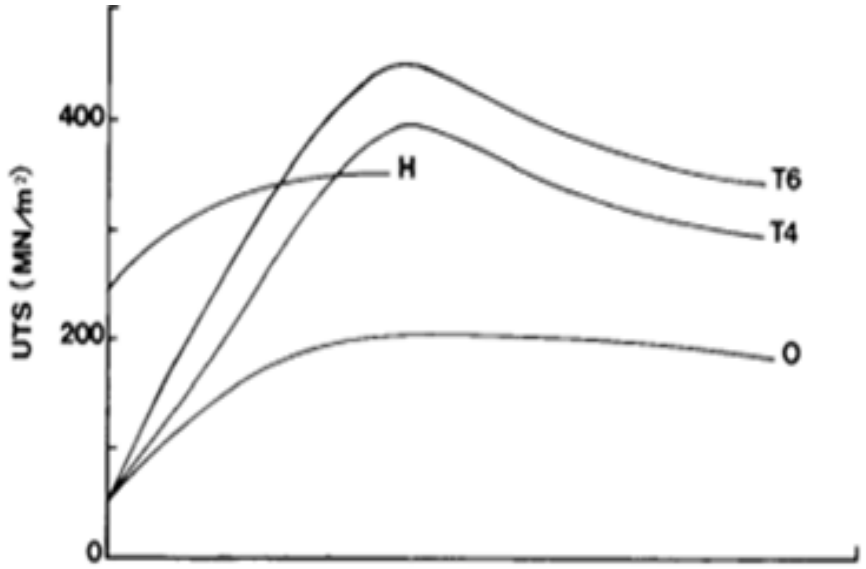

Figure 1.8 Effect of %Cu content on UTS heat treated(T4-T6), strain hardened (H) and annealed (O) conditions [11]

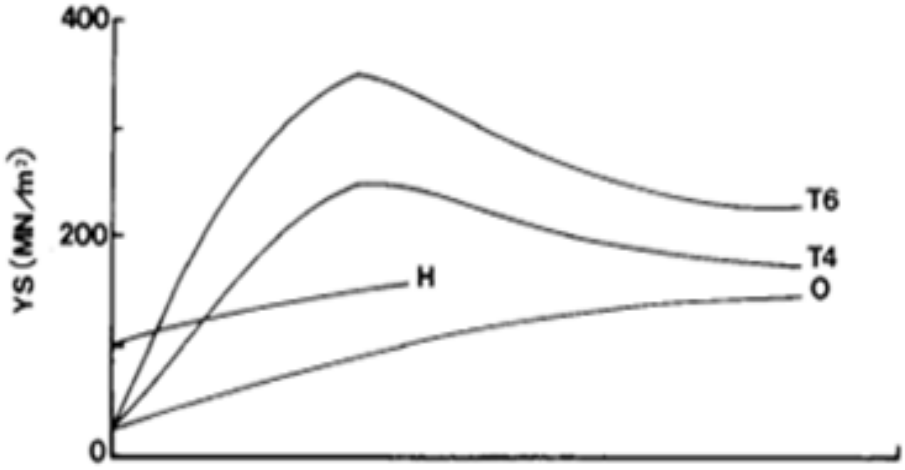

Figure 1.8 (Continue) Effect of %Cu content on mechanical properties heat treated(T4-T6), strain hardened (H) and annealed (O) conditions[11]

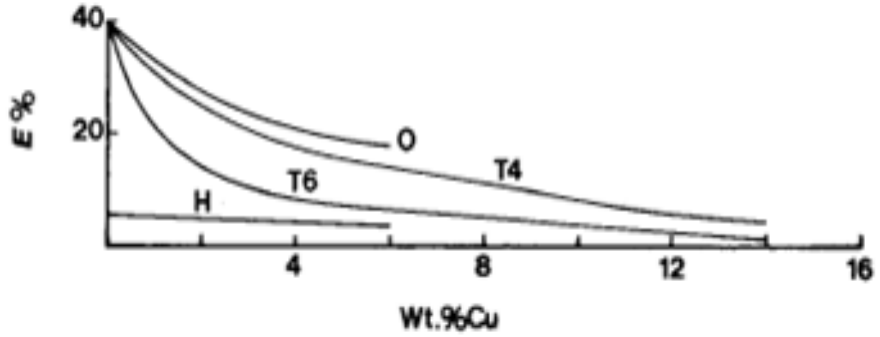

Figure 1.8(Continue) Effect of %Cu content on elongation heat treated(T4-T6), strain hardened (H) and annealed (O) conditions[11]

Manganese

Manganese is usually considered as an impurity in aluminum alloys and its content should be controlled. Despite having a low solubility in aluminum, addition of Mn yields beneficial effects on certain alloy systems. Mn mainly used for hardening to increase strength of wrought alloys with cold-working and shape corrector of acicular, needle-like and plate-like Fe impurities to reduce embrittlement[2,10]. Manganese has no significant adverse effect on corrosion resistance and can also introduced for adjusting chemical surface finishing and anodizing.

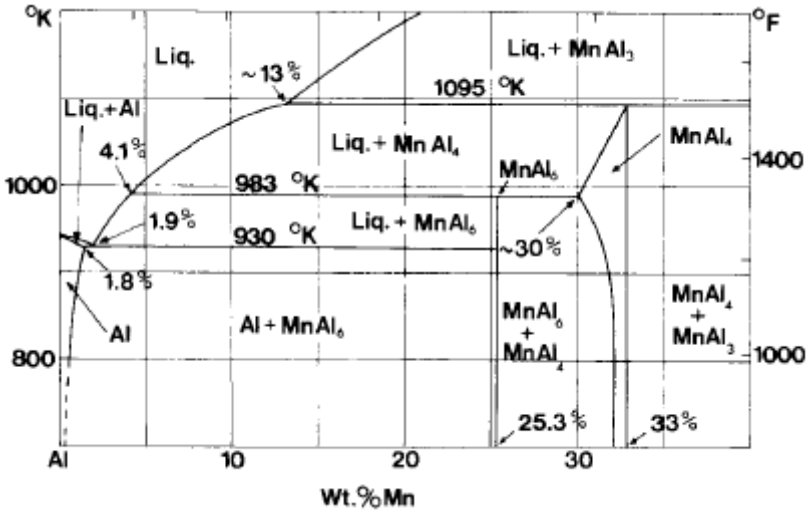

Figure 1.9 Al end of Al-Mn Equilibrium Diagram[11]

- Addition of 1.25 wt% Mn into 3xxx wrought alloys improves cold forming without any rupture occuring, especially while production of beverage cans.

The wt% Mn+Fe level should be kept under %3.7 to prevent formation of large $(Mn,Fe)Al_6$ particles[10].

- Addition of 0.75 wt% Mn to Al-Mg alloys increases strength and decreases ductility(Figure 1.10). This system exhibit good welding and corrosion resistance properties[10].

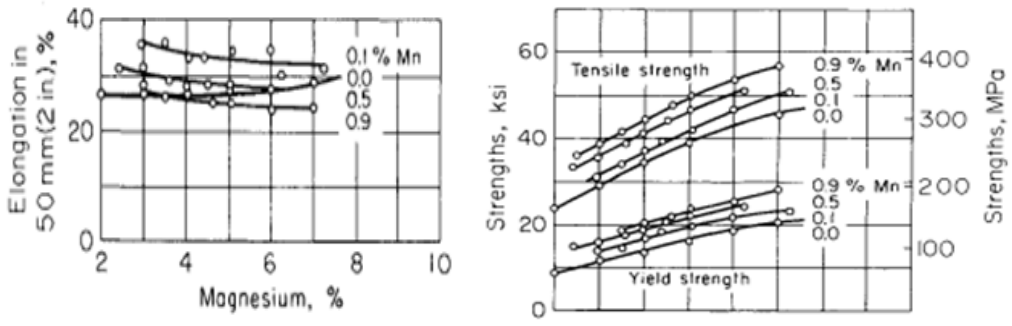

Figure 1.10 Effect on mechanical properties of Mn addition to Al-Mg

Zinc

The first alloying constituent for commercial aluminum products was Al-Zn binary alloys. Nowadays Al-Cu and Al-Si alloys replaced for most Al-Zn application as addition of Zn alone results hot tear of castings and reduced stress corrosion cracking of wrought alloys yet alone slightly improving mechanical properties. Nevertheless, they still stand for where electrolytic protection necessary for corrosion[10].

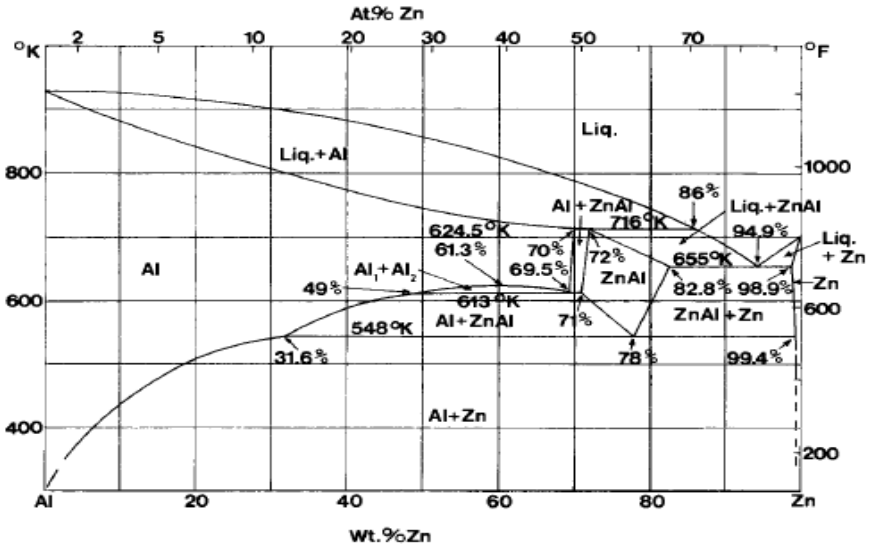

Figure 1.11 Al-Zn Equilibrium Diagram[11]

Aging temperatures of Al-Zn alloys are very low that products can be aged hardened even at room temperatures. This is a useful feature for heat treating complex shaped products without cracking or damaging more easily.

1.1.3 Alloy Designations

Before stepping into alloy types, it is good to mention aluminum alloy designations approved world wide. To select and specify an alloy with spesific properties for given application, its composition and state of heat treatment must be defined. The designation system for aluminum alloys created by North American Aluminum Association(AA), under registeration of American National Standarts Institute(ANSI) standart H35.1 and it is the most common system because of its simplicity. The designations of registered aluminum alloys are shown below tables.

Table 1.1 Aluminum wrought alloys designations [9]

1xxx	Al	Cold work
2xxx	Al-Cu-Mg (1-2.5% Cu)	Heat treat
2xxx	Al-Cu-Mg-Si (3-6% Cu)	Heat treat
3xxx	Al-Mn-Mg	Cold work
4xxx	Al-Si	Cold work (some heat treat)
5xxx	Al-Mg (1-2.5% Mg)	Cold work
5xxx	Al-Mg-Mn (3-6% Mg)	Cold work
6xxx	Al-Mg-Si	Heat treat

Table 1.1 (continue) Aluminum wrought alloys designations [9]

7xxx	Al-Zn-Mg	Heat treat
7xxx	Al-Zn-Mg-Cu	Heat treat
8xxx	Al-Li-Cu-Mg	Heat treat

1xxx defines the pure aluminum that have natural impurity limits. In this group, aluminum has a minimum 99,00% or greater purity. The last two of four digits indicates the fraction of the purity value of the aluminum. For example 1070 aluminum has a 99,70% purity. If the second digit of the designation other than zero(from 1 to 9), implies special controlled impurities. Designation of series from 2xxx to 8xxx differs than 1xxx series as the second digit indicates spesific alloy additions and the last two digits of all series designates the different alloys in the groups[12].

Table 1.2 Aluminum cast alloys designations[9]

Aluminum, ≥99.00%	**1xx.x**
Aluminum alloys grouped by major alloying element(s):	
Copper	2xx.x
Silicon, with added copper and/or magnesium	3xx.x
Silicon	4xx.x
Magnesium	5xx.x

Table 1.2 (continue) Aluminum cast alloys designations[9]

Zinc	7xx.x
Tin	8xx.x
Other elements	9xx.x
Unused series	6xx.x

Designations of casting alloys almost similar yet a bit different at the same time than the wrougth alloys. First of all, pure cast aluminum and cast alloys have a decimal digit to indicate whether the product is in the cast state (xxx.0) or ingot state (xxx.1 or xxx.2). This applies to all series. For the 1xx.x series, the second two digits designates to the purity of aluminum, whereas the second two digits of the other entire series indicates nothing significant apart from stating different alloys[12].

1.1.4 Temper Designations

The designations of tempering processes of aluminum alloys are valid for both wrought and cast alloys. Temper designations stated with capital letters for major heat treatment process and following digits indicates the process sequences. Additional digits may be used for indicating different tempering conditions. Basic temper designations are explained briefly below.

F stands for As Fabricated state of the material which means no spesific heat treatment or cold working procedure followed after forming processes (rolling, forging, extrusion etc.) or casting processes (die casting, sand casting etc.)[9,12]

O stands for Annealed state. ‘O’ indicates that the product heat treated above the recrystallization temperature to achieve lowest strength levels and maximize the workability and toughness for wrougth alloys. Annealing is not a common process for

cast alloys yet some products may subsequently annealed after die casting to improve dimensional stability and ductility[9,12]

H stands for Strain Hardened state, used for the non-heat treatable alloys. The digits coming after the capital indicates numerous processes after strengthening the product by cold-working. Strain hardening only applicable for wrought alloys and designation divides into sub-groups below[12,13]

H1 – Strain Hardened

H2 – Strain hardened and partially annealed

H3 – Strain hardened and fully annealed

H4 – Strain hardened and painted

Additional digits used for indicating cold-work degree (i.e. hardness level) of the product.

HX2 – ¼ Hardness

HX4 – ½ Hardness

HX6 – ¾ Hardness

HX8 – Full Hardness

HX9 – Extra Hardness (UTS exceeded)

H temper designations may have a additional third digit corresponding to special finishing applications applied on the materials to modify chemical or physical conditions[12].

W stands for Solution Heat-Treatment for unstable alloys that can naturally aged at room temperature after the process. Digits coming after capital letter specify the cooling time by fractional numbers[12]

T stands for Solution Heat-Treatment for more stable wrougth and cast alloys at room temperature and divides into sub-groups below. Additional digits can be added for stress relieving conditions for wrougth products. [12,13]

T1 - Cooled from high temperature forming and naturally aged

T2 - Cooled from high temperature forming then cold worked and naturally aged

T3 – Solution heat treated then cold worked and naturally aged

T4 – Solution heat treated and naturally aged

T5 – Cooled down from high temperature forming and artificially aged

T6 – Solution heat treated and artificially aged

T7 – Solution heat treated and overaged

T8 – Solution heat treated then cold worked and artificially aged

T9 – Solution heat treated then artificially aged and cold worked

T10 – Cooled down from high temperature forming, cold worked and artificially aged

1.1.5 Wrought Alloys

1xxx alloys have very low strength due to low level of alloying elements that prevents dislocation motion through the material to increase strength. The ease of plastic deformation gives those alloys a perfect formability and workability. Besides, fewer alloying elements means there are a lot less intermetallic compounds to disperse along the pure aluminum surface thus corrosion resistance is extremely high. Also, pure aluminum is highly reflective and a good thermal and electric conductor as electron mobility is much easier in pure materials than alloys[14]

Applications: Properties of these alloys makes them very appropriate for packaging (household foils, food containers, etc.), electronic devices like electrical cables, capacitors, heating equipments (heat exchanger strip, radiator tubes, etc.), lighting applications (reflector casings, laser mirrors, etc) and decoration (furniture fittings, outdoor applications, etc.)[14].

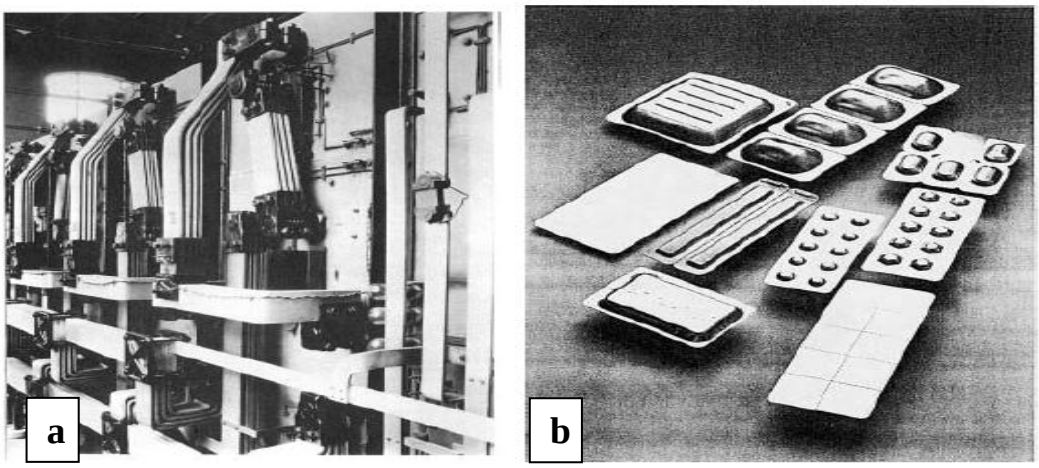

Figure 1.12 a)Pure Aluminum bus-bar(1350) and b)pill containers (1100) [12]

2xxx series are the second most strengthful alloys coming after 7xxx series. These alloys are suitable for precipitation hardening increases the fatigue, mechanical and high temperature properties with addition of copper (3-6 wt%) and magnesium whereas necessary (0-2 wt%). However, this type of materials tend to corrode in stagnant environments without necessary heat treatments as copper precipitates along grain boundaries and create a anodic-cathodic reaction zones. Solution heat treatment reduce the stress corrosion cracking risk(understanding Al alloys). Several elements also can be added in with caution to adjust spesific properties like strength (Mn, Ag, Ni), welding(V, Zr, Ti), aging behavior (In, Sn, Cd) and machinability (Pb)[14].

Applications: These alloys are used for high strength structural applications such as aircraft fittings, wheels, military vehicles, bridges, forgings for trucks, screws, bolts, fittings, machinery components[12]

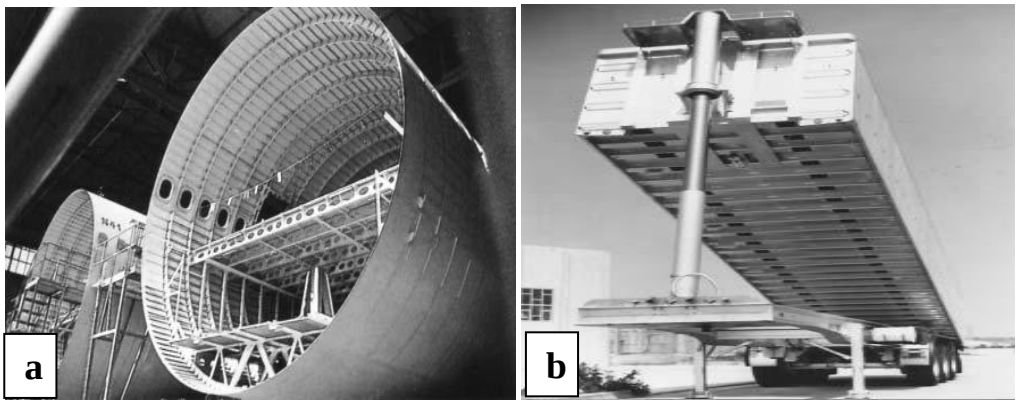

Figure 1.13 2xxx alloy a)Aircraft internal structure and b)Trailer structures[12]

3xxx Manganese makes the alloys very ductile so this type of series is suitable for forming processes like pressing, rolling and drawing. Fine Mn particles also stabilizes the grain growth while annealing which slightly improves the strength. Addition of Fe improves castability and surface conditions in forming operations. Like 2xxx series, Mg is added to help increasing mechanical strength. Also 3xxx series alloys exhibit good corrosion resistance[14]

Applications: Beverage cans, architectural sheets, automobile radiators[12]

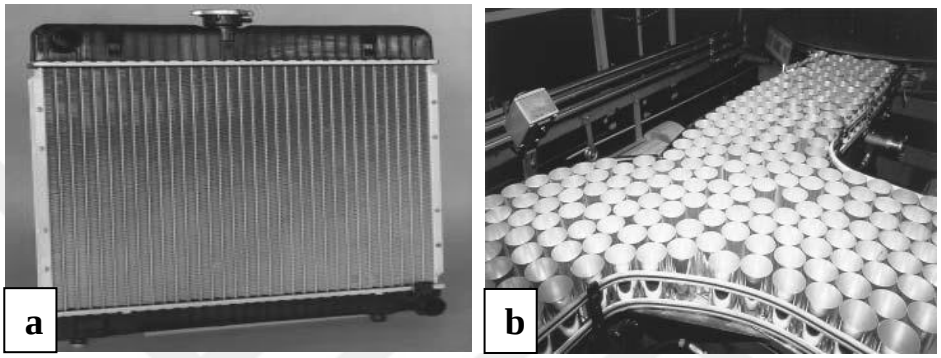

Figure 1.14 a)3002 alloy radiator and b)3104 alloy beverage cans[12]

4xxx alloys are low ductile thus have low formability alloys as brittle intermetallic compounds and elemantal Si precipitates along the material Al-Si alloys are much more used in forging complex parts like pistons and cast parts as Si reduces the shrinkage while casting and increases the flowability of molten metal[2]. Elements P, Ca, Ni added in to adjust mechanical properties. 4xxx alloys are susceptible to humid environment corrosion[14].

Applications: Cladding alloy for brazing sheets, automobile chassis welding applications[12]

Figure 1.15 4043 alloy welding wires on automobile structure[12]

5xxx series are the Al-Mg alloys which are the most strengthful non-heat treatable group, appropriate materials for outdoor, marine and automobile applications since they have good formability, toughness, corrosion resistance(under certain circumstances), weldability and high anodising quality at the same time. Mg is a great solute metal for Al as their atomic sizes are close to each other, yielding a good solution strengthening. Magnesium solution above 3 wt% not recommended for high temperature applications as material sensitizate[14]. Cr and Mn can be added in to improve corrosion behavior and toughness[10].

Applications: anodised and electrocoloured facade panels, scaffolding, ship building, platforms, press formed body-parts and chassis components[12]

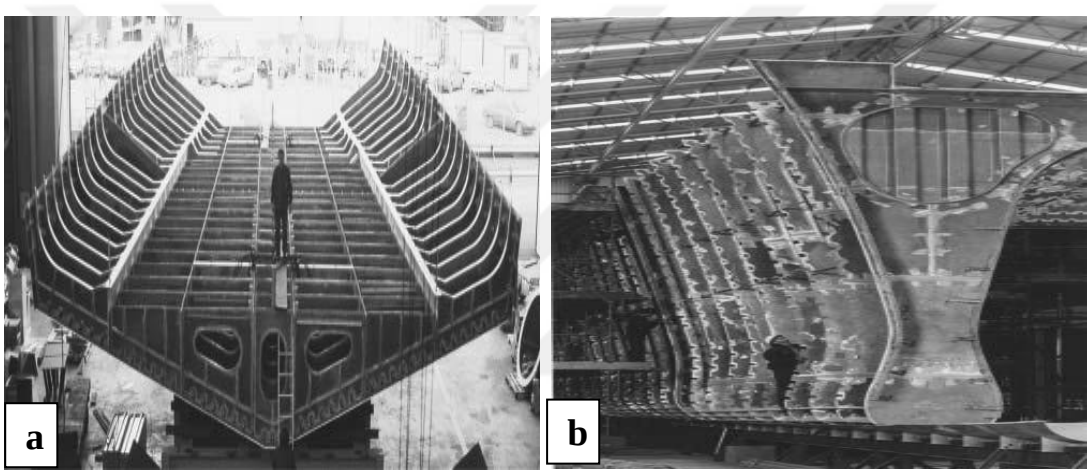

Figure 1.16 a)5xxx alloy High speed boat hull and b)high speed ferry hull[12]

6xxx alloys are precipitaton hardening Al-Mg-Si alloys. They have a much better strength, welding, corrosion, formability properties than 5xxx series. Addition of Si up to 12 wt% forces the Mg_2Si particles to precipitate and improve mechanical abilities.

Furthermore, 6xxx series can be produced with extrusion with the addition of low melting point elements (Pb, Bi) for machining products as they improve the chip breakability[10]. Like 5xxx series, Cr can be added in to control grain growth mechanism while heat treating, improve corrosion resistance and electrical resistivity [14].

Applications: automotive outer body-panels, railcars, doors, windows, ladders, off-shore, brazing sheet, roof structure[12]

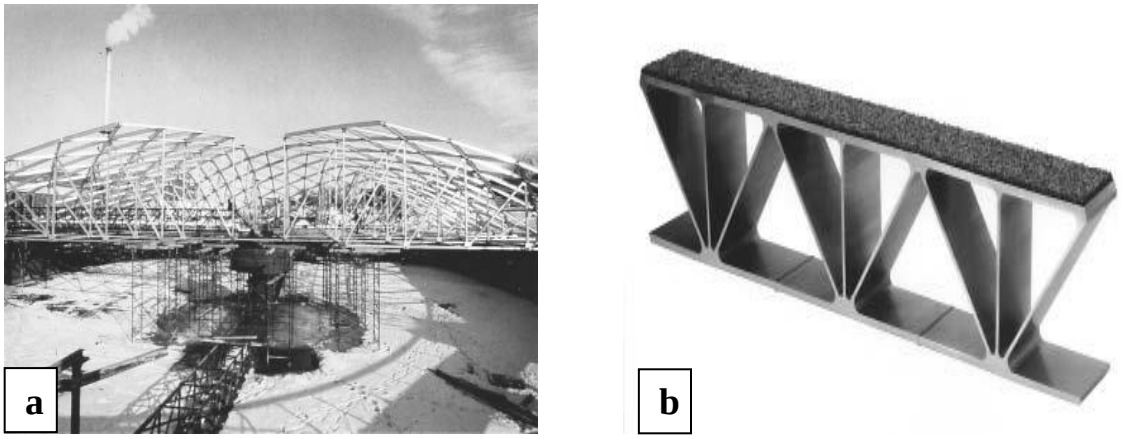

Figure 1.17 6063 alloy a)roof construction tubes and b)stiffened deck shape

7xxx series are the ultra-strength Al-Mg-Zn-Cu alloys because of their superior response to heat treatment(precipitation hardening). Like some 2xxx series, Mg and Zn increases strength forming $MgZn_2$ intermetallic phase while age hardening. The presence of Cu improves the aging behaviour and quenching abilities[10]. However,Mg, Zn and Cu reduces overall corrosion resistance of the material. As with 6xxx series, Cr addition up to certain levels increases the corrosion resistance as well as Ag[14].

Applications: aerospace, space exploration, military and nuclear applications, ski poles and tennis rackets[12]

8xxx series consist of Al alloys containing both major elements and miscellanous elements. Al-Li and Al-Fe binary system alloys are the main products of this series which alloyed with major elements Mn, Zn, Si and other minor elements like Ca, Ni and Sn to produce materials for different purposes. The combinations of these elements yields various application products from stiff aerospace parts and aluminum foils[14].

Applications: Al-Li alloys are stiff materials due to high solubility of Li in Al and good responsiveness to heat treating operations yielding coherent $LiAl_3$ precipitates. This type of alloys are useful for aerospace applications. Al-Fe-Si alloys are suitable for foil making and heat exchanger material. Al-Ni-Fe ternary system alloy products are good corrosion resistant materials for high temperature aqueous environments appropriate for nuclear powerplant applications[14].

1.1.6 Cast Alloys

Cast Al alloys are nearly identical systems as wrougth alloys yet there are some important differences between them. Cast Al alloys contain larger amounts of eutectic former elements (widely Si) than the wrought alloys to obtain optimum flowability to fill the blank mold and reduce shrinkage porosity by feeding the solidifying metal. Alloys containing Si up to 12 wt% (eutectic point of binary system) allows casting complex shapes more easily and eliminates scraps effectively. Cast Al alloys divide into the series as below.

2xx.x series are heat treatable Al-Cu (4-5 wt%) alloys generally containing Mg, Fe and Si impurities. Alloys containing 8-9 wt% Cu exhibit good mechanical properties without any further heat treatment can replace Al-Cu-Si ternary system alloys where necessary, although they exhibit lower strength and castability[13]. Cautions have to be taken on the heat extraction and grain refinement while solidification during permanent mold and rigid mold casting as feeding abilities of these alloys are relatively lower than Si – rich alloys[2]. Addition of Mn reduce hot-shortness risk at the expanse of castability degree. Replacing Ni upon Fe yields good high temperature strength. Ag increases to the response to heat treatment[10].

Applications: Aerospace, aircrafts, switchgear, piston heads, bearings[12]

Figure 1.18 Cast Aircraft component 201.0[12]

3xx.x series are heat treatable Al-Cu-Si or Al-Si-Mg alloys which is the most widely used cast alloy group due to their higher Si content provides fluidity and their greater response to heat treatment. Some alloys contain higher Si content where fluidity is necessary whereas some other contains higher Cu to increase strength and machining. Alloys near Hypoeutectic Si concentration are suitable for casting of complex parts.

Alloys with Hypereutectic Si concentration (12-30 wt% Si) exhibit good corrosion resistance[2]. Further, the 3xx.x alloys are suitable for various conventional casting applications (sand, permanent mold, die casting, investment) as well as newly developed thixocasting and squeeze casting processes.

On the other hand, Al-Si-Mg ternary alloys are the first selection where greater castability and corrosion resistance needed. Generally Cu containing alloys are more stronger than those have Mg, yet some alloys can compete in terms of strength owing to their excellent heat treatment response. Be addition is another way to increase mechanical properties[2].

Applications: Automative engine blocks, pistons, gearbox case, aircraft construction parts [12]

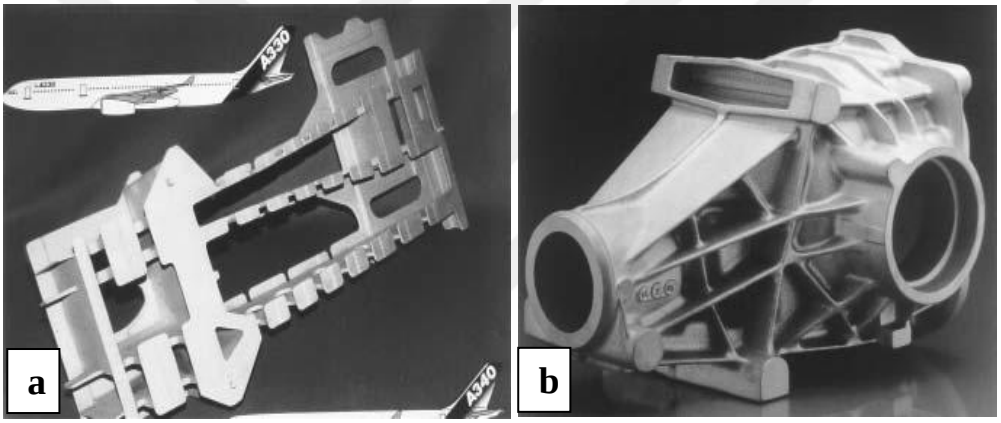

Figure 1.19 a)Turbo frame A356.0-T6 b)380.0 alloy automobile real axle housing

4xx.x series are non heat treatable Al-Si binary alloys which exhibit good flowability, good corrosion resistance, good weldability with moderate mechanical properties. Mg can be added to improve strength and hardness with heat treatment[13]. Moreover, addition of eutectic modifiers like Na or Sr to control Si rich eutectic precipitates in hypo-eutectic alloys (wt% Si<12) and P for hypereutectic alloys (wt% Si>12) can be beneficial to adjust strength and ductility[2].

Applications: Housings for typewriter and computers, marine and architectural applications, dental equipments[12].

5xx.x series are non heat treatable Al-Mg alloys which have good corrosion resistance to marine applications (materials with high quality i.e. low impurity levels) with moderate

strength values. Al-Mg alloys require much more caution than Al-Si alloys while casting as larger riser and greater chilling effect needed for heat extraction to obtain proper products[13]. Also, Mg has a high tendency of oxidization especially at molten state causes to form oxide particles along the cast part while pouring, creating handling difficulties and undesirable second phases affecting the quality of the product. Note that alloys containing >7 wt% Mg are heat treatable to stabilize their chemical composition rather than increasing strength[2].

Applications: Anodized decorative parts, seawater applications[12]

7xx.x series are heat treatable Al-Zn-Mg alloys. 7xx alloys are very prone to aging as they can reach the strength limit within a month undergoing naturally aging. Artificial aging can accelerate the aging process to improve hardening, whereas annealing improves the dimensional stability[13]. These alloys exhibit average mechanical properties and good corrosion resistance (with a controlled composition). Casting and solidification phases require cautions and practice as castability is weak high solidification rates promotes microsegregation[2].

Applications: Furnitures, gardens, Office machines, farming equipments[12]

8xx.x series are heat treatable Al-Sn alloys which is the first selection materials for bearings and bushing parts where achieving comperessive and fatigue strength and corrosion resistance is the main purpose. Alloys containing 5-7 wt% Sn are widely used on casting applications. Many of major alloying elements, Cu, Mg, Si for example, added to improve different properties of the products[13].

Applications: Bearings, bushings [12]

1.2 Casting

1.2.1 History of Casting

The manufacturing habits of humanity seems to be started at Neolitic Ages, nearly 10.000 years before today. Early humans began to beat materials to shape them into a useful form. During the next 5.000 years, fire has introduced to clay for manufacturing ceramic potteries, which will be utilized to melt materials other than stones. With this exploration, humans realized to shape materials more easily than beating. The history of casting begins from this checkpoint, ending the neolithic age to shift bronze age[1].

The first objects produced with casting is axes made of native copper. At first, the process includes only melting the metal in the ceramic pottery and pouring on carved stone molds as in Figure 1.20 below. Development of furnaces and introducing charcoal as fuel helped to achieve and maintain the necessary temperature for melting and create a reducing media inside the furnace leads to the discovery of smelting[1].

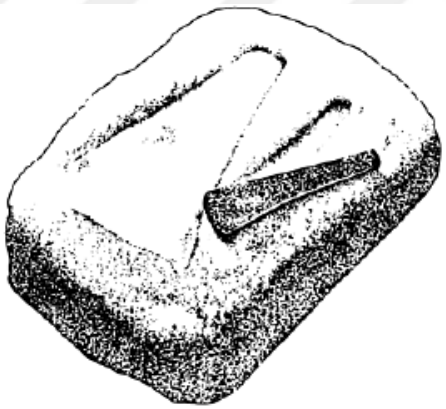

Figure 1.20 Bronze age stone molds [1]

The first alloy cast within the bronze age was Cu-As 4 wt% i.e arsenical copper. This alloy was in use through a vast area from British Islands to Middle East. The addition of tin into molten copper, whether on purpose or involuntarily, lead to the invention of bronze, an alloy which has improved properties such as strength and surface quality than earlier cast products. Evidence found around the world show that first closed-die casting and lost wax casting(first sand casting attempt) experiments are carried out in the bronze age[1].

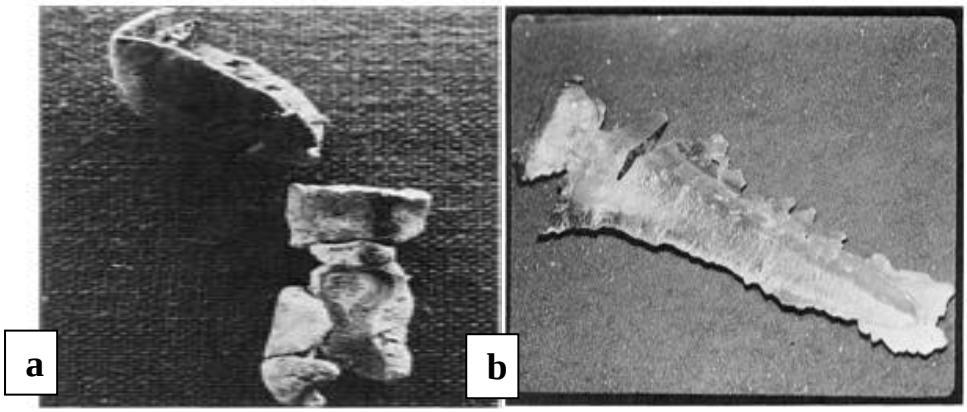

Figure 1.21 a)Lost Wax patterns and b)cast sword[1]

About 1500 years after the Bronze age, the world entered a new age called Iron Age with the processing of Iron. Chinese people built massive statuary with the development of cast iron in about 600 BC. European nations introduced with cast iron much long after its invention about 15th century. Cast iron was the first choice for bell and gun production. By the 18th century, cast iron was a significant material for structural purposes like bridge constructions[1].

By the end of the 19th century, aluminum is produced in pure form by Charles Hall and Paul Heroult. With the development of chemical reduction process, prices of aluminum dramatically declined and made an impact on the casting production, becoming an important engineering material for automative and aviation industry[13]. Introducing permanent molds and high pressure die casting methods upon sand casting supported the producers to develop new alloys and casting methods. Today, aluminum and aluminum alloys are one of the most preferable materials for vast majority of products[2].

1.2.2 Advantages and Disadvantages of Aluminum Castings[2]

- Aluminum exhibit excellent fluidity for casting thin sections
- Low melting point of aluminum reduces energy consumption
- Processes are can be fully automated
- Multicomponent parts can be cast as a single part
- Capital investment costs are less then wrought products
- Improved solidification characteristics

- Appropriate surface finish properties for aesthetic applications
- Solidification of complex geometries can results surface discontinuities
- Ductility of wrought products is better than cast products

1.2.3 Factors Effecting Mechanical Properties

1.2.3.1 Microstructure

Grain size

Grain size is directly related with mechanical strength according to Hall – Petch equation (1.1) below[16].

$$\sigma_y=\sigma_0+k_y(d)^{-1/2} \quad (1.1)$$

where σ_y is yield stress, σ_0 is materials constant for starting dislocation movement, k_y strengthening coefficient and d is the average grain diameter. Mostly, smaller grain size is a return of heterogeneous nucleation in metallurgy.

There are various ways for promoting heterogeneous nucleation in aluminum alloys explained briefly below;

a) It is possible to obtain smaller grain sizes with rapid undercooling according to the nucleation theory of crystals due to reduction of required energy for create stable nuclei within the liquid metal [17].

b) Addition of grain refining elements remarkably reduce grain size in aluminum alloys. The most common grain refiners for aluminum are Ti master alloys or both elemental Ti and B. The formation of $TiAl_3$ and TiB_2 phases increase the number of nucleation sites for aluminum and decrease grain size[1].

c) Modification of Al-Si alloys with small fractions of metallic Na,Sr, Ca and P yields finer sized and distributed eutectic structure. Silicon eutectics are usually precipitates in needle-like shapes, which acts as crack initiator sites and decreasing strength and toughness. The most useful modifiers for hypoeutectic alloys are Na and Sr whereas P for hypereutectic alloys. Each element obstruct the growth of silicon in eutectic phase and yields finer lamellar structure[2,5]

Grain refinement processes are advantegous for minimizing shrinkage and hydrogen porosity and eliminating hot cracking. The result of prohibition of these defects are

better feeding characteristics, mechanical properties, heat treatment response, post-casting finishing and tear resistance[1].

Dentride Arm Spacing (DAS)

Dentride arm spacing usually stands for secondary dendrite arm spacing (SDAS) in metallurgy (where exists). SDAS can be reduced with increased cooling rate(Table 1.3). Reducing dendrite arms spacing in microstructure results the same outcome as reducing grain sizes; better mechanical properties. Despite that, the mechanism of these two is not the similar as no grain boundary forms between dendrite arms thus Hall-Petch equation should be unvalid[3].

Table 1.3 Effect of cooling rate on DAS[2]

	Cooling rate		Dendrite arm spacing	
Casting processes	°F/s	°C/s	mils	μm
Plaster, investment	1.80	1	3.94–39.4	100–1000
Green sand, shell	18.0	10	1.97–19.7	50–500
Permanent mold	180.0	100	1.18–2.76	30–70
Die	1800	1000	0.20–0.59	5–15

There are several theories to explain this phenomena. A small misorientation could be arised due to high undercooling rates along the solidifying structure. Besides, high undercooling rates inhibits the growth of dendrite spaces and increases the nucleation sites for interdendritic phases. Further, these interdendritic phases don't have much time to coarsening, yielding a more homogenous structure[3].

According to another theory, high undercooling rates prevents bifilms unfolding, which is an entrapped defect[5] in the liquid metal due the turbulance while pouring. Bifilms emerge as round particles at the beginning of solidification and they grow detrimental sizes (up to 100 mm within the casting weighing several tonnes) as the time elapsed. Restricted growth of SDAS hinders the growth and unfolding of bifilms therefore increasing ductility of castings[3].

1.2.3.2 Porosity

Hydrogen Porosity

Hydrogen is the only significantly soluble gas in aluminum and aluminum alloys. Hydrogen solubility of liquid aluminum (0.65 mL/100 g) is far more greater than solid aluminum(0.04 mL/100 g) (Figure 1.22). Due to these differences at solubility values, large amount of dissolved hydrogen in molten metal becomes excess while solidification and may precipitate along the solid metal according to nucleation and grain growth theory, just as other solid phases do[2].

Hydrogen porosity occurs in two forms within the product; interdentridic and secondary porosity. Interdentridic porosity has more substantial importance than secondary porosity as it is observable at higher concentrations of hydrogen[2].

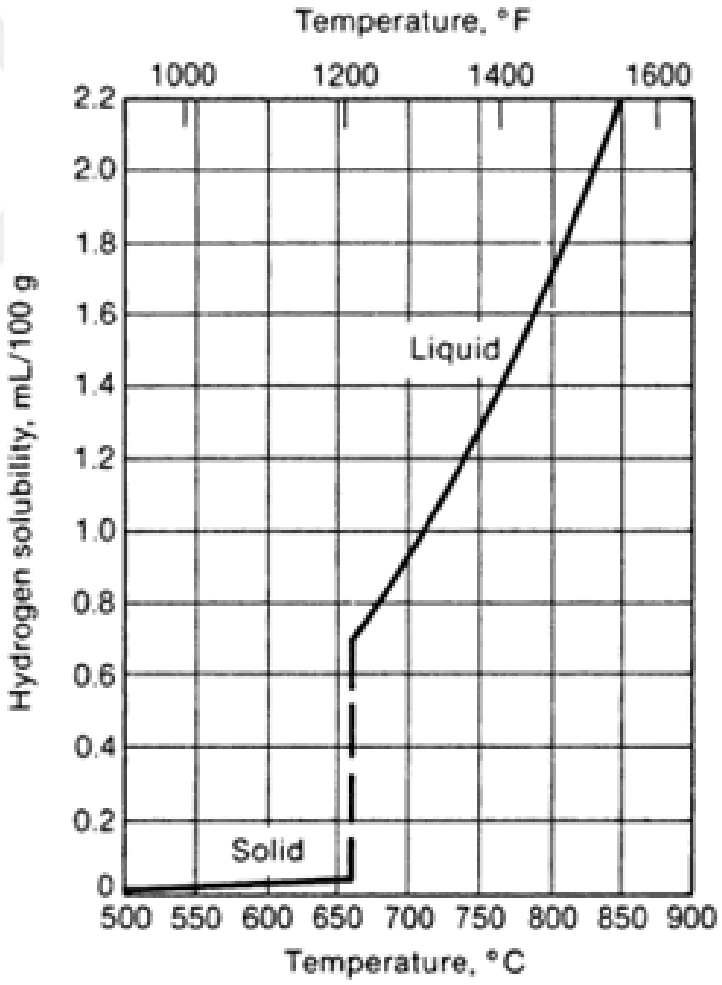

Figure 1.22 Solubility of Hydrogen in Aluminum[1]

The main source of hydrogen is the moist medium within the greensand molds or the incompletely dried refractories. The contact between liquid metal and aggregate mold, cores, tooling equipments offers hydrogen diffusion into the melt. Oxide forming alloying elements like magnesium could reduce the hydrogen diffusion resistance into the molten metal as oxide regions act as a hydrogen nucleation site.

Moisture containing salt fluxes and salt coated flux tubes can also increase hydrogen solution in the molten metal. Increment of hydrogen porosity directly affects the mechanical properties of sand cast aluminum alloys as seen in figure(1.23).

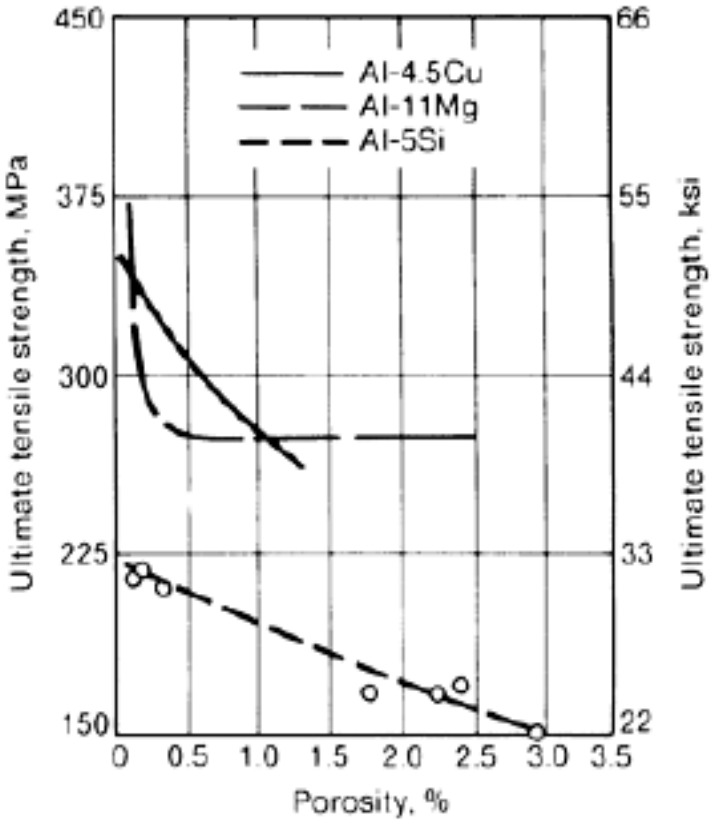

Figure 1.23 UTS vs. Hydrogen porosity for spesific Al alloys [1]

Shrinkage Porosity

Shrinkage porosity arises from the difference between liquid metal and solid metal volume. Many metals contract during solidification. For example, the volumetric change during solidification of Al alloys is 3.5-8.5%. Shrinkage porosity is related to

both solidification range of the metal and liquid/solid fractions of final product. As a metal starts to solidify, a fairly strengthful shell forms around the hot metal[2].

While the solid shell keeps on cooling, the process is under control of the solid state expansion and thermal coefficient, which is much lower than liquid metal and solid/liquid interface. If the tensile forces exceeds surface tension forces, the process results with shrinkage porosity. Shrinkage porosity could be hindered with enhanced grain refinement, feedability and reduced oxide contents[2].

1.2.4 Casting Methods

1.2.4.1 Non-Permanent Mold Casting Variations

Sand Casting

It is the simpliest and one of the most versatile type of non-permanent mold casting. Production of various alloys is possible with different shape and sizes under favour of freedom on designing. For lower or medium production rates and quantities, sand casting has the advantage of cheapest equipment and tooling prices. The dimensional accuracy is relatively lower and surface finishes of the products are poor, depending on the sand grade[1].

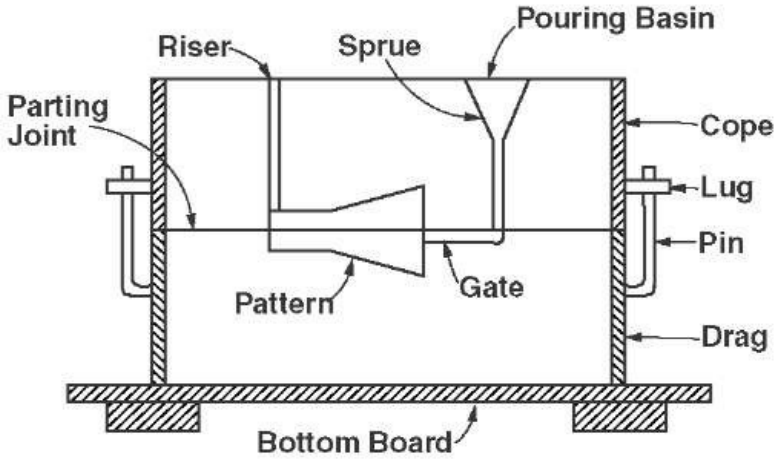

Figure 1.24 Typical Sand casting Mold [17]

Process involves pouring of molten metal into the mold cavity formed by wooden, composite or metal patterns, which are spesifically designed depending on the shape of final product. The runners and gates either can be attached to the pattern or manually

carved into the sand mold. Sprue pattern separately placed onto the pattern before sand molding. Chiller materials like copper, iron can be placed at the desired sections in the mold cavity[1].

The mold is compacted around the patterns equipments to obtain a solid structure to prevent deformation of the mold during casting. The permeability of the sand has to be taken into account while compaction of the sand mold as the gases will only extracted through the mold. Finally, sand mold shredded to reveal final product after molten metal solidified[2].

General Properties of Sands

Sand is a general word to describe molding materials used to produce sand molds. Since the origin of sand casting, a couple of different molding materials introduced which are not actually "sand" during the development of this method. Nowadays this materials are called as "aggregate molding materials" [5]. No matter how different they are from each other, all sand types should meet the requirements listed below[19];

- Dimensional and thermal stability
- Suitable particle size and shape
- Unreactivity with liquid metals
- Non-wetting liquid metals
- Non-volatile ingredients
- Economic
- Purity, cleanliness and stable pH
- Compability with binders.

Sand Requirements

Permeability

Permeability is a measure of how easily the exhaust gases transfered through the mold wall. In greensand molds, evaporation of moisture causes an expansion up to 30 times greater than its liquid state. Same dynamics also valid for the organic binders in dry molds that burn-out and transform to exhaust gases while casting[4]. If these gases entrapped inside the mold cavity they cause surface blows defects on solid casting[5].

Permeability of the sand molds is directly depends on porosity of the mold. Porosity degree can be controlled by grain size distribution of aggregate sand. A narrow grain size distribution increases porosity and creates a path for exhaust gases. Greater porosity degrees may lead to penetration of the liquid metal inside the mold wall. On the other hand, broader grain size distribution decreases porosity as finer grains fill between larger grains, leading a denser mold wall and reduces permeability[1].

Fineness

Fineness is a measure of grain size of aggregate sand materials. The grain size is determined by passing a sample of aggregate material through a series of sieves. Most foundries use AFS standart for grain fineness. The openings per inch of sieve which is the largest amount of sample pass through designates the fineness of the aggregate material. A detailed explanation of AFS grain number could be found[20].

Grain size of the aggregate material effects the surface properties of casting. Finer grains provides a smoother surface than coarser grains. However, finer grains reduce permeability as previously mentioned. Sacrifising between smooth surface and permeability of the mold is inevitable as both grain size and permeability inversely proportional[4].

Refractoriness

Refractoriness is the ability of the sand mold stay inert towards the liquid metal at high temperatures. Lower refractoriness of aggregate materials could cause reactions with molten metal, producing undesirable compounds that harmful for both sand mold and molten metal[5].

Green Strength

Green strength is a measurement for retaining the shape of the greensand while forming the mold, transfering the mold, pulling off cores or patterns, pouring liquid metal. A greensand mold should have sufficient green strength to resist external forces mentioned without deformation. Higher green strength makes easier to handle and use of the mold but reduces the formability of the greensand. Green strenth value is directly depends on clay and moisture content of greensand[4].

Dry Strength

Dry strength is the ability of aggregate mold to protect its shape during casting in dried conditions. The molds have enough dry strength to avoid erosion with liquid metal flow. Too much high dry strength results hot tearing and fracturing of solidifiying metal[20].

Collapsibility

Collapsibility is a degree of break down of the aggregate mold while knocking out An optimum collapsibility make much easier to brake the mold and pull out the cast product without any damage[4]

Durability

Durability roughly defines the "expiry date" of the sand mold. It is the ability of the aggregate mold to withstand multiple useage without losing its properties[20].

Sand Types

Selection of molding material is the essential stage of the sand molding, depending on cast metal type, core and mold preparing equipment, customer spesifications on final product etc. Most common sand types are described below;

Silica Sand

Silica sand is the most widely used aggregate material, consist of mainly quartz formed silica (SiO_2), ilmenite ($FeO\text{-}TiO_2$), magnetit (Fe_3O_4) or olivine [$(Mg,Fe)SiO_4$)]. It is easily available all around the World, has a high melting temperature and good particle size and distribution. Yet, phase transformation of α-quartz to β-quartz at 530 ^oC creating undesirable and uneven dimension changes around the mold cavity during casting. (e.g aluminum)[1].

Casting of materials that has a higher melting point like ferrous alloys, process is more complicated as β-quartz transforms to tridymite at 870 ^oC and contracts again and finally transforms to irreversable stable phase cristobalite at 1470 ^oC. The percentage of cristobalite increases as aggregate molds recycled and could reduce the probability of mold contraction when used on ferrous alloy casting, but this phenomena remains as a problem on lower melting point materials[1].

Figure 1.25 Silica Sand [21]

Zircon Sand

Zircon sand is a Zircon-Silicate compound ($ZrSiO_4$), highly refractory[20], low thermal expansion coefficient(stable mold properties at high temperatures), high thermal conductivity, round shaped aggregate mold material which makes it the first choise for steel foundries[1]. The chilling rate of zircon is four times greater than quartz sand which gives an enhanced ability of heat removal to the sand mold, but creating difficulties on thin sections. Zircon sand requires less binder than silica sand because of natural high denstiy and round shaped particles.

Figure 1.26 Zircon Sand [22]

Despite of all benefits, zircon is more expensive material than conventional silica sand. But the real cost of zircon sand comes from the material itself. Higher density means higher weights at the same volume, thus requiring higher energy consumption and strengthful equipments for automatic molding machines. High hardness of zircon sand makes them more abrasive towards molding equipment. Situations get worse with recycling of sand as sharp-edged zircon particles ratio increases, resulting more harmful materials[5].

Olivine Sand

Green colored, a forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4) compound, an alternative for silica sand which is suitable for steel casting. It has a lower thermal expansion and reaction tendency towards molten metal than silica[1]. However, olivine sand obtained from crushing rocks into small particles, yielding angular shaped particle that harmful for molding equipments. Olivine sand only responds for alkaline binders, making reclamation of sand more challenging. Iron content has a determining role on refractoriness level and has to be controlled for successful castings[5].

Figure 1.27 Olivine Sand [23]

Chromite Sand

($FeCr_2O_4$) is a black, highly refractroy angular sand suitable for steel casting foundrys. It has twice as much thermal expansion of zircon sand and it contains hydrous compounds which forms gas defects on castings. Chromite usually employed as a facing sand for silica sand molds and it causes chromite glaze, resulting poor surface properties of products. Furthermore, decomposition of chromite into fayalite (Fe_2SiO_4) and grunerite ($FeSiO_3$) reduces refractoriness and the chance of reclamation of sand molds[5].

Figure 1.28 Chromite Sand[24]

Greensand Molds

The term greensand refers to a low-strength, highly plastic sand that contains bonded water and clay mixture. It is the most common sand mold type for foundries as the ingredients of the aggregate mold are fairly abundant, cheap and minimal toxic content. Greensand molds are easy to produce and recycle as well since there is no need for chemical binders or baking process. The limitations of greensand molds are; they are rather fragile than dry sand molds and deform easily if required consolidation of aggregates not achieved or under heavy loads of cores or liquid metal used for casting. Humid content could cause condensations over the cores or chills inside the mold cavity so precautions have to be taken[5].

Bentonite

Bentonites are most commonly used clay for greensand molding. The arrangement of atoms produces a flat-layered structure as shown in Figure 1.29. This structure adsorbs water on the surface of the layers, creating clay-water bonds which holds the greensand solid.

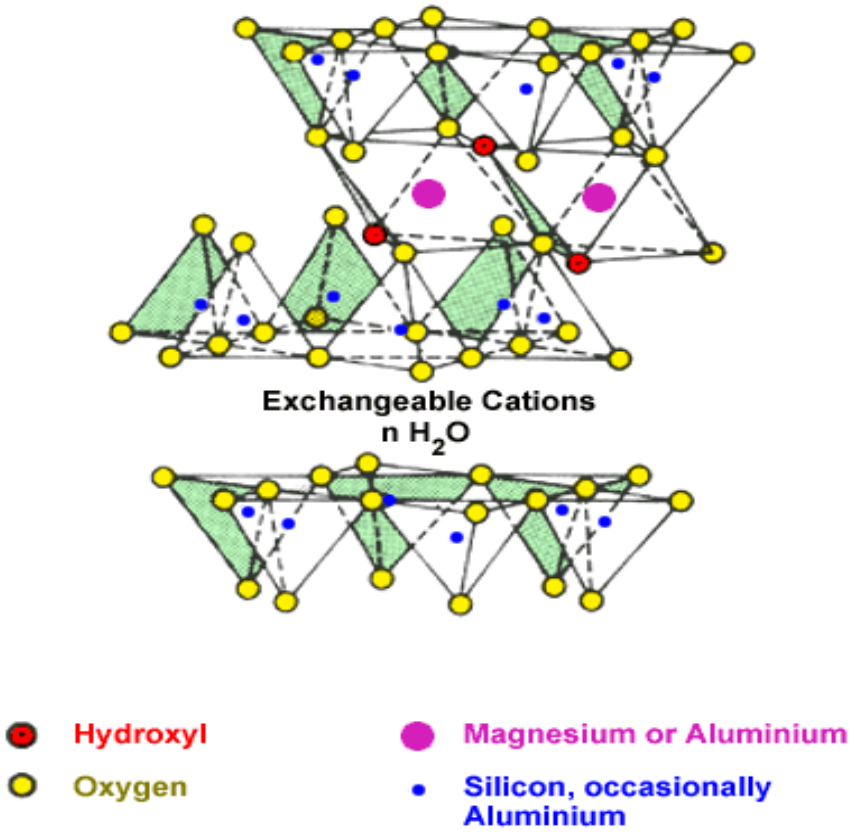

Figure 1.29 Bentonite atomic structure [25]

Bentonite exist in two forms; western bentonite and southern bentonite. The difference comes from the elements that takes place of aluminum atoms in the molecule structure. Sodium can be found in western bentonite whereas calcium is the exchange element in the southern bentonite[1].

Both exchange elements increase ionic activities to attract water molecules between the plates, yet resulting different properties. Western bentonite is a strong, durable, and effective water adsorbant. Southern bentonite is less durable, adsorbs less water to swell. Their low strength is advantegous for shaking out the molds and high density flowing through the complex patterns where employed with less pressure[1].

Clay-Water Bonds

As previously mentioned, bentonite clay bond with water to neutralize their ionic unbalances. This action creates a coating layer around clay particles and a bonding network (Figure 1.30) between clay and water molecules throughout the greensand.

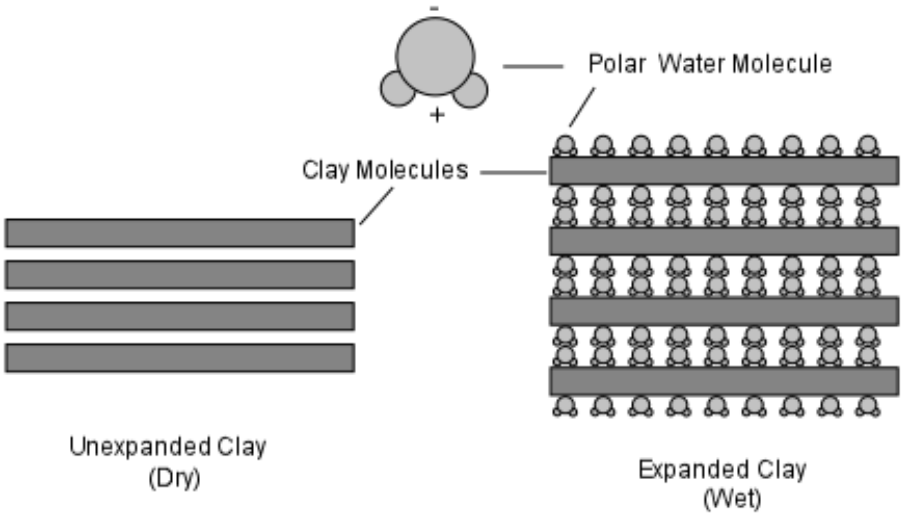

Figure 1.30 Water adsorbtion on clay particles [26]

Excess ions on the surface of clays create an electric field along the particle. Water molecules firstly attracted to these fields to possess electrical neutralization. At a critical water content, the bonding strength rises to the maximum (Figure 1.31) as the distance between clay particles reaches an optimum level that water dipoles are closest to the plate surfaces. The distance between clay particle will be increased as the critical water

content exceeded. Therefore, the water becomes liquid again and loses the bonding feature[27].

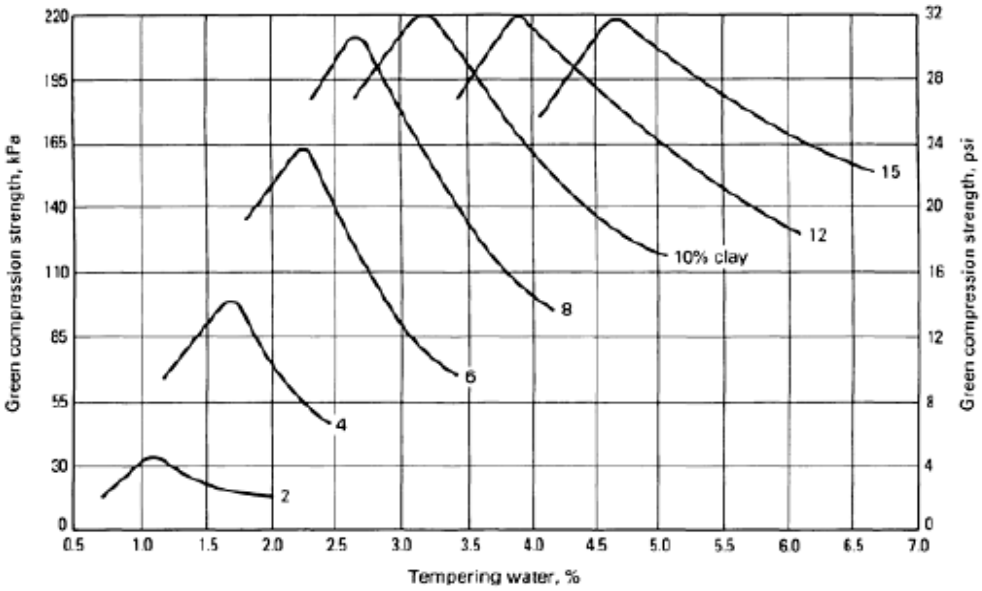

Figure 1.31 Green compression strength change of southern bentonite vs. water content[27]

Lost Foam (Evaporative Pattern) Casting

is a sand casting method that utilizes a (usually) PS (polystyrene) pattern covered with unbonded sand mold. The main purpose of this method is creating a mold cavity for molten metal to fill while pouring which will be formed by evaporating foam beads when contact takes place with molten metal. This method is very much like investment casting, but they separate in terms of pattern evaporating sequence as the pattern forming elements used in investment casting being eliminated before pouring liquid metal[2].

For this process, a pattern made of PS beads have to be produced by lost foam pattern molding processes and assembly with other parts of the pattern and gating system (Figure 1.32a). Strict controlling on pattern system is a necessary as assembling weaknesses can increase scrap rate of cast parts. An optional coating can be selected for smooth surfaces and adjusting permeability, which controls the extraction of gases formed during molten metal takes place[1].

After coating, the pattern is placed into a metal flask to covered with unbonded sand. Sand is have to be gently filled into the flask to not damage the pattern and the whole flask system have to be vibrated to allow compactness along the sand mold. Liquid metal poured into the pattern via pouring cup after compaction, evaporating the PS and forming desired cast parts(Figure 1.32b).

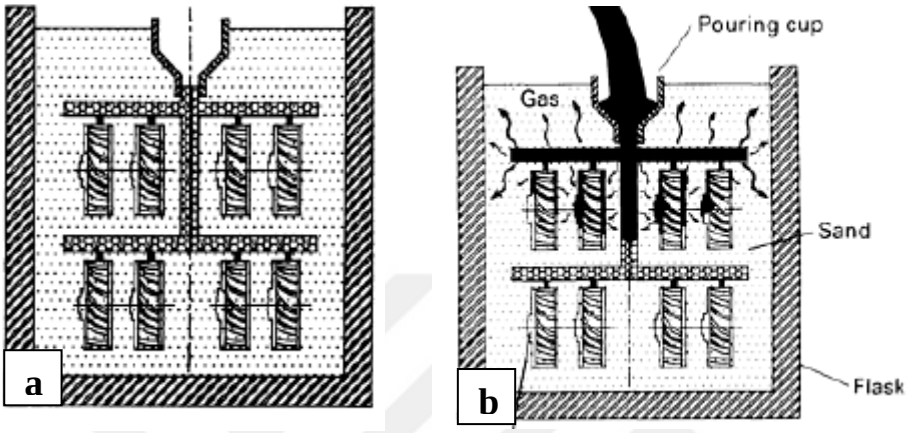

Figure 1.32 a)Sand filled flask. b)Pouring of molten metal [1]

The advantages of lost foam casting are; easiness of process, no cores needed, sand recovery, reduced labor requirements and finish processes, availability of casting complex shaped part[1].

Plaster mold casting

Plaster mold casting employs a slurry plaster material for coating around the pattern. The plaster has to be baked in furnaces to remove excess water and cure to its servicing state after the pattern is removed and plaster get set. This method is suitable for casting of non-ferrous metals like aluminum (especially 3xx series), copper, magnesium and zinc alloys. High reproducibility of complex shapes like impellers (Figure 1.33b) or electronic parts with close tolerances and minimum wall thickness of 1.5 mm is possible[2].

The surface properties of plaster mold casting products are excellent. Due to slow cooling provided by plaster, the damage of thin sections while solidification is eliminated. However, it is not as economical as sand casting or investment casting as mold processing takes some time and additional vacuum equipment might be needed to improve permeability[1,2].

The slurry mixture contains %50-60 gypsum ($CaSO_4.1/2H_2O$) and filler materials (cement, talc, fiberglass, wollastanite). Depending on desired mold properties like permeability, strength, different types of materials and percentages can be chosen. Then water is added into dry mixture to prepare plaster slurry. Once the slurry is ready to use, it has to be poured into flask immediately and carefully without allowing the plaster get set. The molds dried in the ovens for an appropriate temperature and time range to remove water trapped inside the mold system. The molds will be ready for casting after the placement of cores and assembling as shown in Figure (1.33a).

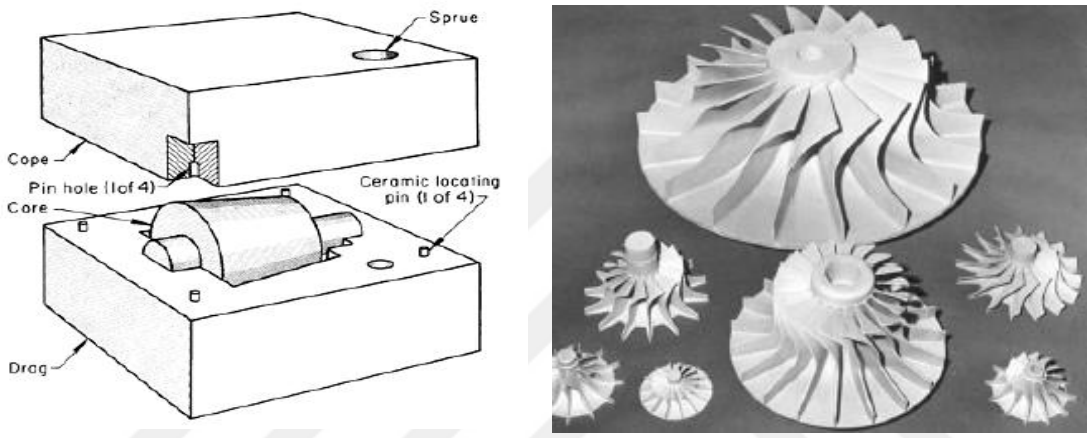

Figure 1.33 a)Mold assembling[1] b)Alloy 224.0 impellers produced by plaster casting [2]

Investment Casting

Investment casting commonly employs ceramic coated low temperature melting point materials e.g. waxes or plastics as casting patterns. Two main processes developed for investment casting; solid mold and ceramic shell process. Since solid mold process is only suitable for small dental and jewelery castings, nowadays ceramic shell process is the first choice for investment casting engineering products[1].

In ceramic Shell process, waxes are the most common pattern forming materials as they have low viscosity, low price, low melting point. Besides, waxes provide wide range of adjustability upon the injection, dimeonsional, mechanical, fluidity etc. properties. paraffins and microcrystalline waxes are widely used than the other types like ozocerite, candellile, beeswax…Waxes are generally blended with resins, fillers, plastics to gain

dimensional stability, strength to improve handling and reducing solidification shrinkage[1].

Waxes are injected in a pattern via extrusion process regarding to their pyhsical state. Wax patterns then placed onto a cluster, which holds multiple patterns together and provide large number small parts production with one casting operation. The clusters dipped into a slurry ceramic bath to form a ceramic film around the patterns. This operation repeated severally until the desired coating thickness achieved. Stuccoing of ceramic films after every dipping prevent cracking and bonding the ceramic layers together[1].

Coated clusters are heated to melt wax patterns and create mold cavities inside ceramic coating(dewaxing). Produced Shell molds are fired to high temperatures (870-1095 ^{o}C) remove excess water, remaining pattern materials, sintering the ceramics and burnout organic compounds coming from slurry. Molten metal poured into ceramic shells through the sprue of the mold to fill the pattern cavities. After solidification of liquid metal, the sand mold covering the ceramic shells removed[1].

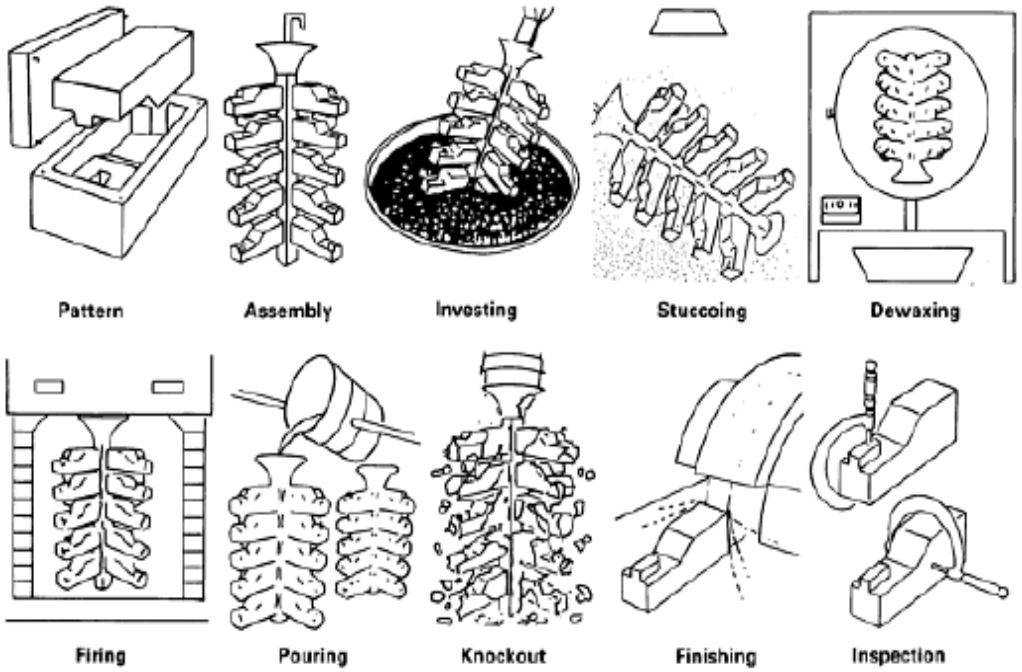

Figure 1.34 Investment casting steps [1]

Vacuum Mold Casting

Vacuum mold casting involves binderless sand molds that hold together between plastic films (0.05-0.1 mm thickness) made of different polymers, LDPE, HDPE, nylon, PP, EVA (Ethylene vinylacetate) with the help of applied vacuum[1]. Selected plastic films heated to coat all over the pattern which contains ventilation holes at the beginning of the process. Then a vacuum (up to 400mmHg/53 kPa) applied to adhere plastic film tightly on the pattern[28]. A special designed vacuum flask equipment is placed either side or on top of the pattern and filled with unbonded sand. The system shaken gently and vacuumed at the same time to compact the sand within the flask. After cutting sprue and pouring cup sections on the cope (upper mold), another plastic film streched over the sand mold and vacuumed again to adhere. The vacuum applied on pattern turned off for separating the pattern from the flask to obtain the cope[29].

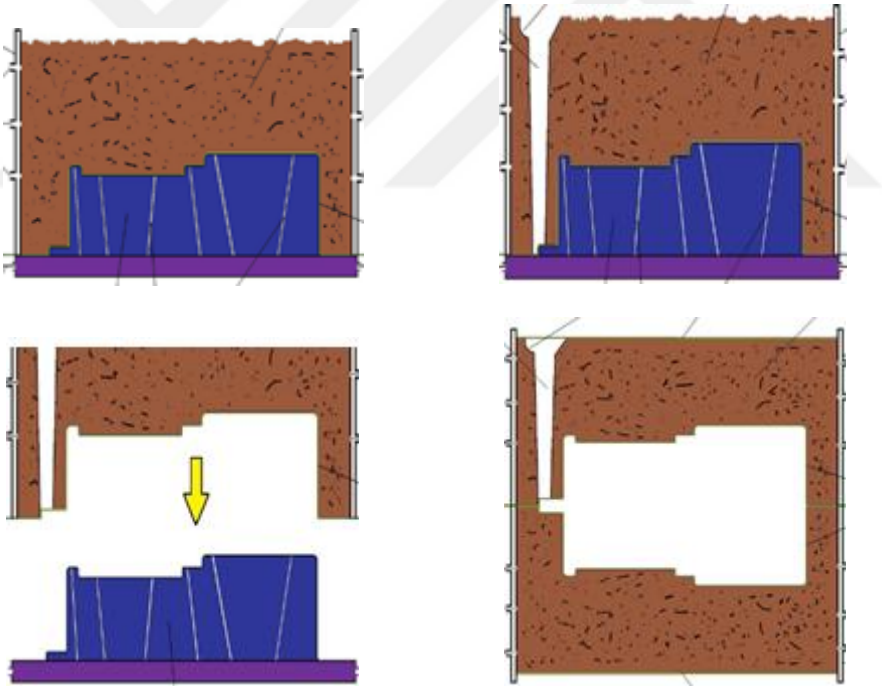

Figure 1.35 Mold preparation of vacuum casting a)drag b)cope c)pattern removal d)mold assembly[29]

The same steps applied for obtain drag (bottom mold) and two halves of the mold assembled. The liquid metal poured into the mold cavity evaporates the plastic films while filling the mold and gases extracted from the system by vacuum pressure. When the product solidified, all the vacuum turned off for release excess sand inside the flask

and reveal final casting. The surface conditions of products are excellent due to lack of water content inside the molds[29].

Although it is not a common method for automation applications and high production rates, the reclamation of sand is much easier than other sand casting methods since no binder is necessary to keep the sand molds together. Besides, the cost of binder is eliminated by this process[1].

Shell Mold Casting

Shell mold casting is a sand casting type which the attached molds are actually shells of resin bindered sand only 10 to 20 mm thickness[2]. The molds are formed by coating the lubricated surfaces of a heated pattern (175-370 ^{o}C) integrated upon a sand box facing to a resin binder containing sand pool[29]. The mixture of sand then poured or blown over the pattern to allow the sand stick onto the pattern surface[2].

The reaction between sand and hot pattern surface forms a sand shell. The Shell is ejected from the surface of the pattern after baking process which hardens the shell for better handling. Same procedure followed to produce the other half of the shell mold and two halves attached together. To prevent leakage, shell-molds buried in casting sand or metal shots before casting liquid metal[29].

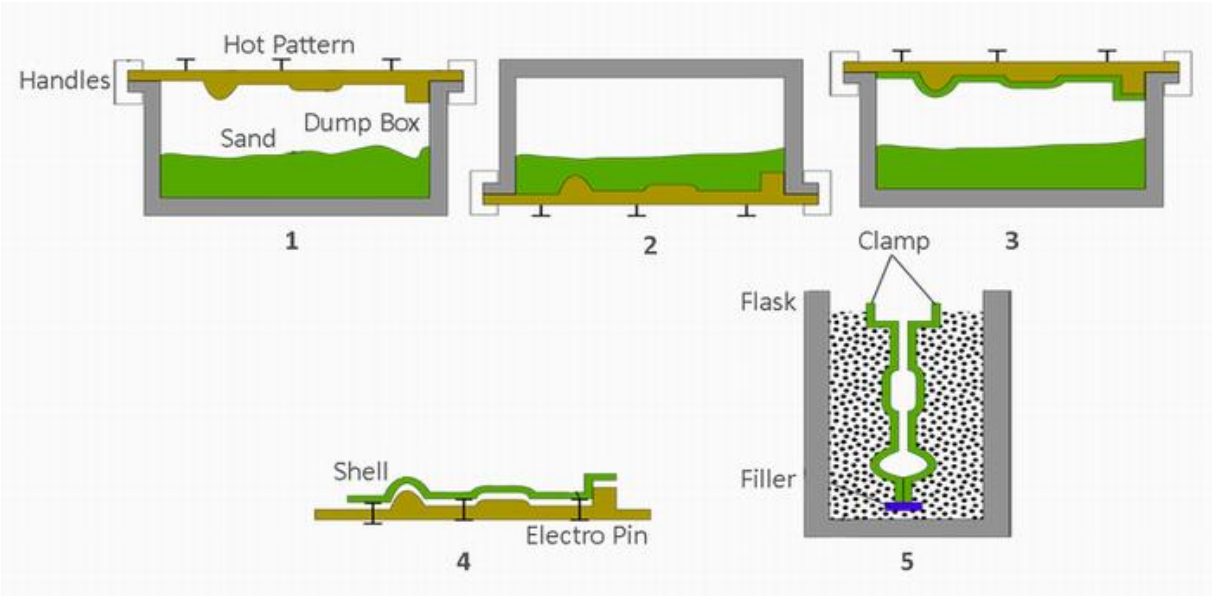

Figure 1.35 Shell mold casting steps [30]

Shell mold casting facilitate good dimensional accuracy and surface quality than green sand castings so further machining may not be necessary. However, since shell-molds contain resin binders, proper ventilation is a must for extracting excess gases. Larger production required to compansate the cost of equipments and binders[29].

1.2.4.2 Permanent Mold Casting Variations

Centrifugal Casting

involves a rotating mold that pushes the molten metal through the mold wall with centrifugal forces. The heat is extracted by mold wall to allow the liquid metal solidfy. The products are isotropic, high quality and inclusion-free. Utilization of gates and risers isn't a necessary. Centrifugal casting is a suitable production method for casting cylindrical or tubular shapes generally[2]. Two basically similar yet different variations of centrifugal casting has developed; Horizontal Centrifugal Casting and Vertical Horizontal Casting[1].

A horizontal centrifugal casting machine can be seen in Figure 1.36 below. The rotating mold placed on a carrying roller that enabling mold diameter changes consist of Shell, spout, roller tracks and end plates. Both expendable and permanent (steel, copper, graphite) molds regarding to quantity or quality of the products[1].

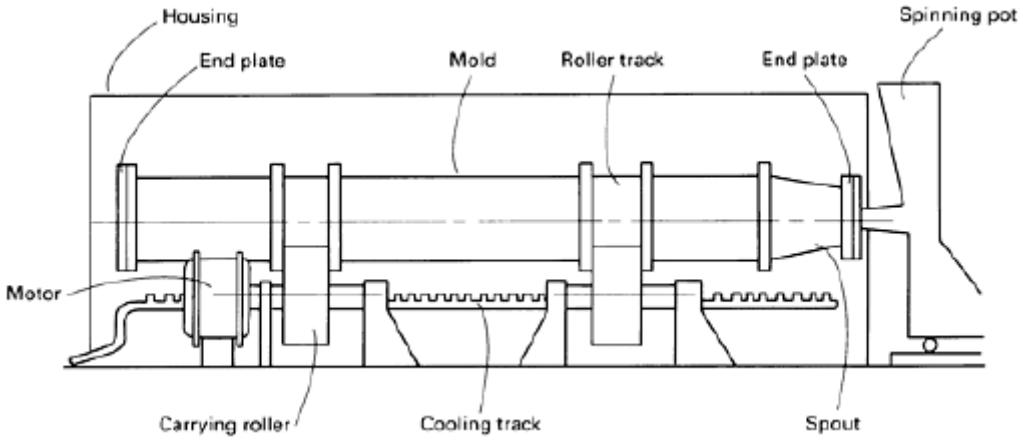

Figure 1.36 Horizontal centrifugal casting system[1]

Pouring quantity of molten metal depends on the final dimensions of the product. Slow pouring rates can cause lap formation and gas porosity as well as low casting temperature. Rotation speed of the mold have to be precisely adjusted to push the molten metal towards the mold wall with minimal vibration to obtain uniform structure.

High-strength low alloy steels, duplex stainless steel, Cr-Mo steel and bimetallic tubes can be produced with horizontal centrifugal casting[1].

Unlike horizontal centrifugal casting, a vertical centrifugal casting consist of a rotating mold about a vertical axis as seen in Figure 1.37. Applications of vertical centrifugal casting is broader than horizontal version. Casting of unsymmetrical or non-cylindrical parts are possible. Higher strength parts can be obtained than static methods[1].

Different types of vertical centrifugal castings used for production of wheels, gear blanks, impellers, rotors, valve bodies etc. Many materials, from metal to non-metal, which can be liquidized for pouring can be cast with vertical centrifugal casting. The cautions taken on horizontal centrifugal casting process parameters are also valid for vertical centrifugal casting[1].

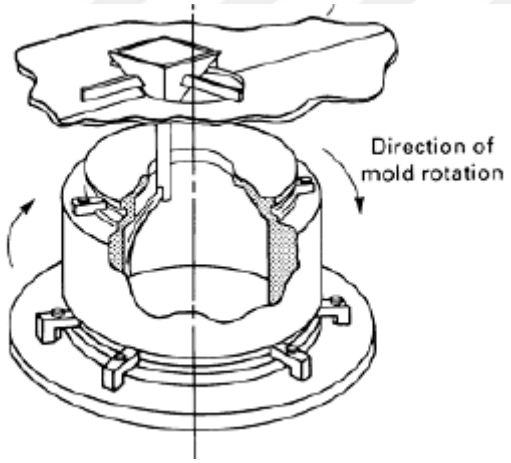

Figure 1.37 Vertical Centrifugal Casting Components [1]

Squeeze Casting

is a duality of forging and casting processes. The molten metal poured into lubricated die cavity gets pressed by a forging tool up to 140 MPa pressure until the melt completely soldified (Figure 1.38) [1]. The applied pressure helps to extract heat within the die effectively, providing a fine microstructure products. Constant pressurizing transfers remaining molten metals into porosities formed during solidification to prevent shrinkage porosity[2].

Squeeze casting suits for production of ferrous and non-ferrous materials that has wide solidification range[2]. This process requires a lower casting temperatures as mold

filling accomplished by applied pressure. Care should be taken on melt volume, pressure level and duration and temperature of the toolings[1].

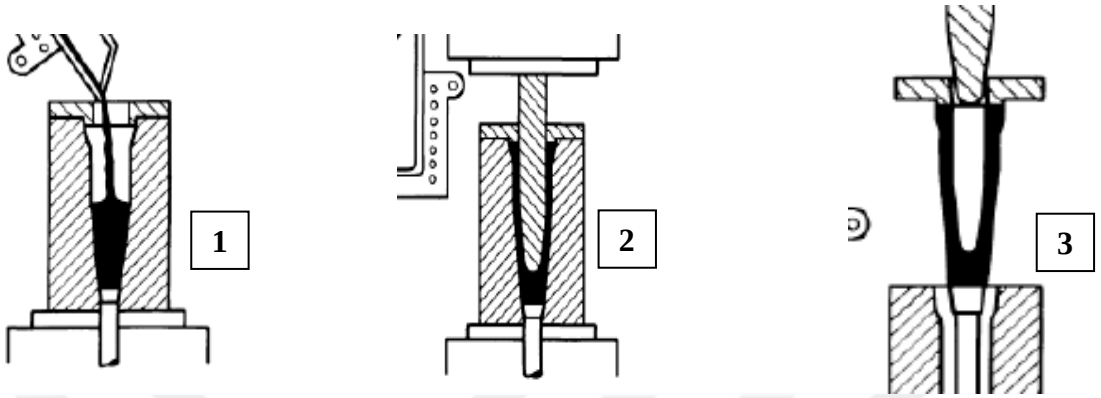

Figure 1.38 Steps of Squeeze casting [1]

Semi-solid Casting

also known as rheocasting, thixo-casting firstly discovered by MIT in 1970's[31]. The process is based on forging, casting and extrusion of a semi-solid material that exhibits high viscosity adequately to protect its shape (like butter or cheese) when standing still and low viscosity (nearly as oil) under shearing stresses that enough to fill the mold cavities like liquid metals even at high solid fractions between solidus-liquidus range[1].

The reason of this unique behavior is the spherulite microstructure of the billet materials . Semi-solid state of forged billets prevent turbulance while casting thus reducing porosity forming posibility. There is also no danger of shrinkage porosity as the cast metal not actually melt[2,32].

Low Pressure Die Casting

is an application of counter-gravity casting[5] uses permanent molds integrated onto a molten metal crucible. The molten metal is carried up to the mold through a filler tube with applied air pressure on molten metal bath (Figure 1.39). The pressure retained until the metal solidifies in the mold and then released for drop back the excess molten metal into the crucible.

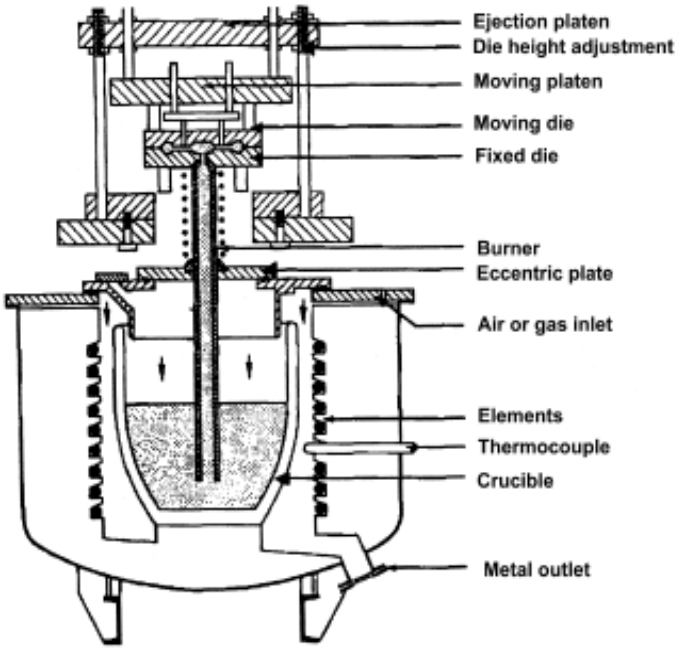

Figure 1.39 Low Pressure Die Casting system[2]

Primary parameters for this method are applied pressure value, pressure application rate and thermal gradients. Minimal pressures up to 0.5 bar is fairly enough for rising the metal into mold cavity[5].

Desired thermal gradients can be achieved and managed by appropriate section design of the mold. The main risk of this process which may result with low quality production is formation of oxides in the filler tube while cast part removed from the molds. This situation can be overcomed by whether applying a back pressure or attach valves on the filler to prevent the falling of molten metal into crucible again and again after each cycle[2].

Vacuum Riserless Casting

shares the same dynamics with low pressure die casting method. The only difference comes from applied vacuum instead of pressure to rise the molten metal into the mold cavity. The only advantage of the vacuum is the maintaining molten metal level tighter so the distance between mold and crucible can be minimized[2].

According to [1] this process can be utilized for multiple number production of small sized components for automative, aerospace and other miscellaneous industries with a variety of methods using investment casting molds(Figure 1.40);

Counter gravity low pressure of air melted alloys (CLA)

Counter gravity low pressure of vacuum melted alloys (CLV)

Check Valve Casting (CV)

Counter gravity low pressure air melted sand casting (CLAS)

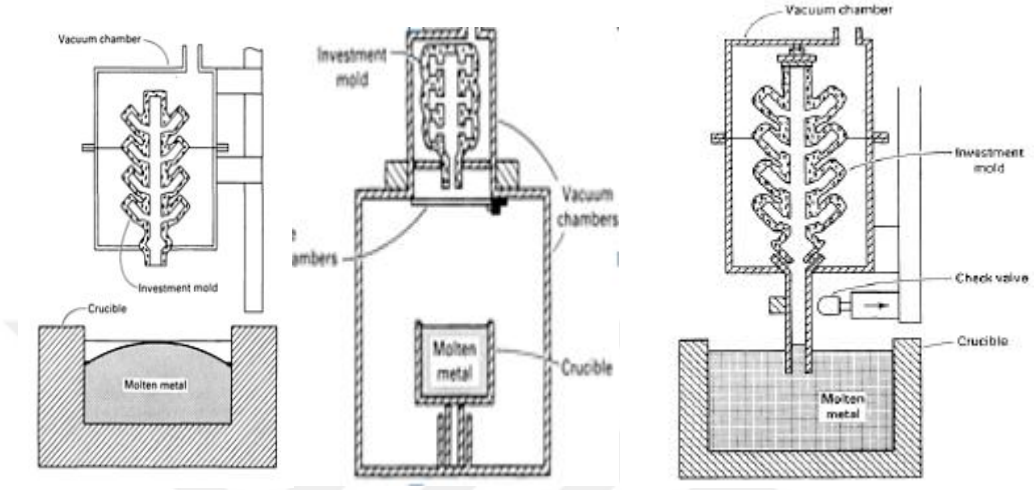

Figure 1.40 a) CLA b) CLV c) CV schemes [1]

Ablation Casting

Ablation Casting is a recently developed sand casting process, patented by J.Grassi et. al. in 2011(patent). The word ablation firstly used in a US-moon shot program. Ablation means carrying away the heat generated by the friction between atmosphere and spacecraft capsule by erosion of ceramic tiles mounted in front of the capsule to prevent whole aircraft vaporising while returning to the earth. In terms of casting, ablation is the erosion of the soluble binder bonded aggregate mold with a cooling liquid jet[6].

Like other aggregate mold castings, the process starts with pouring liquid metal into the mold cavity, then things get really different. In other sand casting methods, aggregate molds are broken by shaking-off only to reveal final product, after complete solidification. In ablation casting however, dissipation of the mold takes place during the solidification with applied liquid jet. The liquid jet is not just useful for dissipation of the mold.

Figure 1.41 Ablation of aggregate sand mold by a water jet[34]

Actually, the main aim of the liquid jet application is eliminate air gap between molten metal and mold. Also, the cooling liquid directly contacts with the solidifiying hot metal. The absence of air gap and direct contact of the cooling jet creates a large amount of temperature gradient and increase solidification rates of casting, thus reduce porosity and secondary dendrite arm spacing (SDAS)[35]. The effects of reducing porosity and grain size results with better mechanical properties[6]. The product will be ready for further operations after all of the aggregate material washed away (Figure 1.42)

Figure 1.42 Completion of ablation casting[34]

Advantages of Ablation Casting

a) The formation of gas layer between molten metal and the mold at non-permeable casting methods prevents the heat extraction. In contrast, higher solidification rate is achievable with ablation casting, due to effective cooling of liquid jet [34,36]

b) Higher solidification rates yields a fine eutectic and grain microstructure with a narrow secondary arm spacing(SDAS), compared to other non-permeable casting methods. This is a substantial advantage for refining eutectic microstructure of Al-Si alloys as the necessity of modification elements like Na and Sr is eliminated[5].

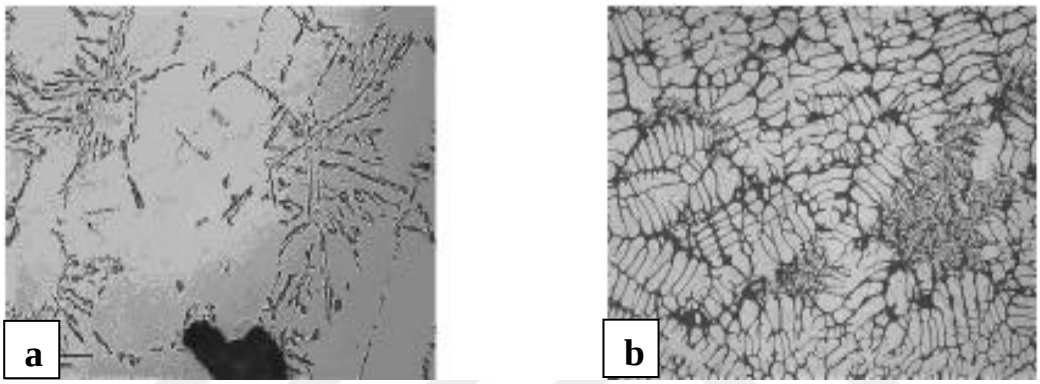

Figure 1.43 a)Unmodified eutectic structure b)fine eutectic microstructure of ablation cast Al-7Si-Mg (356.0)[35]

c) Another benefit of higher solidification rate is reducing gas porosity forming during solidification. As the hydrogen obeys the same rules of diffusion and nucleation rules as crystal phases, there is not sufficient time for a stable hydrogen porosity growth before reaching critical diameter. Lower porosity percentage yields denser and sound casting products[36].

d) Both lower porosity content and fine microstructure results better mechanical properties. In fact, according to literature, the mechanical properties achieved with ablation casting is competitive with permeable and high pressure die casting methods let alone non-permeable casting methods. [5,34,37]

e) Because even the basic silicate-based binder aggregate molds are suitable for ablation casting, the smell and toxic steam arised from chemical binders are hindered. The process itself can be considered clean and environmentally friendly[6].

f) With the elimination of all costs arising from chemical binders, permanent molds, additional equipments for sound castings, modification elements etc., the process surely can regarded as cheap[5].

Practical Applications of Ablation Casting

As previously mentioned, the ablation casting is a recently developed and examined process. So recent that any automation system is yet to be produced. The first commercial customer of ablation casting is the automobile industry. Various aluminum alloy cast parts including steering knuckle, chassis joints is produced with this process[34].

Altough it is not completely integrated to mass production, the commercial products of ablation casting (Figure 1.44a) already won a prestigious casting of the year award in last year. The products are utilized for space frame joint members of a sports car[38].

Figure 1.44 Ablation cast a)joints[38] b)steering knuckle c)B206 alloy swing arm[34]

Apart from aluminum, ablation casting also gave better results for magnesium alloys for automative products according to literature[39]. The customisation for high melting point ferrous alloys and copper alloys is still in advance, promising positive developments[5,6].

CHAPTER 2

2. MATERIALS AND METHOD

2.1 Experimental Procedure

In this study, the microstructures of conventional sand cast and ablation cast A356.0 aluminum alloy parts were investigated and compared with each other. The alloy composition has given in Table 2.1 below, casting sand and silica sand mixture containing 5 wt% bentonite clay and water used for aggregate mold material. Four casting procedures managed for this experiment to gather one conventionally sand cast and three ablation cast parts.

Table 2.1 Composition of A356.0 Al-Si alloy

Al (%)	Fe (%)	Si (%)	Cu (%)	Mg (%)	Zn (%)	Na(%)	Sr(%)	Ti (%)
92,04	0,19	7.2	0,03	0,42	0,01	0.0012	0,0001	0.1

In the preparation of sand molds, aggregate mold material is mixed with water until the amount of water reaches an optimum level to keep sand particles together when compressed. The greensand is filled in a wooden frame and rammed to achieve a compact sand mold. For preparation of upper mold (cope) a wooden L-shaped pattern placed in the frame and buried in the aggregate sand material. Pattern is covered with talc and sculpted from the sides to be given a draft angle that in contact with aggregate sand for easy removal without damaging the cope. The cope is placed onto the drag after pattern removed and the mold is ready for casting.

After mold preparation, aluminum ingots (which are cut for fit in the refractory crucible) pre-heated up to 500^{o}C in *Protherm Alser Teknik* resistance furnace as shown in Figure 2.2. The melting furnace is also heated to 815^{o}C simulteanously. The pre-heated aluminum ingots carried into the melting furnace when the heating of melting furnace is complete. After allowing ingots completely melt, the crucible took out from the furnace and liquid metal poured into the mold cavity, followed by the ablation of sand mold with water and rapid solidification of liquid metal. Then the castings given a

sufficient time for cooling at room temperature and cut again to obtain samples from predetermined sections(Figure 2.1).

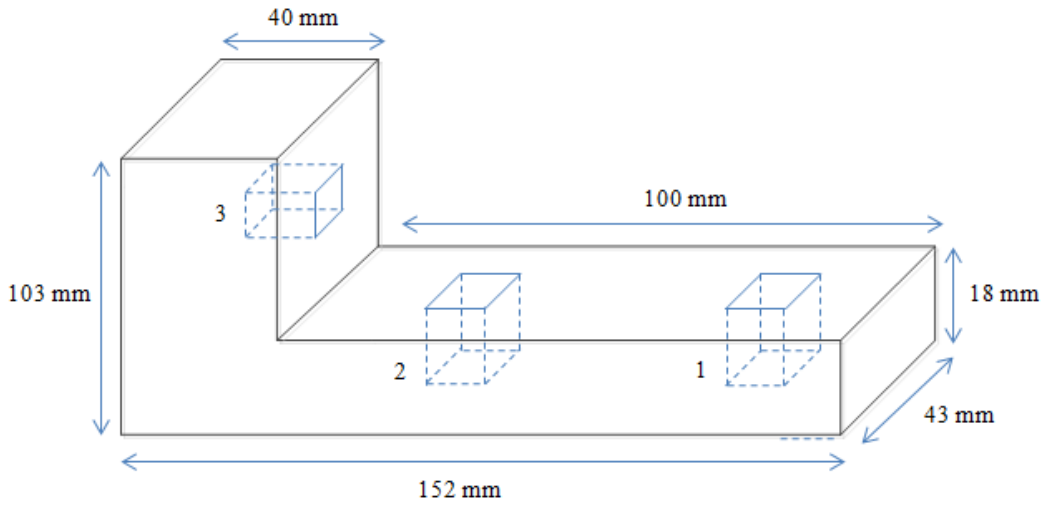

Figure 2.1 Dimensions and sample sections of cast part

Samples were cut into smaller pieces in *Struers Discotom-5* cutting machine with 0.4 mm/sec feed speed. In this cutting machine, the cooling water is applied to prevent the heat and material burr that formed by cutting steel effect. At second step, mounting machine was used to provide convenience handling to be able to use sample in grinding, polishing and optical microscope stages and to eliminate shaking during grinding and polishing. Struers ProntoPress-10 type mounting machine was used under 43 kN pressure at 180ºC for 12 minutes and Hitit phenolic mounting powder was used. Mounting method is shown in Fig 2.2.

Figure 2.2 Mounting method by using Struers ProntoPress-10 mounting machine.

At third step, *Struers LaboPol-21* type grinding machine was used to remove the roughness on the sample surface. Surface damages and deformations by cutting must be removed by grinding. Grinding method with abrasives that starts with coarse ones and graduates to fine ones. In the order of P320, P600, P800 and P1000 abrasive cutting mesh numbers were used for grinding with a suitable coolant to remove debris and heat. Each mesh number was used for up to 3 minutes. The most important thing in grinding method is to remove the roughness and prevent the occurring of swelling on the surface.

At fourth step, *Struers LaboPol-21* type polishing machine was used to create a shiny and smooth surface for optical microscope. 0.5 micron liquid alumina (Al_2O_3) used for polishing as a chemical action.

At the last step before the observation in optical microscope, etching was applied to the samples. Etching is a chemical process to dissolve undesired metal. It also destroys the deformed surface that occurred during grinding and polishing stage. Etching method was applied by using an etchant that obtained by adding 3 ml sodium hydroxide (NaOH) into 300 ml pure water. Samples were immersed into etchant for 30 seconds. Then the samples were first washed with water and then washed with pure alcohol.

At the observation step in microscope, two types of microscope were used. One of them was *SOIF Optical Instruments* and the other one was *Nikon Eclipse L150*. 40x, 100x and 200x magnification levels were used in *SOIF Optical Instruments* microscope whereas 50x, 100x, 200x and 500x magnification levels were used in *Nikon Eclipse L150* microscope as shown in Figure 2.3.

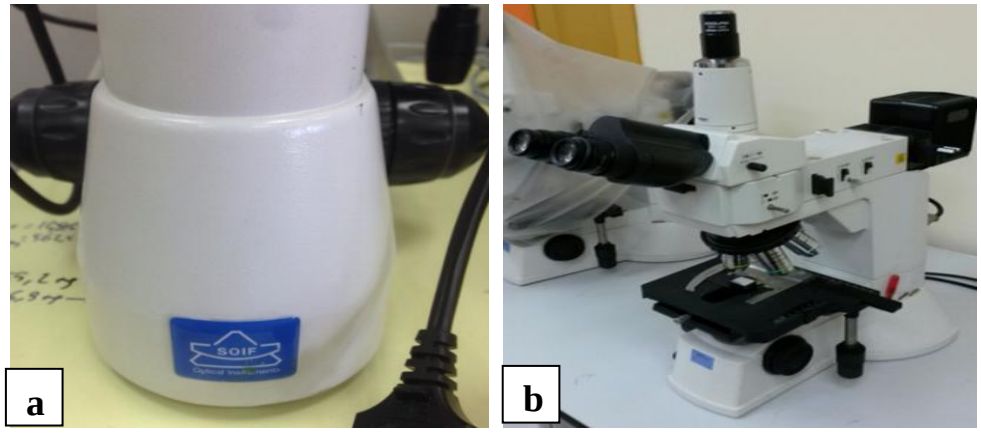

Figure 2.3 Optical microscopes: a)SOIF Optical Instruments, b)Nikon Eclipse L150 microscope

CHAPTER 3

3. RESULTS AND DISCUSSION

As mentioned in Chapter 2, three successful casting processes was fulfilled for this experiment. In this section, the microstructure analysis of both sand cast and ablation cast samples will be briefly explained below. Each samples were given numbers as seen on Table 3.1 below, corresponding to respective sections within the cast part shown in Figure 2.1.

Table 3.1 Sample numbers of cast alloys

	Ablation Casting						**Sand Casting**		
Sample No	E1	E2	E3	E4	E5	E6	E7	E8	E9
Sample Zone	1	2	3	1	2	3	1	2	3

3.1 Sand Casting Results

The microstructures of selected samples of sand cast part can be seen below figures. The microstructre exhibits typical sand casting properties. The coarse and needle shaped Si eutectics are clearly visible. The grain size of Al matrix so large that the dendritic structure of the grains are hardly distinguishable at certain zones (Figure 3.1a-b)) due to slow cooling rates. The formation of porosities also pretty obvious as a result of hydrogen entrainment(Figure 3.2a-b).

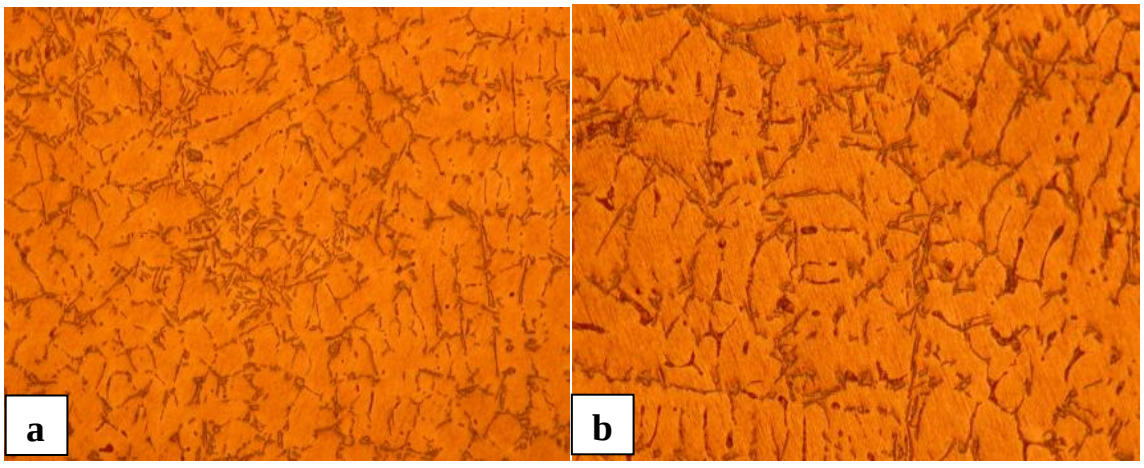

Figure 3.1 Micrographs of sand cast part a) microstructure of sample E7 and b) E9

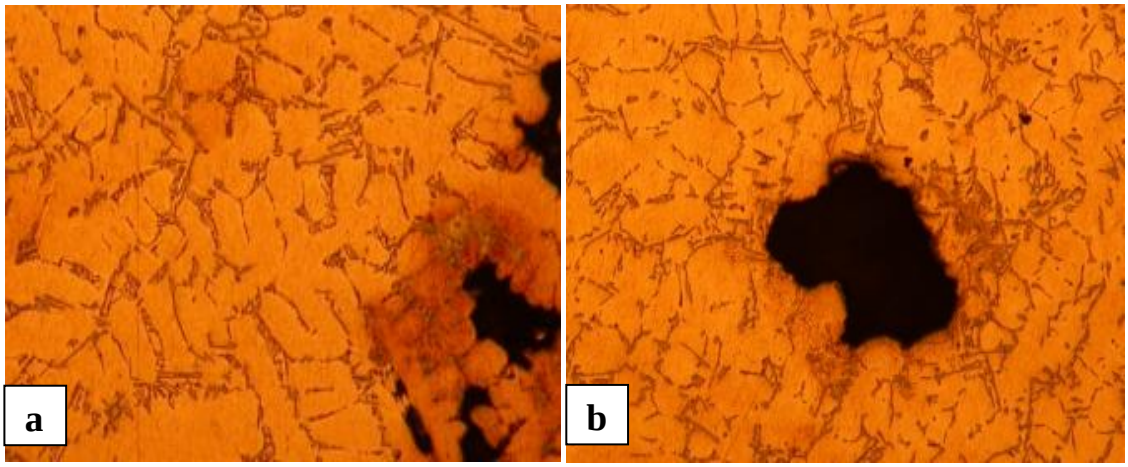

Figure 3.2 Hydrogen porosity in the sample E8 and d) E7 (50x)

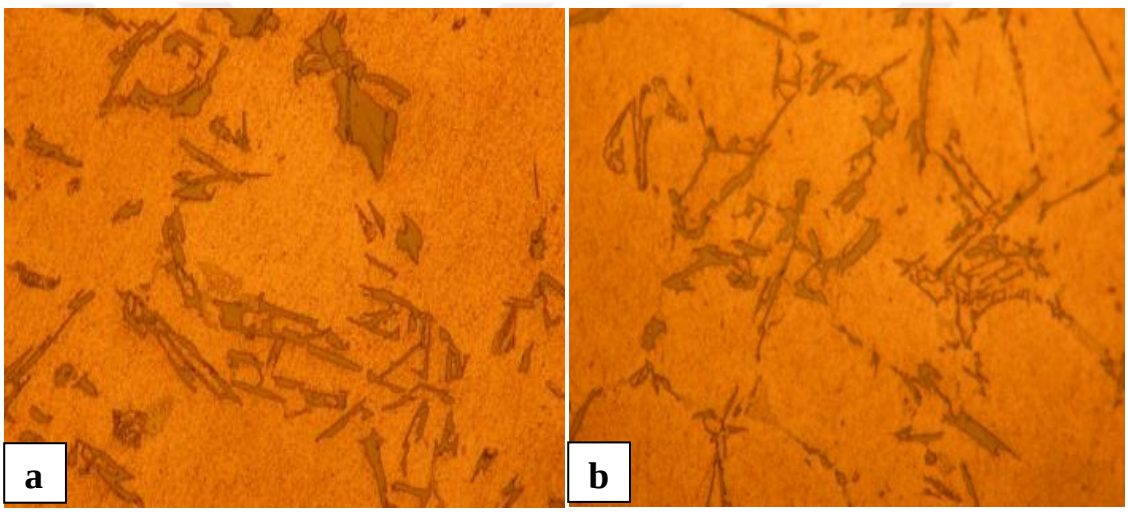

Figure 3.3 Eutectic structure of a) E7 and b) E8 samples (200x)

3.2 Ablation Casting Results

Microstructures of samples belonging to ablation cast parts remarkably different from sand casting samples. The dendritic structure of Al matrix is explicit and grain sizes of both Al grains and Si eutectics are refined to as a result of rapid undercooling caused by direct contact of cold water while ablation of the aggregate sand mold. The current Si eutectic structure matches the chemically modified structure. The transformation of microstructure matches with previous studies of J.Grassi et.al [35] and M. Taghipourian et.al. [37].

Figure 3.4 and 3.5 depicts the microstructure of the sample cast in black casting sand as aggregate mold material. The bonding strength between black sand particles and clay-water mixture was relatively low and this caused handling problems during mold preparation resulted with minor collapsed regions along the cope. Sand mixture has to be compressed tightly to overcome this problem, however it will affect the dispersion of aggregate sand, hence the effectiveness of ablation with water. Nevertheless, the microstructures proves that there is an interaction between soldified metal and water jet.

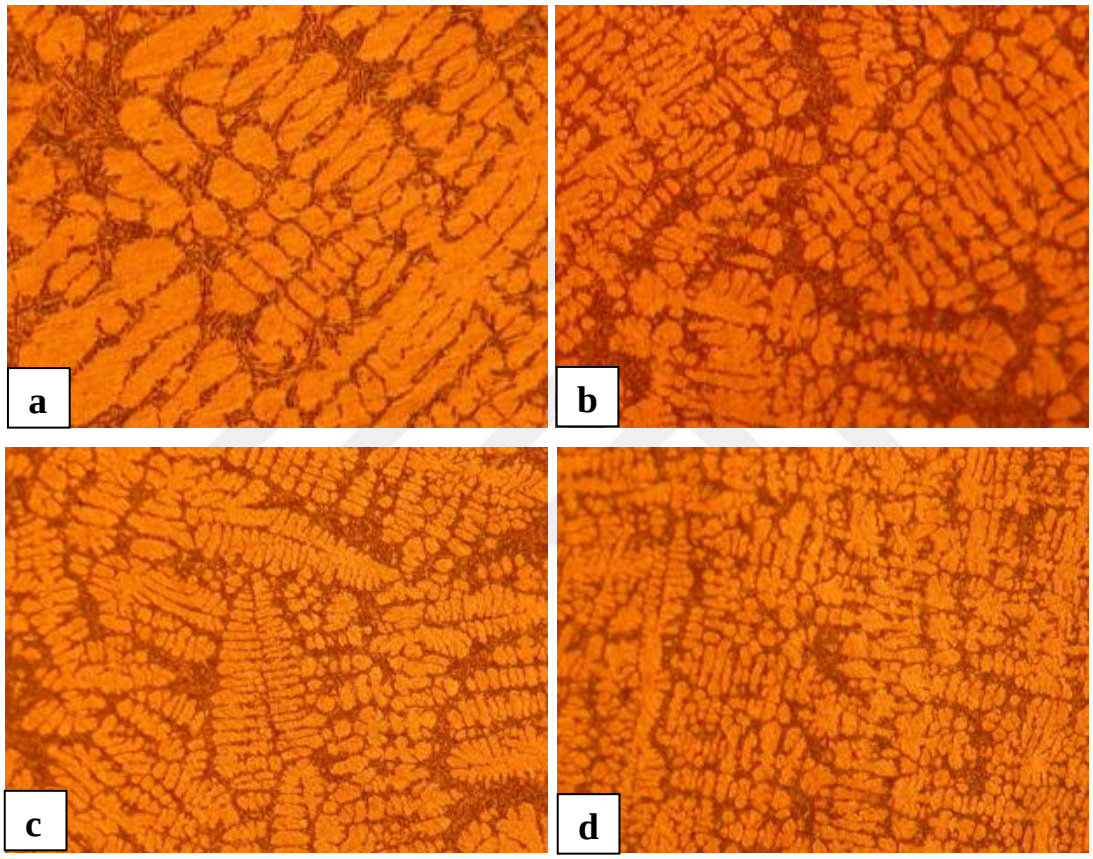

Figure 3.4 Micrographs of ablation cast part a-b) microstructures of sample E5 and c-d) E6 (50x)

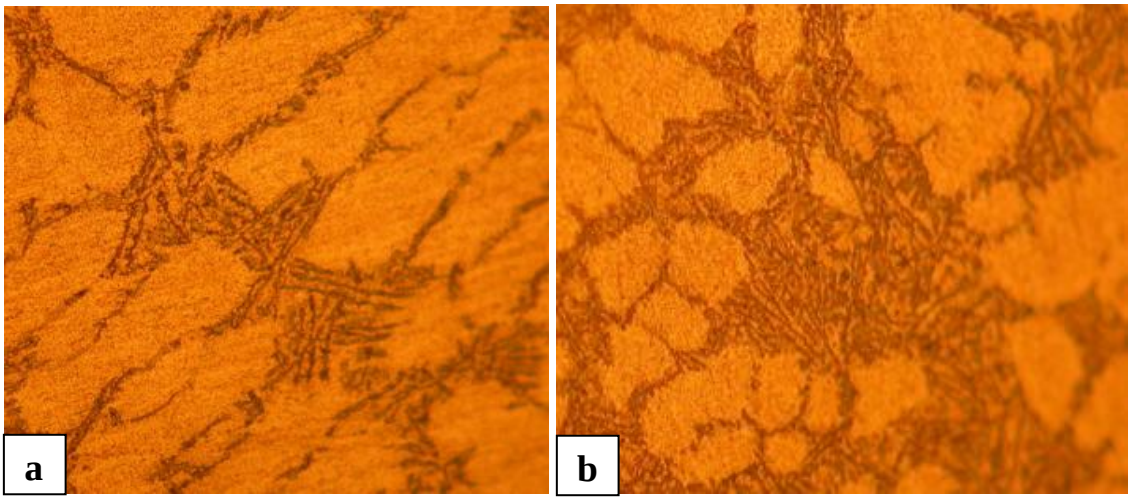

Figure 3.5 Refined Si eutectics along the Al grain boundaries within the ablation cast part (200x)

The microstructure of the part cast with silica sand-bentonite-water mixture resulted with better results in every aspect. The bonding strength was relatively higher than the black sand mold material, so the cope and drag prepared without collapsing danger while handling and casting even though lower compression forces applied, leading better dispersion characteristics of aggregate mold material, enabling water penetration and elimination of reduced ablation effect upon soldifiying metal. Moreover, brass chills are placed at the far side of the cavity to initiate a rapid solidification at the tip of the molten metal(Fig.3.6).

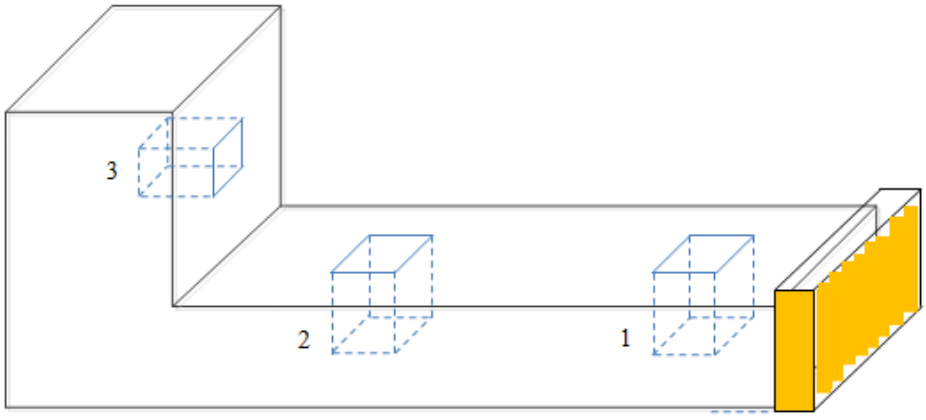

Fig 3.6 Placement of brass chill in the cavity and sample zones.

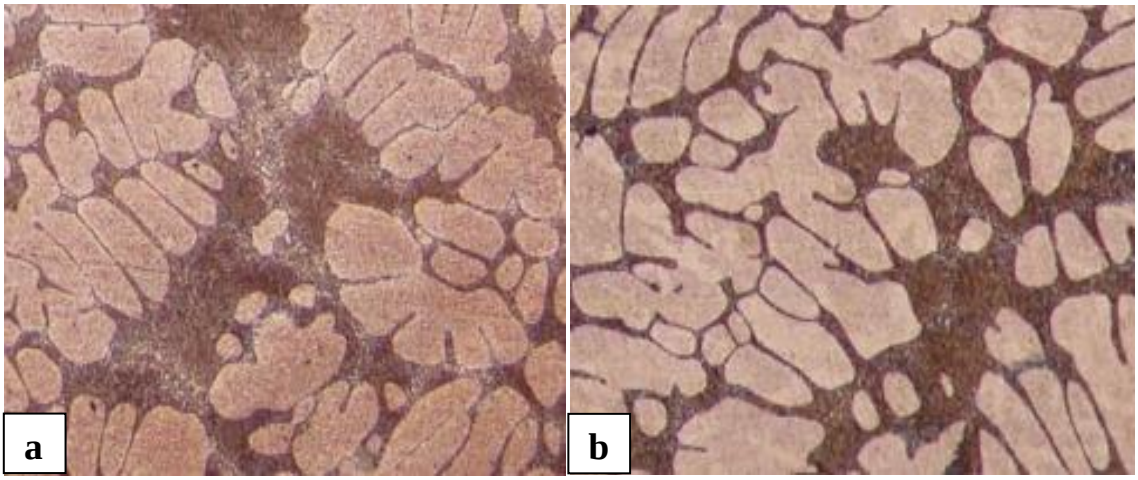

Figure 3.7 a) Refined structure of sample E11 b) E12 samples (50x)

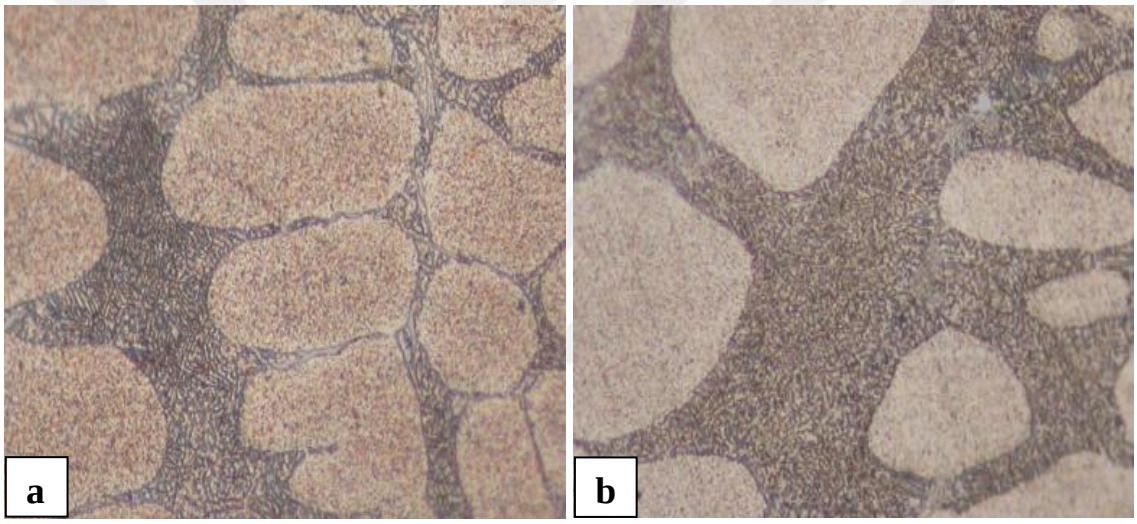

Figure 3.8 a) Extremely fine eutectic microstructures along Al grains of samples E11 b) E12 (200x)

It is clearly visible the eutectic structure is extremely fine to distinguish even at 200x magnification (Figure 3.8), so that the ablation is more effective with usage of silica sand as the water disperse more easily and increase undercooling of the molten metal. The eutectics become clearly visible at 500x magnification as can be seen in below figures(Fig 3.9a-b). Also, the microstructure of this cast part resembles with the earlier studies in the literature much more than the microstructure of the first ablation cast part(Fig 3.10), indicating a more successful process.

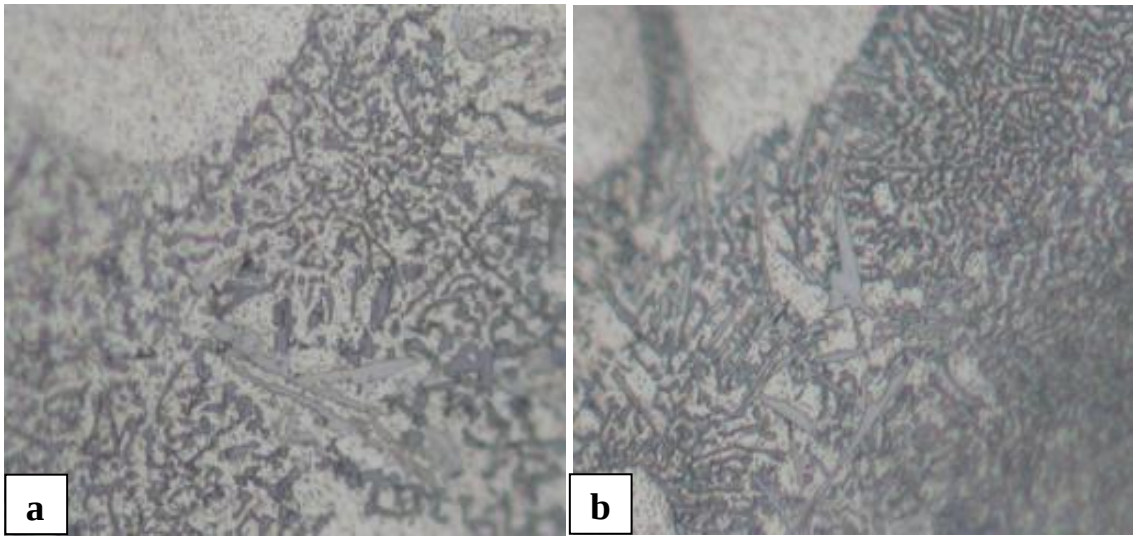

Figure 3.9 a) Extremely fine eutectic microstructures of samples E10 b) E12 (500x)

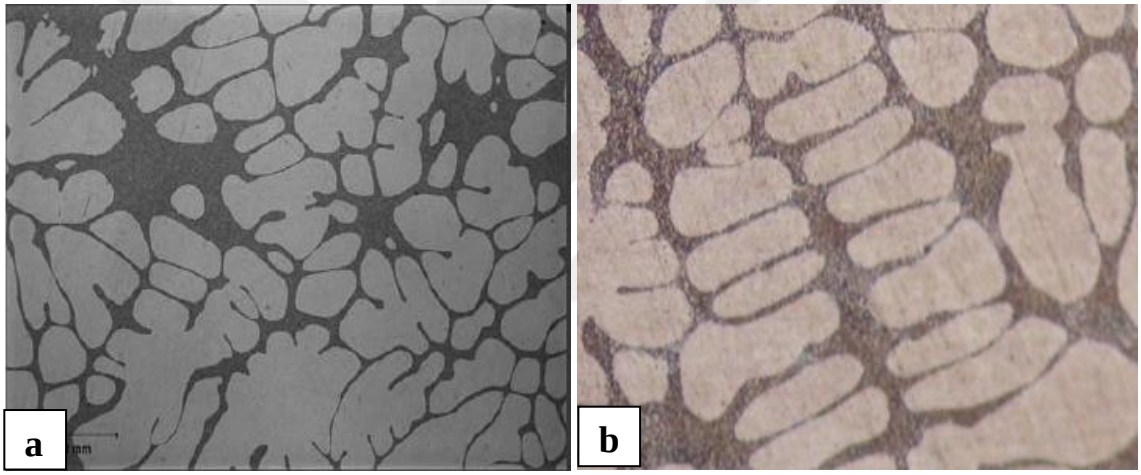

Figure 3.10 Microstructures obtained a) at earlier studies b) in this study

3.3 Secondary Dendrite Arm Spacing Results

The secondary dendrite arm spacing (SDAS) of the samples are calculated with both theoratical and experimental methods and exhibited in the table below(Table 3.2). Theoratical calculations are calculated by using the formula below (Eq 3.1);

$$\lambda_2 = K(Mt_f)^{1/3} \quad (3.1)$$

where K and M are constants[16] and t_f is local solidification time.

According to the datas given the M constant is calculated as $1.19x10^{-17}$ m^3/s, and K constant equals to 5.5 according to the experiments of Feurer and Wunderlin[16]. However, Kirkwood had a different approach upon this constant and his experiments yields K=5[40]. Theoratical SDAS is calculated with both constants.

For experimental values, linear intercept method is followed which based on the counting the numbers of intersections caused by the drawn line on the magnified graphic of the microstructure.

$$\lambda_2 = d/(n.m) \quad (3.2)$$

where d is actual length of the drawn line, n is the number of intersections and m is the magnitude of optical microscope. The figures of the measured microstructures are depicted below.

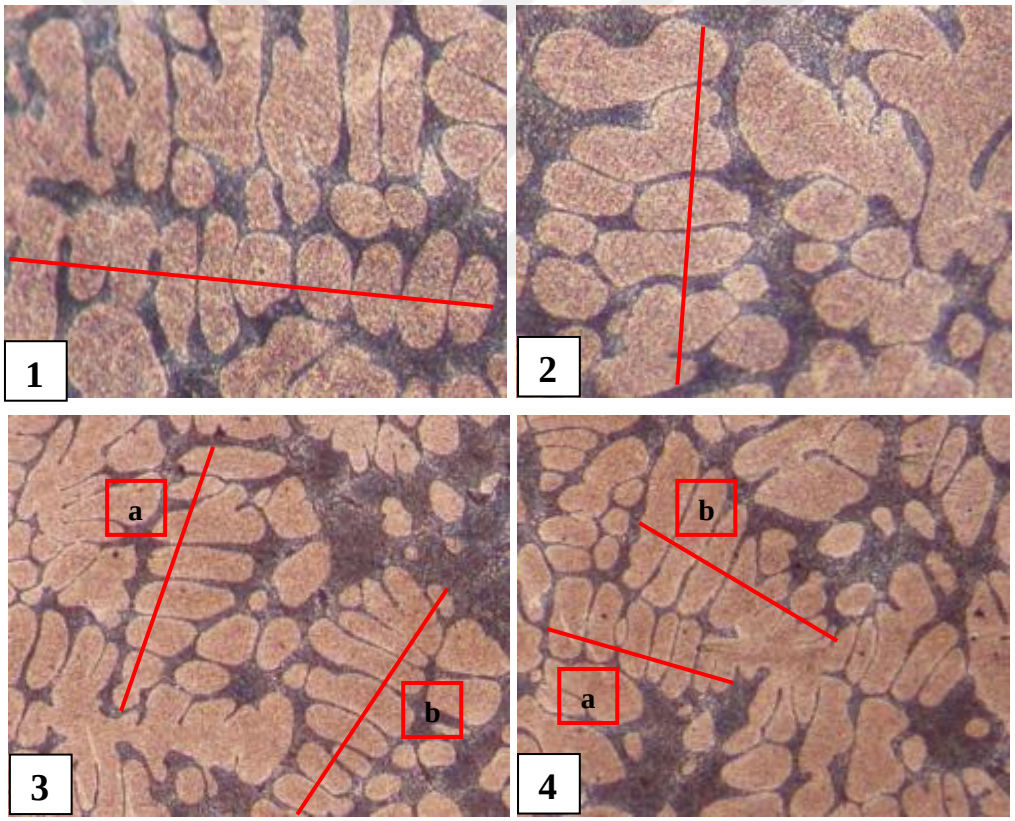

Fig 3.11 Microstructures of experimentally measured SDAS, Figure 1-2 is 100x and Figure is 3-4 50x magnification (Ablation Casting with Silica Sand)

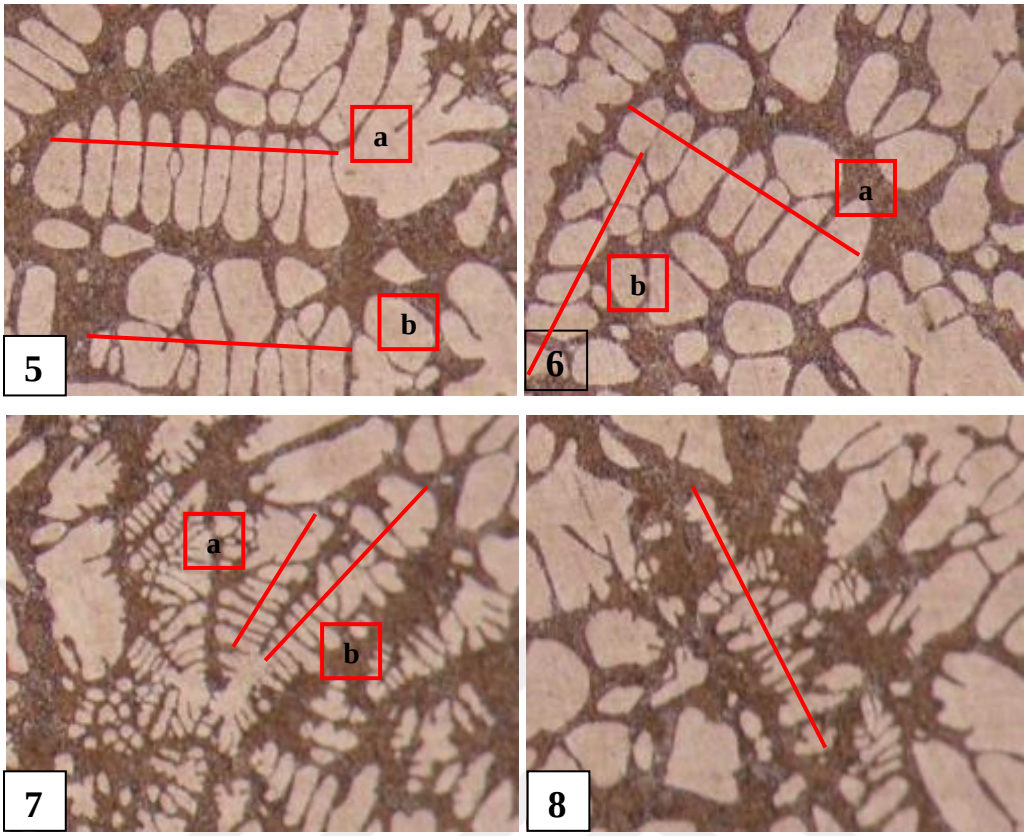

Fig 3.11(Continue) Microstructures of experimentally measured SDAS, 50x magnification (Ablation Casting with Silica Sand)

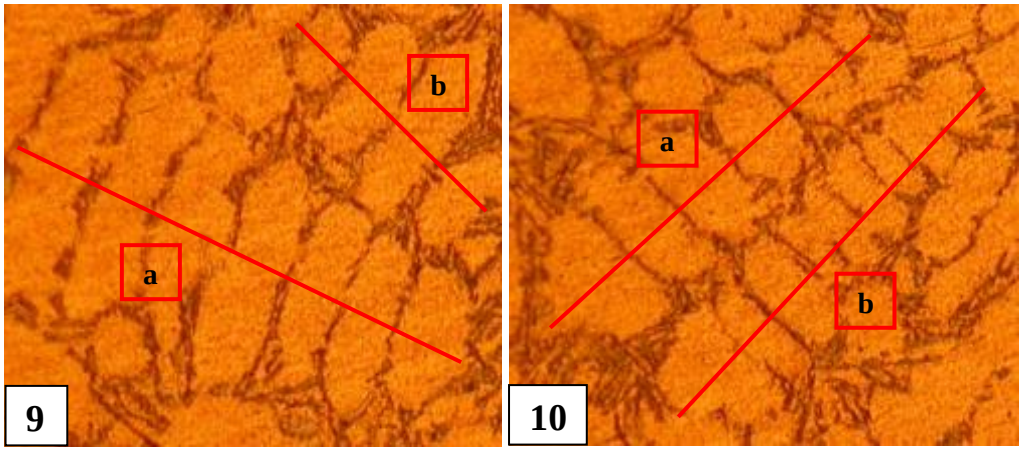

Fig 3.12 Microstructures of experimentally measured SDAS, 100x magnification (Ablation Casting with Black Casting Sand)

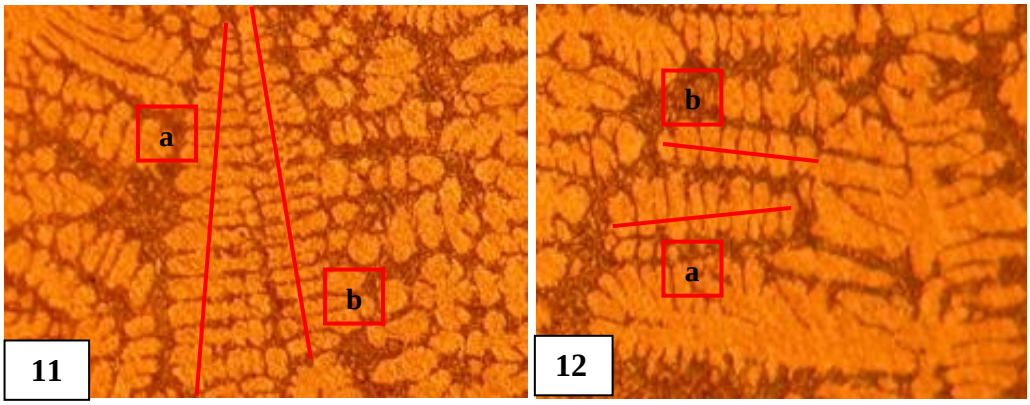

Fig 3.12(Continue) Microstructures of experimentally measured SDAS, 50x magnification (Ablation Casting with Black Casting Sand)

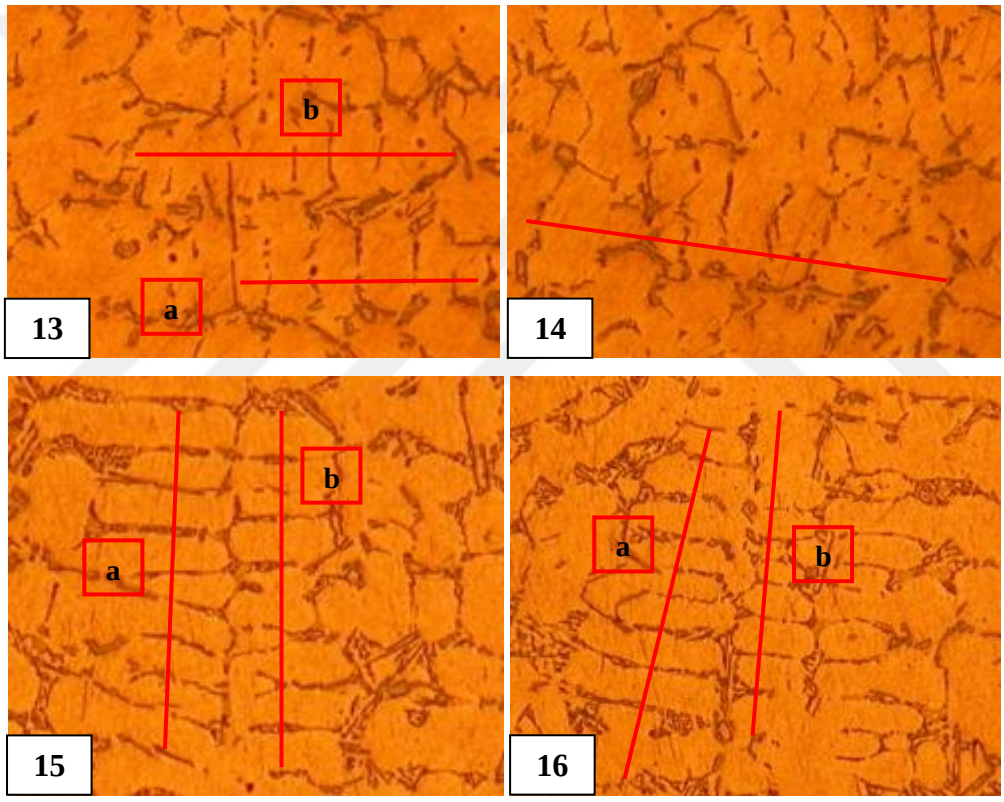

Fig 3.13 Microstructures of experimentally measured SDAS, 50x magnification (Sand Casting with Black Casting Sand)

The required t_f values for theoratical calculations are obtained by determining the t_f value corresponding with experimental SDAS values on the SDAS-Local solidification time graphic which acquired by G.K Sigworth[41], since measuring the cooling rate for this thesis was unlikely.

The measurement results are exhibited on the table below. Note that some values for sand casting procedure are missing because it is impossible to determine the t_f values from the mentioned graphic as the curve does not reach up to the calculated experimental SDAS values.

Table 3.2 Experimental and Theoratical SDAS Values

				Theoratical λ2 Values	
		tf (s)	Experimental λ2 Values	F&W	Kirkwood
Ablation Casted with Silica Sand	1.	130	42	63,6	57,8
	2.	200	49	73,4	66,7
	3.a	890	80	120,7	109,8
	3.b	600	70	106	96,2
	4.a	300	55,5	84	76,4
	4.b	390	58	91,74	93,4
	5.a	290	52,3	83,1	75,5
	5.b	400	60	92,5	84,1
	6.a	400	60	92,5	84,1
	6.b	440	64	95,5	86,8
	7.a	150	45,7	66,7	60,6
	7.b	100	40	58,2	53
	8	100	40	58,2	53
Ablation Casted with Black Casting Sand	9.a	820	77,5	117,5	106,8
	9.b	410	62	93,3	84,8
	10.a	800	72,85	116,5	105,9
	10.b	400	60	92,5	84,1
	11.a	180	45,71	70,89	64,45
	11.b	185	46,6	71,5	65
	12.a	100	38,3	58,3	53
	12.b	120	42,2	61,93	56,3
	12.c	300	54,2	83,5	76
Sand Casted with Black Casting Sand	13.a	1400	97,1	140,4	127,7
	13.b		146,6		
	14		137,5		
	15.a	1100	90	129,6	117,8
	15.b	1200	93,3	140,4	127,7
	16.a	1100	90	129,6	117,8
	16.b		114,2		

It is pretty obvious that the SDAS of the ablation cast samples is much more smaller than the SDAS of the sand cast samples. To make a comparison between the microstructures of both ablation cast samples, one should consider these facts; the SDAS values seems to be quite similar to each other but the SDAS values of the casting which silica sand used are ranging 40-60µm whereas the SDAS results of the other ablation cast part are 45-75µm. The SDAS range for this experiment are shown on the graphic below to compare with other casting procedure values.

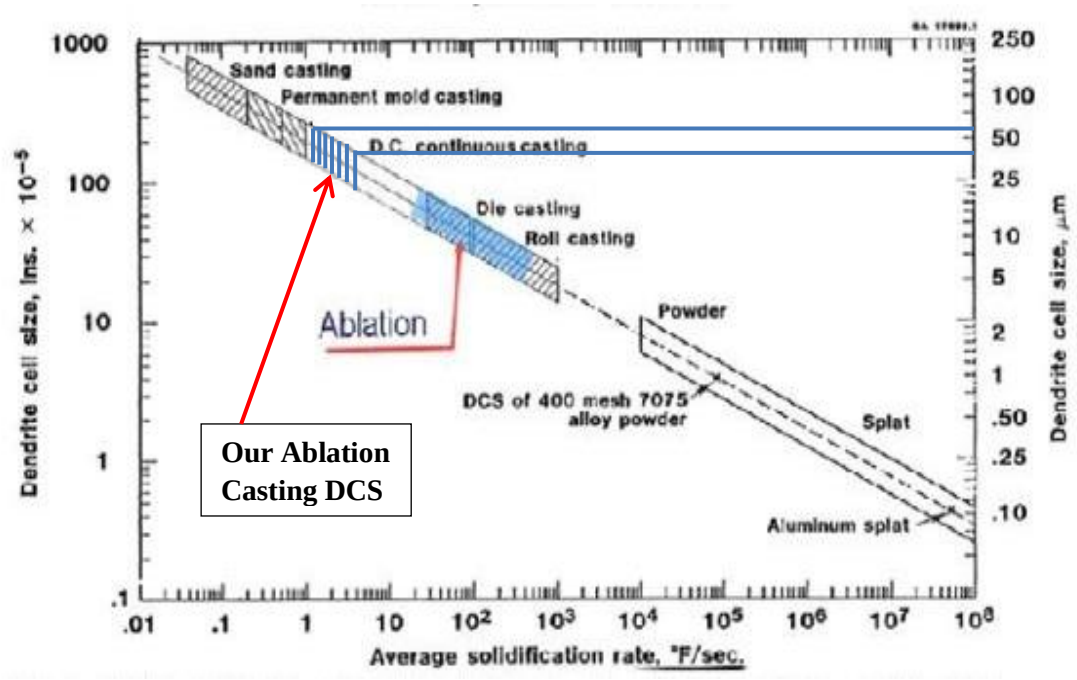

Fig 3.14 Relationship between cooling rate and dendrite cell size for various casting processes[42].

Moreover, the water spray is applied on the silica sand used casting nearly 30 seconds later after the pouring the molten metal to allow the metal form a solid shell, whereas water spray applied immediately after pouring on the other ablation cast part. Despite the time difference water cooling application between both casting procedure, the silica sand used casting resulted with better SDAS values and finer eutectic structure due to better water penetration through the sand mold as stated earlier. Grain size could be reduced further if the waiting period for water spray application is shortened.

3.4 Mechanical Properties Results

The mechanical properties of the samples wasn't measured since the cast parts contain too many closed porosities within the bulk due to lack of vacuum degassing during melting. The mechanical properties of the samples would be deceptive in the current material conditions.

However, the samples of sand cast and ablation cast parts subjected to solution heat treatment with varying durations and their hardness was measured in another thesis studies[43]. The researchers obtained below graphics. The final hardness value of the ablation cast sample doubles the sand cast sample's value at 3 hours of solution heat treatment. The hardness level of ablation cast part subjected to 12 hours of solution heat treatment is relatively lower than the chosen sand cast sample. Yet, the hardness value of the ablation cast part surpasses again the final hardness value of the sand cast sample.

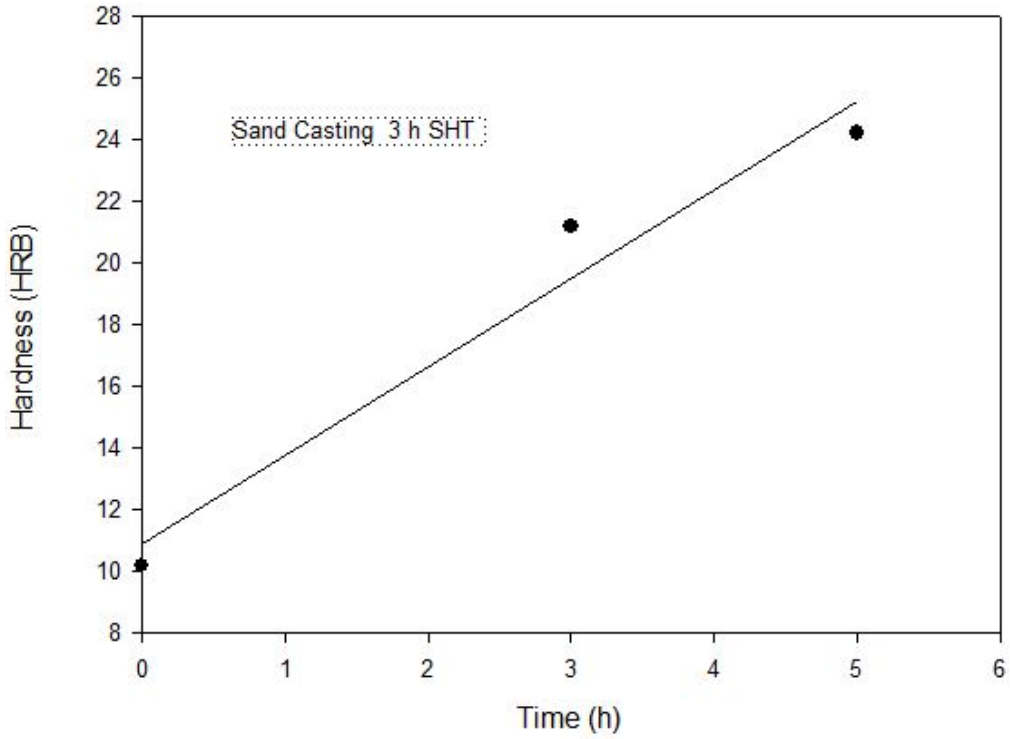

Fig 3.15 Hardness increment of the sand cast sample with 3h solution heat treatment[43]

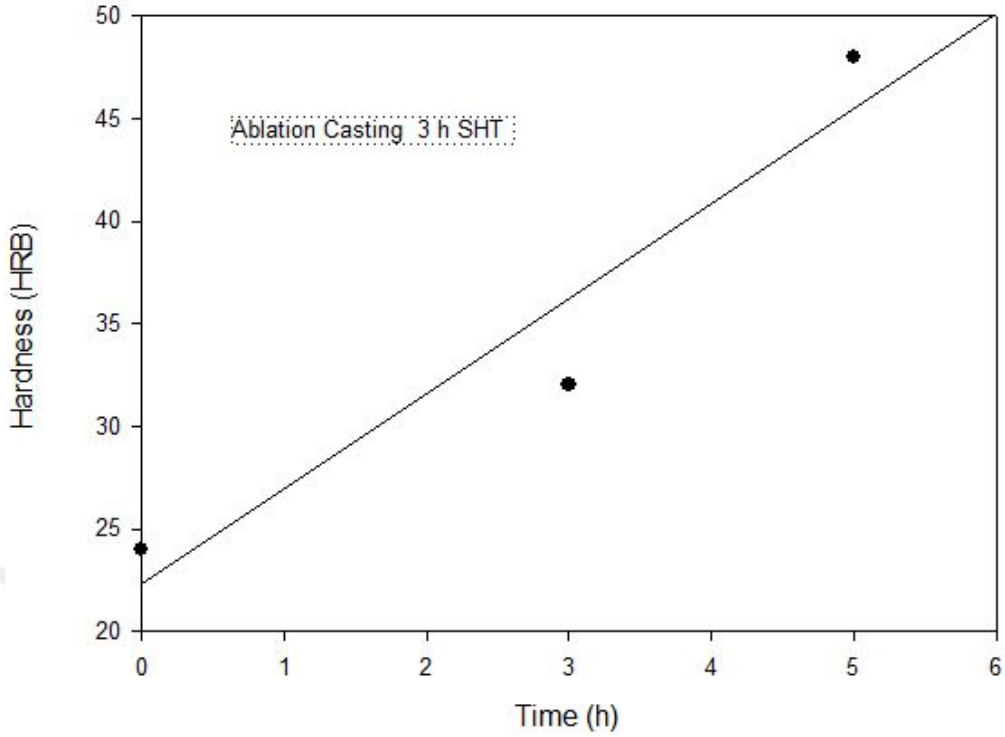

Fig 3.16 Hardness increment of the ablation cast sample with 3h solution heat treatment[43]

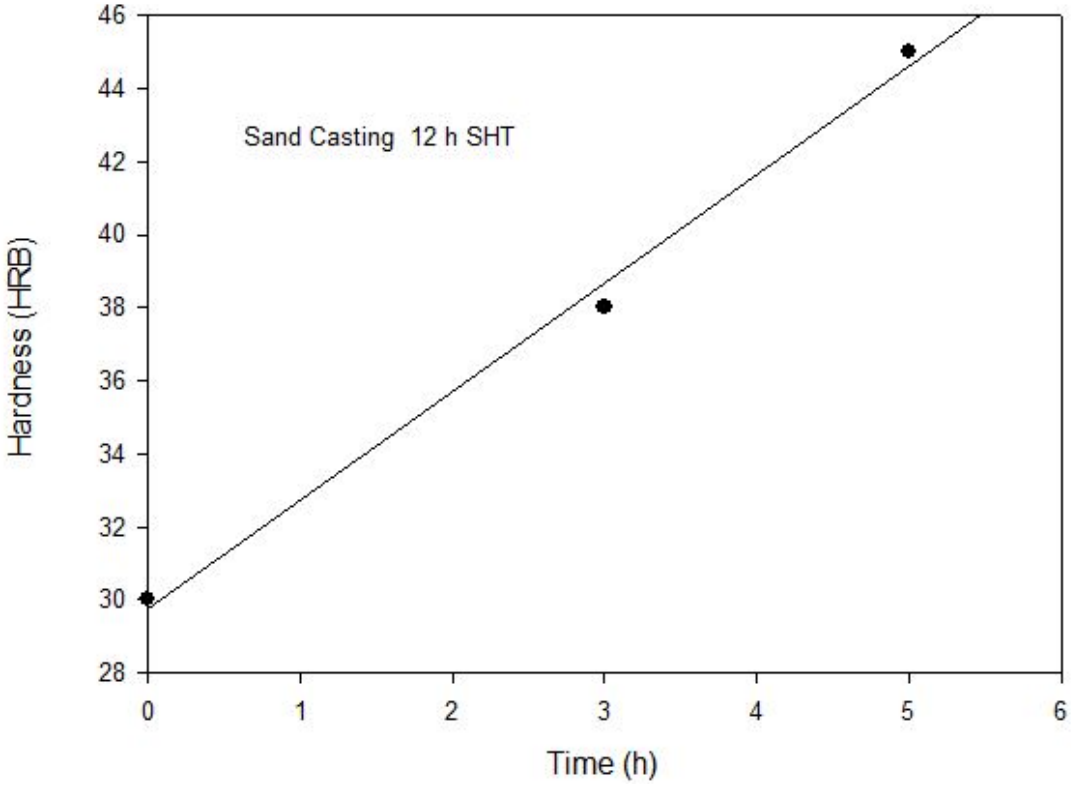

Fig 3.17 Hardness increment of the sand cast sample with 12h solution heat treatment[43]

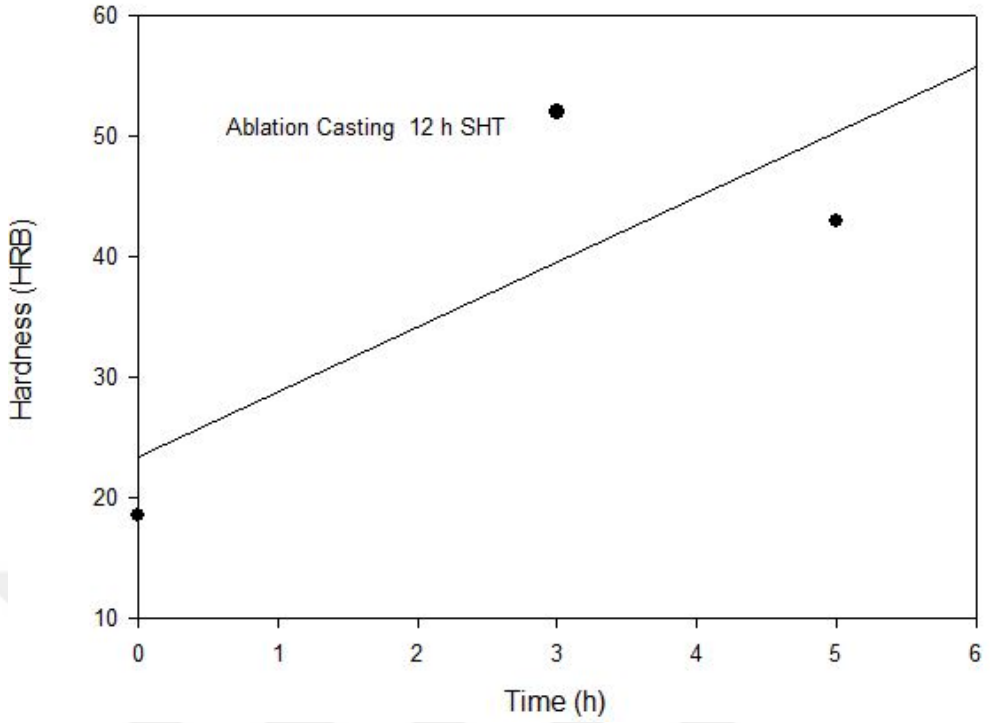

Fig 3.18 Hardness increment of the ablation cast sample with 12h solution heat treatment[43]

CHAPTER 4

4. CONCLUSIONS

- In this experiment, the ablation casting and sand casting microstructures of A356.0 Al-7Si-Mg alloy using bentonite clay containing greensand mold was investigated.
- It was observed that, the microstructure of ablation cast alloy is obviously finer than the sand cast alloy.
- The direct contact of the cooling water with cast alloy increased undercooling rate and resulted fine Al-matrix grain size and Si eutectic structure.
- Hardness of ablation cast product upon solution heat treatment is greater than conventional sand casting product.
- The requirements and cost of eutectic modification elements like Na and Sr is eliminated.
- The cost of chemical soluble binders, and high integrity casting equipments are eliminated and minimized, respectively.
- Harmfulness upon environment is avoided.

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ÖZGEÇMİŞ/CURRICULUM VITAE

EGE DEMİRTAŞ (1990)

E-mail : ege_dem@yahoo.com.tr

Career Targets:

Firstly, I would like to get my master science degree and be expert at my job to apply my theoretical knowledge in practice. I would like to work in a position where I can use Materials Science and Metallurgical Engineering.

Education:

Master of Science : Marmara University - Metallurgy and Materials Engineering (Eng.) – 2013 - Present (3.72/4.00)

University : Gebze Institute of Technology - Materials Science and Engineering (Eng.) - 2008-2012 (2.68/4.00)

High School : Yuksel Ilhan Alanyalı Anataolian Teacher Training High School-2004-2008 (3.68/5.00)

Work Experience:

1-Cengiz Makina Gebze - September 2015 – (presently) Research and Development Engineer

2-Torun Bakır Alaşımları Metal San. Tic. A.Ş Gebze – January 2014 – April 2015 Purchasing Engineer

3-Alstom Grid Gebze - July-August, 2012 Intern Student

4-Altra Optik – January – February, 2012 Intern Student

5-Diler Demir Çelik A.Ş – July – August, 2011 Intern Student

Trainings:

ISO 9001:2008 - Turkish Standards Institutes (TSE) (2012)

Research and Development Engineer Training Program (Inotec Academy) (2015)

Applied Patent Training (SAU) (2016)

Statistical Process Control (Cengiz Makina) (2016)

Languages:

English: YDS 87.50 (March, 2016)

Undergraduate Thesis:

Supervisor Prof. Dr. Sedat Alkoy

Piezoelectric PZT (Lead Zirconate Titanate) Material Production by Alginate Gellation

Other:

B Type driving license (2009).

7th Aluminum Symposium ALUS'07, 8th-9th October (2015)-'Ablation Casting of 356.0 Alloy and Its Microstructure, report presentation.

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1-Prof. Dr. Altan TÜRKELİ (Marmara University-Department of Metallurgy and Materials Engineering)